
A case study on non-parametric design method in ODM collaborative product development

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Abstract: There are two distinct solid design methodologies – parametric and non-parametric approaches. In the past 20 years, most industrial CAD users have been upgrading their CAD design methods from the non-parametric approach to the parametric one. However, with the new trends of globalisation, outsourcing and collaboration, it is timely to ask whether the parametric design is still effective. In this paper, a case study based on the non-parametric CAD modelling approach with a distributed collaborative design system is presented. A real project for a typical mechatronic product is studied in depth. Based on the case study and field observations, we have found that non-parametric modelling methodology enables collaboration in several ways. Further, the non-parametric modelling methodology shows many advantages. A comparative analysis has also been carried out via matching ODM design activities to the strengths and weaknesses of the two approaches. Finally, suggestions for future research directions of collaborative design are given.

Keywords: collaborative product development; parametric design; non-parametric design; feature-based design; design methodology.

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1 Introduction

Traditionally, Original Equipment Manufacturers (OEMs) used Contract Manufacturers (CMs) to balance workloads, lower operation costs and avoid capital expenditures. The CMs were mostly considered low-tech 'brothers', used by the OEMs for 'peak shaving' their production schedules. However, today's modern CMs are involved in every aspect of the OEMs' product development from the design of silicon chips to customer delivery. In this trend, the Original Design Manufacturing (ODM) emerges as an increasing

business model; it has an estimated market of \$US123.4 billion in 2002 according to Gartner's Dataquest (Brown and Wang, 2003); and the trend for OEMs' outsourcing to ODM providers will continue to grow in an effort to shorten development timelines, thus saving the time-to-market for a complex product mix. ODM companies need to achieve and sustain a competitive edge in the product-creation process via collaboration with many partners; 75% of entire product costs are determined during product development (Graessler, 2004).

In an extended enterprise, the collaboration of every resource is now expected (Dabke *et al.*, 1998). Information Technology (IT) solutions must not only augment the capabilities of the individual specialists with computational resources, but must also enhance the ability of collaborators to interact with each other. In addition, the engineering design has to address several complex characteristics such as diverse and complex forms of information, interdisciplinary collaboration, heterogeneous computer environments and software tools among others (Hsu and Liu, 2000; Wang *et al.*, 2002). These characteristics make interactions difficult to support. Traditional approaches of sharing design information among collaborators and their tools, including the development of integrated applications and the establishment of data standards (Prasad, 1996), are becoming inappropriate to support collaborative design practices. This is because of the highly distributed nature of the design teams, the diversity of the engineering tools and the complexity and dynamics of the design processes. More effective and efficient solutions are highly in demand.

This paper presents a study on the non-parametric approach. To illustrate its advantages and shortcomings over the parametric approach, a comparison analysis is included. In Section 2, a literature review is given. To illustrate the issues, Section 3 summarised the CAD requirements in ODM, whereas Section 4 shows a real case with a typical ODM product development cycle. Section 5 introduces the two approaches briefly. In Section 6, observations and the interview results obtained from this case study are summarised. Section 7 gives the comparative analysis. Finally in Section 8, discussions on the future research directions and conclusions are given.

2 Literature review

Comprehensive information about the features and functions of CAD/CAM/CAE software can be found in the study done by Krause and Rothenburg (2004). A good CAD system can reduce the length of the product development cycle and improve relationships with both vendors and customers (LaCourse, 1995). Product design using 3-D solid modelling has become the design method of choice around the world. Therefore, it is important to understand the various design methodologies adopted by each of the CAD vendors (Murphy, 2003). There are two distinct product design methodologies – parametric and non-parametric approaches.

CAD products using the non-parametric approach, such as Mechanical Desktop and CADKEY solids, existed prior to the introduction of parametric modellers. This approach includes Boolean modellers, wherein the model is created by adding or subtracting a set of analytic primitives in order to obtain a desired form. The direct B-rep manipulation modellers, also a non-parametric approach, create the desired model by adding and subtracting new face features or modifying existing faces that belong to a single-part body.

Since PTC introduced parametric modelling with their product, Pro/Engineer, back in the 1980s, we have seen many products of this technology such as UGS, SolidWorks, Solid Edge and, in later years, Inventor and CATIA. Parametric modelling became the dominant design methodology in use soon after 1995 (Anderl and Mendgen, 1995). Closely coupled with the parametric design is the feature-based design concept. Weighing both, we find that the latter carries more significance. Features were originated from the reasoning processes used in various design and manufacturing activities (Cunningham and Dixon, 1988), which were used to associate functional information with shape information. A relatively comprehensive introduction on feature-based product development was given by Shah and Mantyla (1995), whereby a generic feature is defined as a physical constituent of a part that is associated to a generic shape and has engineering significance and predictable properties. It is due to the feature-based design practice that parametric design is made necessary or a viable solution.

