

Chapter 1

Introduction

Product design is concerned with the design of products to achieve the desired functionality, where functionality may involve a number of features, such as usage, safety, durability, aesthetics, and social and environmental issues. To cater to the multitude of functionality issues is not a simple task. Moreover, the intense competition in the global manufacturing environment makes the task even tougher. In order to succeed or even to survive, a manufacturer must be able to deliver their products with speed, diversity, high quality, and at low cost. These present a formidable challenge to engineers in product development. There is an apparent appeal for powerful design assisting tools.

In the past few decades, many powerful computer-aided technologies have emerged, such as computer-aided design and manufacturing (CAD/CAM), computer-aided process planning (CAPP), computer-aided engineering (CAE), etc. Artificial intelligence (AI) technologies find broad applications in engineering design to facilitate quicker and smarter decisions. Product data management (PDM) systems are widely used to manage the vast pool of product information throughout the product life-cycle (PLC). Despite these efforts, designers still face tough situations when making decisions at the early design stage. The need for effective design tools to support new product development and ensure product continuity is paramount. This is where design reuse can play an important role. This chapter introduces the rationale of design reuse and the legacy systems in various domains. The major issues to be addressed in design reuse are discussed.

1.1 Design Reuse – What and Why

1.1.1 Types of design reuse

Design reuse involves various activities that utilize existing technologies to address new design problems. The ultimate aim of design reuse is to assist the designers to develop products that maximize the value of the designed artefacts with minimal resources, cost and effort [Sivaloganathan and Shahin, 1999]. Basically, reuse can be divided into three types with respect to the objects to be reused.

- (1) End-of-life product reuse (Type I), which refers to the reuse and recycling of obsolete products or components such that the components or materials can return to the PLC. This results in savings of natural resources and reduction of environmental impacts [Hata *et al.*, 1997; Kimura *et al.*, 1998].
- (2) Reuse of existing manufacturing resources (Type II). Manufacturing processes inevitably consume energy and resources, especially when the manufacturing equipments have to be redesigned, upgraded, or reconfigured. Therefore, the configurations of different products must be designed in such a way that the production processes can be reused and shared. Production cost can be reduced through the utilization of existing manufacturing resources to accommodate the changing production requirements [Kimura and Nielsen, 2005].
- (3) Reuse of product information and design knowledge (Type III). This type of reuse is a prerequisite for the earlier two types of reuse because design ultimately determines the extent to which the products and the manufacturing resources can be reused. In other words, effective reuse of available resources could not be achieved unless the products are designed to be reusable.

These three types of reuse roughly correspond to the reuse activities in the different stages in the PLC, as shown in Figure 1.1. This book focuses on the third type of design reuse, *i.e.*, the various approaches that support the utilization of knowledge gained from previous design activities. This is based on the belief that knowledge/information reuse enables the reuse

of components and manufacturing resources, and hence is essential to sustainable design and manufacturing.

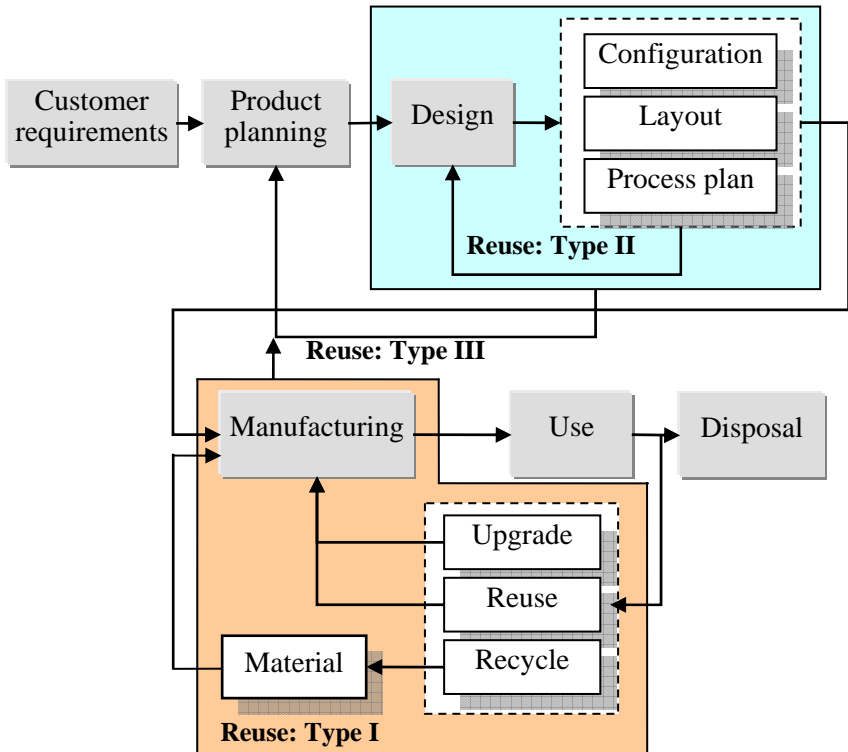


Figure 1.1 Type of design reuse in the product life-cycle

1.1.2 The importance of design reuse

Before an extensive study of the tools to assist design reuse, three fundamental questions have to be answered.

- Why is design reuse necessary?
- Is it possible to apply design reuse?
- Is design reuse methodology effective in product design?

1.1.2.1 Necessity

In today's market, no enterprise can afford the time and resources to design an entire product from scratch. However, wasted work still plagues contemporary product development due to the unavailability of information. Clausing [1998] pointed out two major sources of wasted work, *viz.*, (1) a lack of reusability caused by inadequate planning and excessive variety, and (2) rework caused by a lack of robustness, lack of information, and mistakes.