In the early stages of the development of feature technology, features were usually predefined as parametric templates. These templates have precise geometries to initiate a feature object or for feature recognisers using pattern matching in a specific application. For example, Joshi *et al.* represented each feature as a fixed Attributed Adjacency Graph (AAG) (Joshi and Chang, 1988). In such definitions, only feature syntax (*i.e.*, the topological and geometric relationships between different geometric entities), are precisely predefined, and these relationships are usually fixed. These feature definitions have two limitations. Firstly, they lack the flexibility to be extended. Secondly, the lack of specifications of feature semantics may result in information consistency breakdowns (Otto, 2001). For solving these limitations, several approaches are proposed.

Bidarra and Bronsvoot (2000) proposed a semantic feature modelling approach based on cellular topology. They explained the semantic problems suffered by most current feature modelling systems. Some examples of these semantic problems are the ill-defined feature semantics and the lack of semantic maintenance. However, the detailed feature and constraint class definitions are not given. An 'associative feature' definition was developed (Ma and Tong, 2003) by establishing built-in links among related geometric entities. Self-validation methods were defined for keeping feature validation and consistency.

Another issue about feature definition is feature instantiation method. This refers to using procedures or declaratives. The major difference between these two methods is that specifications of feature properties and procedures for instantiating a feature instance are combined together in procedure feature definition while they are decoupled in declarative feature. A merit of declarative feature definition is that more modularity is achieved by the separation of feature definitions and feature representations. Hence, a specific system definition which is independent of feature utilisation is possible (Shah and Mantyla, 1995; Venkataraman *et al.*, 2001).

Currently, most of the CAx systems are feature based. To enable collaborative and concurrent engineering, feature information must be represented such that engineering meaning is fully shared among CAx applications. Chen *et al.* (2004) described a unified feature modelling scheme for information sharing among different CAx applications. The unified feature model is essentially a generic semantic feature model for different CAx applications covering three-level relations among geometric and non-geometric entities.

In the past, to support the coordination of interorganisation co-design, Electronic Data Interchange (EDI) applications were implemented (Bensaou, 1999). The concepts of product master model (Hoffman and Arinyo, 1998) and integrated product model (Noort *et al.*, 2002) were proposed. They were then adopted in one way or another, each contract manufacturer shares the OEM's virtual private network and adopts the OEM's infrastructure such as design tools and business processes. However, because of the high investment required to create a working relationship, it is therefore difficult to switch to a higher value partner if one arises. Hence, whenever a new project starts, the choices of partners are often, 'by default', the partners who involved in the last project. This has been the common model in relationships between tier one suppliers that work for many years with automotive companies.

Recently, the trend of collaborative product development, the ODM business model, creates new challenges for CAD solutions. This business model builds upon the nature of cross-functional product development teams introduced in the realm of concurrent engineering. In essence, it is the merging of concurrent engineering to the concept of highly effective and well supported virtual team collaboration. This includes not only the processes of collaboration, but also the infrastructures and environments that enable and nurture it. The key driver for collaborative product development is outsourcing, which is quickly moving away from the default partner arrangements. It has been reported by Domazet *et al.* (2000) that to enable information sharing across the networks of different organisations, an agent-based framework coupled with STEP standard can be adopted. However, the 'partner by choice' is a much looser type of partner relationship. The outsourcing partner retains its own infrastructure, processes and design tools; it does not need to adapt to the OEM's systems (Ulvinen, 2000). Human-to-human interfaces, not data-to-data interfaces, are central here.

A number of solutions have been offered in the literature (Wang *et al.*, 2002) for collaborative product design. Systems have been developed based on common product models in distributed environments (Babu *et al.*, 2004; Bettaieb *et al.*, 2004). CIMdata Inc. (2001) provides a comprehensive overview about the requirements of collaborative product design systems, in which they coined the term 'collaborative Product Definition management (cPDm)'. However, the majority of the solutions are based on parametric feature-based approach for the product model, which imposes associative relations among the product elements. This approach confines the solution to a single sophisticated CAD/CAM platform. This very requirement of a common system limits the selection of partners significantly.

3 CAD functional requirements by ODM

In the ODM oriented business model, the OEM gives information to its ODM companies on a 'need-to-know' basis, and each ODM company then does the same to its subcontractors. This approach eliminates most data exchange issues and protects the OEM's intellectual property.

The technical functions required by ODM can be classified into the following seven aspects:

- 1 Generally speaking, ODM requires an effective and efficient technical communication data format. While collaborative product development has been concerned with the careful structuring of products, workflows, teams and organisations, it emphasises on creating the environment for effective, free flowing and *ad hoc* collaboration among peers whose insights complement one another. This is so because the team resource is far greater than the sum of their individual efforts (Mills, 1998). Hence, the technical documents, including CAD models, should allow manipulation by any team members within the scope of the collaborative project according to the designated roles across the boundaries of companies.
- 2 Proprietary applications must be seamlessly integrated with the product model format. Such applications include, but are not limited to, tooling development software, standard component libraries, analysis algorithms, process and resources planning and management systems.
- 3 Due to the nature of iteration in collaborative engineering, the product model must be transferrable from one team to another. It means that the information model worked on by one party could be handed over to another party without information loss. Hence, the final product model is a result of accumulative team work. It has to be in a commonly adopted data format such that all the references made to it are associated with a consistent set of product entity pointers. Furthermore, the jobs in different stages can be taken care of by different engineers without difficulties. This also requires the product model to be explicit without implicit constraints.
- 4 The product model should have the flexible decomposing methods such that different parties can work on it concurrently in a modular manner and can be easily incorporated into the master model without causing any party to rework or to wait.
- 5 The product model can be supported via public network, especially the internet.
- 6 The product model must be reusable across different projects over the time within each partner company or even in those permitted partners. This requirement enables companies to accumulate the engineering knowledge and practice know-how within their embedded product models.
- 7 The product model should not reveal the essential technical rules used at different stages by different partners.

In order to relate these requirements to the real application scenarios and to obtain the insight about ODM collaborative design processes, a case study on a mobile printer product is presented below.

4 A case study

This case study was made possible due to the author's involvement as the supervisor for one of the mechanical design engineers in the project. Field interviews were conducted with a broad cross-section of roles. These include design engineers, managers and other CAD-support personnel. In addition, individuals from other groups who assisted the design engineers in their work (*e.g.*, external engineers in mould making, die making, as

well as product and process engineers), were also interviewed. The impacts were analysed on different design stages such as conceptual design, detailed design and tooling design. Information sharing in this ODM company was studied in detail.

The topics covered in the interviews included the following:

- the nature of the design engineering processes
- the features and capabilities of parametric and non-parametric CAD systems
- the nature of the product management and the relations with CAD systems.

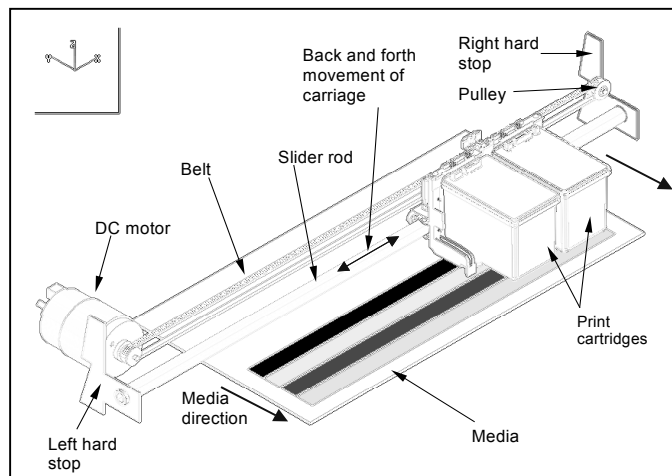
The project was started with an inherited early desktop product design as shown in Figure 1 (Shelley *et al.*, 1997). The design principles are described by Bockman *et al.* (1994). The critical cartridge mechanism is shown in Figure 2. The mobile printer business is a niche market, in which targeted users are mobile workers like sales executives, financial service consultants and photographers.