Reuse of prior knowledge is crucial to design rapidity and continuity. Effective product design requires an efficient retrieval and utilization of information. However, designers are constantly frustrated by the lack of means to access the relevant information. This is not necessarily caused by the paucity of product data. Instead, the proliferation of data makes the retrieval of relevant information a daunting task. Therefore, designers are in a dilemma of being "drowned in data but thirsty for knowledge" [Rezayat, 2000]. There is an urgent need for effective information management based on design reuse.

1.1.2.2 Applicability

In order to apply design reuse, it is required that a set of designed products already exist and the related design information is accessible. This should not be a problem for an established company because there is usually a pool of designed products. Typical in the industry, product development is evolutionary rather than revolutionary. According to statistics, only about 20% of an OEM's investment is on new design while about 80% is on the reuse of existing products, with or without modification [Rezayat, 2000]. Thus, design reuse can be applied in a broad variety of industries. Figure 1.2 shows a typical product development road-map. The horizontal axis is the time divided into years and quarters. A family of products (denoted by the hexagons) is distributed in three tiers, namely the high tier, mid tier and mass tier, according to the market segmentations shown on the vertical axis. The curve on the right shows the production volume in the different market segmentations. From this road-map, it can be observed that there is a constant migration of technologies from the higher end to

the lower end as time proceeds. This ensures the continuation of product development within a corporation.

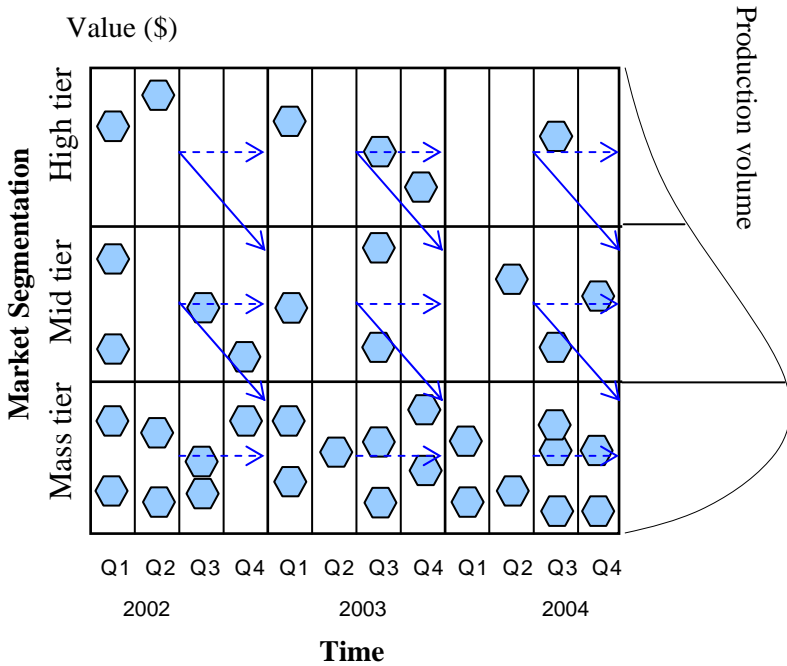


Figure 1.2 A typical product development road-map

1.1.2.3 Effectiveness

The effectiveness of design reuse should be validated by the improvements in the key factors of production, namely cost, quality, and time-to-market. It is expected that production efficiency can be increased because the designers do not have to start from scratch. Product quality can be improved by reusing the sub-systems or components which quality and validity have been proven. In addition, the outcome of the design can be better predicted, which is valuable to the early decision-making stage. By properly reusing existing technologies, significant benefits can be achieved with respect to cost, time, product quality, and performance [Duffy and Ferns, 1999] (Figure 1.3).

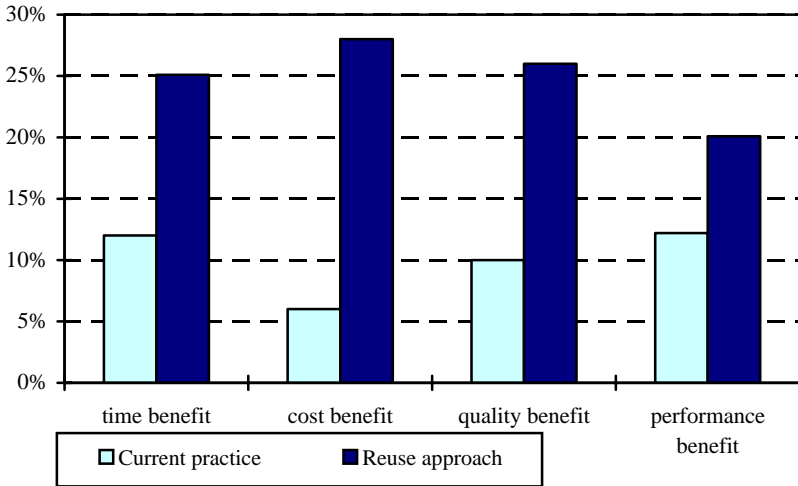


Figure 1.3 Current and foreseeable benefits of design reuse [Duffy and Ferns, 1999]

To support design reuse activities, it is necessary to understand the characteristics of product design at the conceptual stage. It is also important to be aware of the capabilities of design reuse and the available tools and techniques. These topics are discussed in Sections 1.2 and 1.3, respectively.

1.2 Product Conceptual Design

Among the several stages of product design, which usually encompass requirement analysis, conceptual design, embodiment design, and detailed design, the conceptual design stage is of paramount importance. This can be shown with two observations. Firstly, the conceptual stage allows for high design freedom, *i.e.*, the designer is less constrained to make decisions at this stage. Secondly, the cost of a product is largely determined at this stage. It is estimated that about 75% of the manufacturing cost is committed by the end of the conceptual stage [Ullman, 1997]. In the subsequent stages, it becomes increasingly difficult and costly to compensate for the initial flawed designs. This situation is illustrated in Figure 1.4.

Conceptual design is a design process that involves intense decision-making. A systematic, procedural process model must be developed to manage these decision-making activities. A few notable design theories that have dealt with this problem include the systematic approach [Pahl and Beitz, 1996], total design [Pugh, 1991], robust design [Clausing, 1994], the theory of inventive problem solving (TRIZ) [Altshuller, 1984], axiomatic design [Suh, 2001], *etc.*

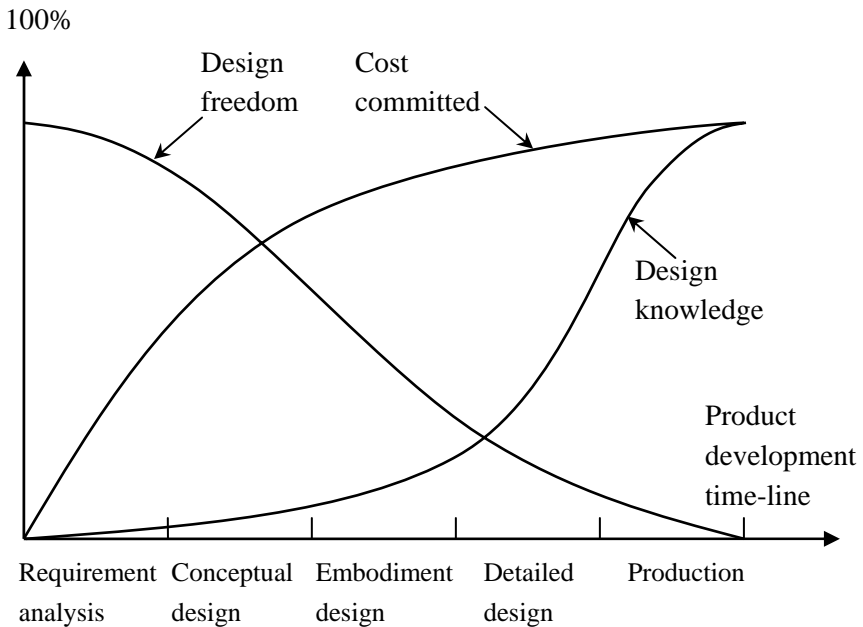


Figure 1.4 A product life-cycle viewpoint of design freedom, product cost and knowledge availability

At the early design stages, decisions have to be made on the project definition, design specifications, concept generation, concept evaluation, and the preliminary production issues. The effectiveness in carrying out these activities depends a lot on the availability of information, and the way in which the information is processed. However, the conceptual design stage is characterized by information deficiency and uncertainty. It

is not until the final design stages that design knowledge becomes substantial. A paramount problem is how to carry out design based on the limited amount of information at the conceptual stage. Collection of information from existing products is a possible way to solve the problem. However, product information is highly unstructured and appears in diverse forms. Significant effort is required to capture product information, and utilize the information in new design problems.

1.2.1 Product family design

In conceptual design, the target can be the design of a single product or a set of related products, *i.e.*, a product family. A product family refers to a group of related products that share common technologies and address a series of market segmentations [Meyer and Lehnerd, 1997]. Product family design is a nascent but rapidly maturing field of research [Simpson, 2004]. The rationale of product family design is to provide product variety while maintaining production efficiency [Pine, 1993a]. Product variety is defined in terms of customer requirements, which are addressed by variegated product performance. Thus, a product family has to be designed to cover a ranged set of performance requirements. At the same time, production efficiency has to be ensured through considering commonality, compatibility, standardization and modularity among different products [Meyer and Lehnerd, 1997]. This is achieved through developing common technologies and components, which can be shared among different products.

Product family design and platform-based product development have been widely applied in the industry. A few successful projects in the industry are presented next.

Black & Decker – Power tool family Black & Decker used modularization to produce the entire range of the power tool products using standardized components, such as motors, bearings, switches, cord sets, cartons, fasteners, *etc.* [Lehnerd, 1987]. The product variety increased while production cost and lead-time decreased drastically.

Sony – Walkman family Sony introduced the Walkman with a variety-intensive strategy [Uzumeri and Sanderson, 1995]. The company built its models on common platforms and used modular design to provide variety. Sony also adopted an incremental innovation strategy and targeted different market niches with different models.

Swatch – Swiss watch family Swatch produced a large variety of watches by using a modular design and combining different standard chunks. A number of watch models with different configurations (hands, faces, wristbands, etc.) were created with a relatively small selection of movements and cases [Ulrich and Eppinger, 2004].

Xerox – Copier & typewriter family Xerox employed a modular design strategy in the design of its typewriters. Xerox also focused on reuse in product development to maximize the number of modules that are carried over from one generation to the next. This helps to lower development costs and decrease the lead-time [Erixon, 1996].

Boeing – Commercial airplane family Boeing developed its commercial airplanes based on a strategic ‘stretching’ of the basic models to accommodate different load capacities (*e.g.*, passenger number and cargo weight) and flight range [Sabbagh, 1996].

The major concern in product family design is the management of the trade-offs between product commonality and product performance. Usually, an increased commonality leads to a higher production efficiency, but at the expense of individual product performance. Decisions have to be made at the early design stages about (1) the proper divisions of the market segmentations, (2) the structure and content of a product platform, (3) the attributes of the common components under the product platform, and (4) the optimal combination and adaptation of components. Thereafter, it is important to evaluate (5) the effectiveness of the product family with respect to cost and product performance.

Information deficiency and uncertainty is a big hindrance to product family design. Usually, a designer is faced with immense freedom to develop a product family. It is not trivial to set the right parameters as a

good starting point, *e.g.*, little is known about the consequences of setting a parameter at a specific value. Therefore, it is necessary to find ways to collect the relevant information and use it to ensure design optimality. The design reuse methodology presented in this book is one of such efforts to meet this challenge.

1.3 Major Issues in Design Reuse

Design reuse encompasses the design activities covering the entire product design processes. It involves various issues ranging from theoretical to practical, and technical to managerial. Sivaloganathan and Shahin [1999] summarized the developments in design reuse and classified the efforts into seven categories.

- (1) Focused innovation for product development, which is largely a management issue addressing the planning of products and market segments to increase the market share.
- (2) Cognitive studies on reuse, which emphasize the identification of patterns in the artifact information and use them to answer specific questions.
- (3) Computational perspective of design reuse, which focuses on the reasoning of information retrieval, utilization, and adaptation. AI technologies play an important role in this area.
- (4) The use of standard components, which emphasizes the cost effectiveness in manufacturing and efficiency in assembly.
- (5) Design reuse tools, which refer to various stand-alone assisting tools that enable more efficient information manipulation, such as the market segment table, design structure matrix (DSM), *etc.*
- (6) Design reuse systems, which integrate multiple tools to carry out the design reuse processes of interest. The systems may differ in scope and complexity based on the nature of the target problem.
- (7) Problems of overuse, which identify the limitations of design reuse and the pitfalls for applying design reuse.

Other interesting issues in design reuse include environmental concerns, organizational strategy, and educational issues. Although these

issues are comprehensive to a certain extent, they are presented in different levels of abstraction and lack a consistent framework. With an emphasis on the efficacy of applying design reuse to product design, this book concentrates on the issues related to the design reuse processes, which include a design reuse process model and the techniques associated with each and every individual process. These are discussed in the following sub-sections.

1.3.1 Design reuse process

To properly organize the design reuse process, a comprehensive design reuse process model is required. Systematic design reuse method involves two interrelated processes: information collection and information reuse. The former refers to design-for-reuse, which involves information modeling and information processing to identify relevant knowledge. The latter refers to design-by-reuse, which aims at the effective utilization of the information. Design-by-reuse is mainly concerned with information retrieval, solution synthesis and evaluation. Finger [1998] has identified four issues concerning the design reuse process, *viz.*, representing, capturing, organizing, and retrieving. This division is similar to the processes presented in traditional case-based reasoning (CBR), which is centered on '4Rs', *viz.*, retrieve, reuse, repair, and retain [Watson, 1999].

These process models have been criticized for being based on a non-holistic model, *i.e.*, the overall design process has not been well-organized [Smith, 2002]. A relatively complete design reuse process model was proposed by Duffy *et al.* [1995]. It consists of three processes and six knowledge resources (Figure 1.5). This model is enlightening in that it identifies the role of knowledge resources, the flow of information, and the requirements of information processing. An effective design reuse system has to provide tools to facilitate the design processes and manage the relationships between the knowledge resources.

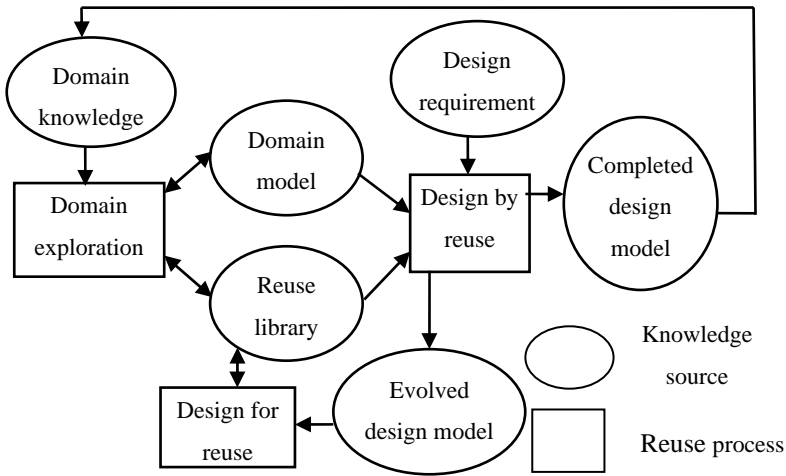


Figure 1.5 A design reuse process model [Duffy *et al.*, 1995]

1.3.2 Product information modeling

The representation of the product information directly influences the effectiveness of design reuse. Since the product data are inherently heterogeneous and volatile in nature, the representation scheme has to deal with information completeness, conciseness, and integrity. The exchangeability of product information is also an important issue to be considered for collaborative design. Generic modeling languages, such as UML (Unified Modeling Language), CML (Compositional Modeling Language), STEP (Standard for the Exchange of Product model data), XML (eXtensible Markup Language), *etc.*, may facilitate the process. These modeling languages provide a common syntax with well-defined semantics to model a broad variety of physical processes and objects. However, their applications have been restricted by the efficacy to deal with representation flexibility and rigor.

One important aspect of information is product function. The use of function effectively separates the design intent with the physical implementation, and hence, design is partially exempted from early engagement to specific physical structures. Function-based product design

has been recognized as an effective means to conceptual design. Therefore, the representation and subsequent reasoning about function has been under extensive study [Umeda *et al.*, 1990; Iwasaki and Chandrasekaran, 1992; Gorti and Sriram, 1996; Qian and Gero, 1996; Pahl and Beitz 1996; Roy *et al.*, 2001]. Relevant research issues include the representation scheme based on functions and flows, the building of function structures, the usage of taxonomy, the relationships between function, form and behavior, *etc.* Production information representation is further discussed in Chapter 3.

1.3.3 Product information analysis

Product information that is collected based on the representation schemes discussed in the earlier section is not necessarily reusable. Information is reusable if it can be easily retrieved and assembled to support solution generation. A notable difficulty faced by product engineers is that the information at hand lacks association with other types of information, and hence could not be directly reused. Techniques are required to transform product data into reusable forms. Thus, information analysis is another important issue in design reuse.

Information analysis usually involves the assignment of rules and the recognition of design patterns from the original data. This may be carried out at different levels of the product development, such as customer requirement analysis [Jiao and Zhang, 2005], building of product architectures [McAdams *et al.*, 1999; Hölttä *et al.*, 2003], process planning [Treleven and Wacker, 1987], and logistics [Kim *et al.*, 2002; Huang *et al.*, 2005]. Various AI techniques have been applied in such an effort, such as machine learning, data mining, neural networks, and heuristic methods. Chapter 4 discusses this issue in greater detail.

1.3.4 Design synthesis

Design synthesis has different implications according to the nature of the target problem. For example, Chakrabarti [2002] divides synthesis into five levels, *viz.*, synthesis as designing, synthesis as problem solving,

synthesis as design solution generation, synthesis as design problem and solution generation, and synthesis as exploration. Based on the design reuse framework presented in this book, design synthesis refers to the generation of solutions based on reusable components. In order to do so, three factors have to be considered, *viz.*, (1) knowledge of the components or artifacts, (2) methods and techniques to implement the solution generation activities, and (3) knowledge of how these methods and techniques can be carried out.

Methods to carry out synthesis differ in scope and level of automation. Typically, design synthesis is carried out manually, or through the interactions between humans and computers. These methods are applicable to problems where simple retrieval and adaptation are involved. On the other hand, to achieve a more efficient product design, automated compositional synthesis is required. Automated design synthesis is especially useful for solving large combinatorial problems, such as configuration design. To do so, a proper formulation of the design problem is necessary so that the computers can read design inputs, visit relevant data, and compute and present the synthesized results. Usually, automated design synthesis involves a set of predefined design objectives based on which the computers can evaluate the candidate solutions to search for the optimal ones. Design synthesis can be carried out using various computational tools, such as agent-based methods, genetic algorithms (GA), simulated annealing (SA), branch-and-bound method, *etc.* Chapter 5 presents the various methods to carry out design synthesis based on optimization.

1.3.5 Solution evaluation

The feasibility and optimality of a design concept is assessed using the concept evaluation schemes. The major difficulty in this process is that a mathematical model is often out of the question due to the complexity of the problem. In particular, two obstacles are prominent. Firstly, evaluation usually involves multiple criteria that are inherently incommensurable. The designer can aggregate the criteria into a multivariate utility function, or alternatively he/she can carry out the evaluation based on

multi-objective optimization. However, a multivariate utility function is not easy to formulate; and the trade-offs are hardly manageable when many objectives are involved. Secondly, the logical management of the evaluation process is not trivial. The designer has to identify sufficient information and develop logical steps to compute the objective functions.

Due to these obstacles, early stage solution evaluation is difficult and has been relying on intuition and experience. This strategy is far from efficient and reliable due to the limitations of human capacity. Efforts have been made to tackle this problem by using systematic methods with computer support. For example, the quality function deployment (QFD) method has been widely applied to translate the customer needs into design specifications, and to further identify the most promising conceptual solutions. Another influential body of researches lies in quality engineering, and most notably the Taguchi method, which adopts prescriptive strategies in the design and manufacturing processes to ensure product quality. In Chapter 7, the issues in product quality evaluation and control are discussed.

Based on the discussions, this book is aimed at addressing these issues using an integrated framework with the supported of computational tools.

1.4 Engineering Design Reuse Applications

Design reuse is a multi-disciplinary research topic. This section discusses the applications of design reuse in different engineering domains, including software engineering, mechanical and electro-mechanical engineering, and manufacturing. Although this book focuses more on mechanical and electrical product design, the design reuse rationale is applicable to multiple disciplines. Thus, design reuse applications in different areas are complementary to each other, and can expand the visions of engineers from different fields.

1.4.1 *Design reuse in software engineering*

Design reuse as a research topic stems from computer science and software development. Reuse in software engineering has been

successfully implemented at different levels: from the low-level code reuse to component reuse, and high-level system and project reuse. Reusable objects include code segments, components, structures (skeletons), documentation, report, test component, plans, *etc.*

Object-oriented (OO) design is a main enabler of software reuse. It is basically a software decomposition technique, which elicits systematic thinking to facilitate reuse, and provides environments and languages for programming. As compared with the classical functional design, OO design is based on a modular decomposition of a system and the concept of classes of objects, instead of the functions that the system performs [Jette and Smith, 1989]. An important implication of this difference is that OO design features a high-level abstraction at design time. This is a significant improvement to the classical procedural, flow-oriented design approach, in which reusability is not considered.

The most important concept in OO design is *Class*, which is an abstraction of a set of objects that share the common characteristics, structures, and operations. A class defines a data structure which consists of a set of attributes used to describe an object, and a set of methods used to define the operations that this object carries out. The key features of OO languages can be found in [Jette and Smith, 1989] and include:

Abstraction, which refers to the representation of objects with a high level of generalization. In other words, only information related to the nature of an object is retained, while the other non-essential information is ruled out. The class is a resulting data structure of abstraction. Class can be used to represent non-structured data as well as structured data.

Inheritance, which enables a class, called an heir/descendant, to obtain some of its features from another, called a parent/ancestor. Thus, the infrastructure of an OO system embraces a hierarchal structure of objects such that the descendants in the hierarchy can reuse the attributes and methods of the ancestors.

Polymorphism, which is an important consequence of inheritance. It allows descendants to override some of the attributes or methods of the

ancestors provided that some prescriptive measures have been taken to define of the original data structure.

Encapsulation, which is a mechanism of information hiding. Encapsulation separates the external aspects of an object from the internal implementation details. The external aspects are accessible to other objects while the internal implementation are hidden from other objects. This ensures that only methods on the class could access its implementation [Meyer, 1994].

Software reuse has been extensively studied and widely adopted. A few successful design reuse applications are presented next.

Toshiba Fuchu Software Factory A standard life-cycle model is used to produce software at Fuchu. This factory embraces a motto of 'Promote Reuse', and reuse is fully supported by management. Reusable software were developed and stored in a large reuse library. Every project is encouraged, and in fact mandatory to review possible candidates for reuse at the start and throughout the project development. These practices have helped the company to achieve a 14% gain in productivity annually [Rada, 1995].

HP Corporate Engineering Software Reuse Program This program has been proposed to provide solutions to consulting, training, methods development, and pilot projects [Griss, 1991]. A hypertext-based software reuse tool was developed to integrate tools, and maintain links between all software work projects. A prototype called Kiosk provides a hypertext framework for manipulating libraries, such as InterViews, or other C and C++ libraries.

Reuse at IBM IBM established a reusable part center at Boblingen, Germany in 1987, which aimed at production of highly generic reusable software components for worldwide use within IBM [Wasmund, 1993]. Reusability is considered throughout the cycle of software development, which involves five major steps: (1) define the goal, (2) determine critical success factors, (3) define the required activities, (4) validate the plan, and

(5) execute the activities. These efforts have resulted in a tripling of reuse rate in IBM, Boblingen.

Reuse at NEC The NEC software engineering laboratory made a retrospective analysis of its business applications and recognized 32 logic templates and 130 common algorithms [Rada, 1995]. These templates and algorithms are classified and stored in a reuse library, which was in turn integrated into NEC's software development environment. A 7:1 improvement in productivity and 3:1 improvement in quality was reported.

Reuse in software engineering is both challenging and rewarding. To succeed with reuse, engineers and managers must see it from a systematic perspective. The design reuse practices must be formalized by including support for reuse in software development methods, tools, training, incentives, and measurements [McClure, 1997].

1.4.2 Design reuse in mechanical and electro-mechanical engineering

As compared to software design reuse, design reuse in mechanical and electro-mechanical design is more complicated. An apparent reason for this is that the products involving solid models of components are much more difficult to modify and customize. In general, the design of these components/products involves a more complicated process of mapping from the functional domain to the physical domain. Moreover, the functionality of the products is more complicated as a result of different combinations of components. Hence, the compatibility among interacting components requires more consideration. Specifically, the interface must be designed properly to avoid possible conflicts.

Modular design is an established method in this domain. The most successful modular product is probably the personal computer (PC). A PC usually consists of a set of functional components, such as central processing unit (CPU), storage devices, memory, power supply, graphic processor, input devices, *etc.* Standard interfaces are developed to connect

these components so that they can be easily mounted on a main board during the assembly of a PC system.

The Cambridge Engineering Design Centre (EDC) in UK focused on the development, validation and dissemination of advanced design methods for mechanical systems [Clarkson, 1998]. The major research methods include: (1) functional synthesis, (2) embodiment generation, (3) design optimization, and (4) designer guidance. Reuse of knowledge is a central theme that unites these methods. Applications have been reported in aerospace, healthcare, and other special projects.

A-Design combines multi-objective optimization with a multi-agent approach for automated design synthesis [Campbell *et al.*, 1999, 2000]. It is capable of accepting changing design inputs and decision-making based on previous experience. These capabilities make the system intelligent and adaptive to dynamic environments. It has been used to design weighing machines and MEMS accelerometer.

Schemebuilder[®] [Cousell *et al.*, 1999] is a commercially available system for mechatronics conceptual design. The system is developed based on comprehensive knowledge representation and function-means tree to enable mapping between the functional domain and the physical domain. AI techniques have been adopted to support design reasoning. However, the interface design and the compatibility of different sub-systems have not been addressed in this system.

Other applications of design reuse in mechanical and electro-mechanical products include the design history tool [Chen, *et al.*, 1990], FAMING for design innovation [Faltings, 2002], issue-based information systems [Conklin and Burgess-Yakamovic, 1991], the multiple viewpoint modular method [Smith, 2002], LearninIT in circuit breaker design [Stahovich, 2000], *etc.* Reuse has been implemented at different levels in these systems. Usually, a system only provides partial support to reuse, *i.e.*, only a particular type of information is reused, such as layout, design history, modules, and reasoning. It is desirable to extend reuse as much as possible through more effective knowledge manipulation techniques.

1.4.3 Design reuse in manufacturing

Reuse in manufacturing can be applied at three levels. The methods involve both managerial and technical aspects, which are discussed next.

1.4.3.1 Management level reuse

With the increasing product variety and complexity, the number of process variations increases in terms of machine tools, fixtures, setups, cycle times, and labor [Wortmann, *et al.*, 1997]. Process variety may have an adverse impact on production efficiency and cost because it introduces significant constraints to production planning and control. Therefore, a paramount problem is how to effectively manage the process variety according to the product variety based on the existing operations and manufacturing resources.

The management of product variety has been supported by various tools and systems, such as PDM, bill-of-materials (BOM), Generic bill-of-materials (GBOM), *etc.* These tools and systems further facilitate the reduction of components in the inventory and resources to handle the components [Fisher *et al.*, 1999]. Moreover, the manufacturers can better control their resources by designing optimal supply chain configurations. Examples of resource management include the enterprise resource planning (ERP), material requirement planning (MRP), manufacturing resource planning (MRP II), *etc.*

However, the information provided by these systems may not be effectively reused. This is attributable to the limited capacity of the systems and the inefficiency of the tools to use information. Therefore, data mining technologies have been applied to extract useful data patterns for a more effective information reuse, such as graph-theoretic approach [Romanowski and Nagi, 2002], text mining and graph matching [Jiao *et al.*, 2005], and associating rule mining [Jiao *et al.*, 2005].

1.4.3.2 System level reuse

Manufacturing systems have different forms which are suitable for different production rationales. Accordingly, the reusability of the systems

is different. Table 1.1 summarizes the features of different manufacturing systems in terms of their reusability.

Dedicated manufacturing lines (DML) A DML is a fixed production line that produces identical or similar products in high volumes. Typically, each dedicated line is designed to produce a single product or part. In DML, the production rate is very high. However, to produce components with different features, and at low volume, the reusability of DML is minimal.

Group technology (GT) GT is based on the rationale of grouping parts with similar production processes [Rolstadas, 1991]. This grouping results in cellular manufacturing structures, with each cell dedicated to a cluster of similar parts, and operates much the same as in the traditional DML. GT is capable of reducing setup time, inventory, and tool usage. It is flexible and allows organizations to be more responsive to the market changes.

Flexible manufacturing systems (FMS) FMS is a manufacturing philosophy and technology that is capable of producing product variants, with shifting volume and mix [Hopp and Spearman, 2001]. From the perspective of producing a variety of products, FMS is a reusable system. However, the throughput of FMS is low, especially when considering the high equipment cost.

Reconfigurable manufacturing systems (RMS) RMS has its significance in changing the system itself to adapt to the changing product variations. It combines the high throughput of DML with the flexibility of FMS. This has been made possible by: (1) a system composed of machines that are adjustable in scale and capacity to meet the changing requirements of the market, and (2) a manufacturing system that has the capacity to produce all members of the part family [Koren, *et al.*, 1999]. Thus, reuse is an inherent nature of RMS.

Table 1.1 Features of different manufacturing systems

Type	Flexibility	Scalability	Machine structure	Throughput	Tools	Reusability
DML	No	No	Fixed	High	Multiple	Low
GT	Yes	No	Fixed	High	Multiple	High within manufacturing cells
FMS	Yes	Yes	Fixed	Low	Single	Reusable for different products
RMS	Yes	Yes	Adjustable	High	Multiple	High

1.4.3.3 Reuse of machine tools

The capacity and adaptability of machine tools show different levels of reusability. Machine tools that are used in the DML are highly specific, and hence are not reusable for other production requirements. On the other hand, CNC machines are all-purpose machines that can accommodate a wide range of production requirements. To increase the reusability of machine tools, a modular structure has been widely adopted. A modular structure of the machine tools is defined as a set of pre-fabricated standard components that can be assembled rapidly into a variety of design configurations to address the production requirements. In fact, RMS could not have been effectively applied without the modular structure of machine tools. Successful applications of modular structures have been reported, such as modular jigs and fixtures [Nee, *et al.*, 1995, Rong and Zhu, 1999], and modular machine tools [Stake and Blackenfelt, 1998; Koren and Kota, 1999].

1.5 Barriers to Design Reuse

Although the design reuse methodology has many attractive features, such as the potential for cost savings, quality enhancement, time reduction, it is difficult to implement. This problem arises not only from the technical aspect, but also from organizational, communication, and psychological aspects. Moreover, improper reuse may cause unexpected cost and excessive waste of resource, which can be frustrating. Therefore, it is worthwhile to study these barriers and find ways to overcome them.

Technical difficulties mainly arise from the inherent nature of information and knowledge. In particular, design information is highly unstructured. Not only does the information consist of many facets, which cannot be represented in a consistent and exchangeable manner, but the same type of information can be represented in different formats. For example, many CAD modelers have their proprietary data structures for representing the geometric information of a product, which restricted the communication between them.

From the organizational perspective, design reuse is restricted by the traditional individual project-based management strategy. Companies usually do not provide incentives for engineers to engage in design reuse because such an effort does not directly add value to the project at hand. The reluctance of the managers to apply design reuse may be justified by the observation that if the time required to reuse a part is approximately greater than 30% of the time required to design the part from scratch, design reuse will fail [Girczyc and Carlson, 1993]. This observation is not necessarily applicable to all circumstances. However, it is reasonable for managers to detect evident benefits of design reuse before they would adopt such a methodology.

Communication can also be a big problem because individual designers may find it difficult to reuse the designs, experience, and insight of others [Busby, 1999]. This causes problems in the design reuse activities, including indexing, retrieval, and modification. For example, designers may have difficulties in finding the relevant designs to address new problems especially when the past designs have been developed in an environment different from the current one. Furthermore, the differences in the environment and the problem itself may make the understanding and modification of past design formidable.

Psychological problems happen when the designers feel no excitement or self-satisfaction to reuse other's ideas. Hence, some designers are reluctant to borrow existing ideas.

Other than these barriers, design reuse should not be applied for its own sake. In fact, excessive reuse can be harmful for a company. It can lead to design fixation and kill creativity if designers fail to seek solutions beyond the current reuse repository.

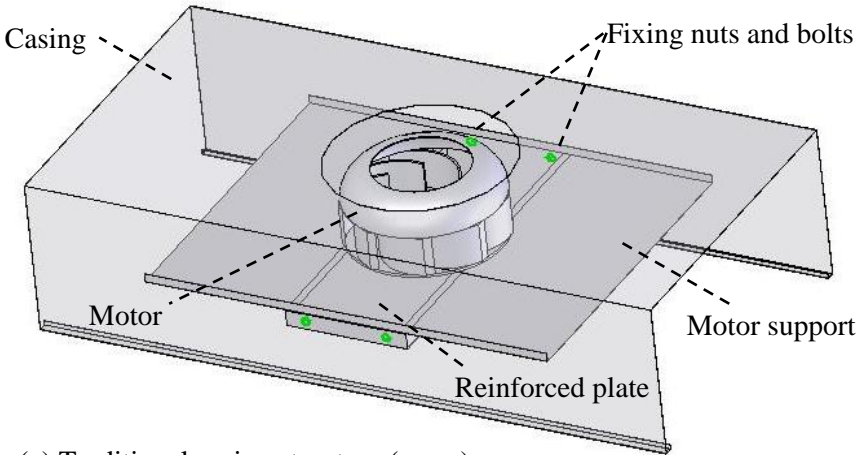
As an example, the authors of this book participated in a project aiming at applying the design reuse methodology to design an industry product, namely, the fan filter unit (FFU). Part of this project involved the design of the FFU casing. Figure 1.6 shows Solution A provided by the engineers using a design reuse method. The motor is fixed on a supporting plate, which is in turn underpinned by a reinforced plate. The reinforced plate is fixed on the casing walls using four nuts and bolts around four corners. Since this structure has been used and tested in many cases, it is very safe and well-documented. Only minor changes are needed to accommodate new design requirements. Consequently, the casing was designed quickly and efficiently, and the manufacturing and assembly is routine and cost effective. In comparison, Solution B was created by engineers without considering design reuse. In their design process, the traditional structure cannot provide the desired features. Therefore, they redesigned the casing structure such that the motor is supported by a bottom plate connected to the top cover plate using four long bolts. The entire supporting sub-assembly is, in turn suspended on the upper plane of the casing. This new design requires much more effort, time, and cost. However, the performance of the product improved significantly in terms of noise and vibration performance.

Without a proper design scenario and the design criteria, it is impossible to determine which solution is better. Nonetheless, this example is not aimed at comparing which solution is better. Rather, it highlights the point that design reuse is not omnipotent and that it should not be applied in all circumstances.

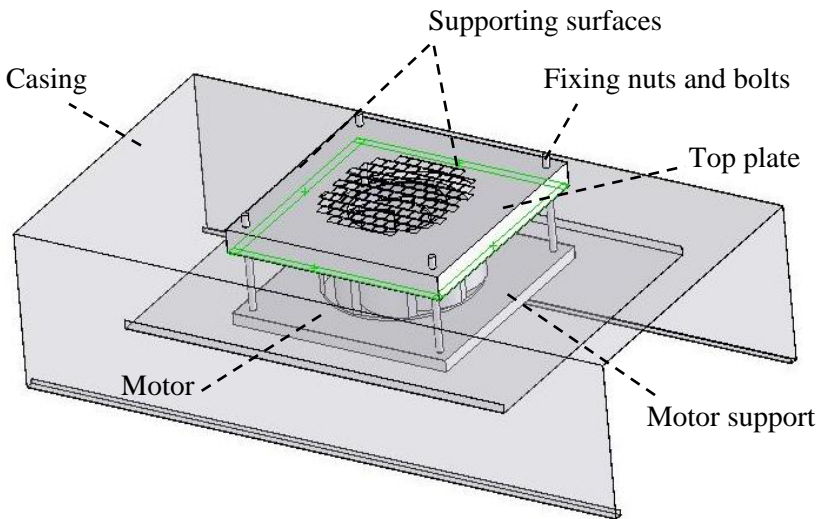
1.6 Summary

In this chapter, product design methodologies relevant to design reuse are discussed. Based on the discussions of the major issues in design reuse, it is evident that a comprehensive design reuse process model must accommodate the modeling, analysis and optimization requirements during the entire design process. Engineering design reuse applications are extensively studied with different disciplines, namely software engineering, mechanical and electro-mechanical engineering, and

manufacturing. Furthermore, the barriers of design reuse are discussed to avoid possible pitfalls of reuse and 'overuse'.



(a) Traditional casing structure (reuse)



(b) New casing structure (without reuse)

Figure 1.6 FFU casing structure with/without design reuse

In the subsequent chapters, the techniques in design reuse are addressed progressively. Chapter 2 provides a literature review of the design reuse systems and the commonly used computational tools. Chapter 3 focuses on the modeling of product information. Chapter 4 investigates the technologies to carry out information analysis. The optimization and product evaluations issues are discussed in Chapters 5 through 7. Two design reuse systems with different applications are developed in Chapters 8 and 9, namely Chapter 8 proposes a product family design reuse methodology, and Chapter 9 focuses on the product embodiment and detailed design.