Figure 1 An inherited early product model



Source: Shelley *et al.* (1997)

Figure 2 Critical components in the printing system

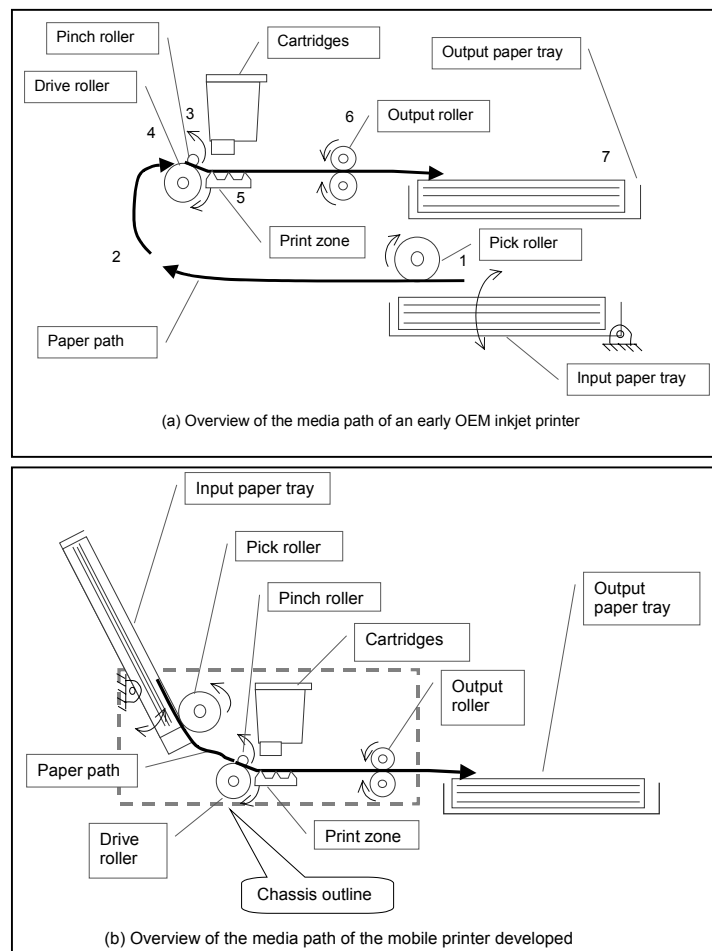


4.1 Conceptual design

Let us look now into the development processes. The first step was to go through the conceptual design with the following technical challenges: smallest footprint, lightweight, high photo quality printout and fast throughput. The constraints were using the common cartridges of the OEM's products and the design quality for high volume production.

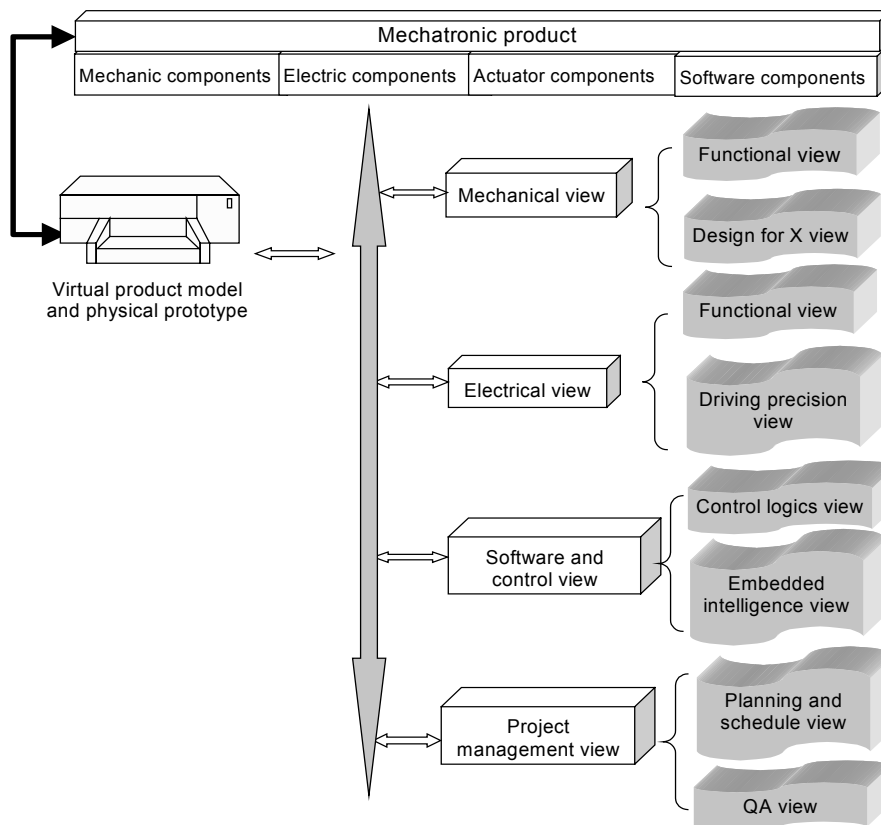
Using the conceptual design of the previous product model as shown in Figure 1, the new design achieved excellent innovation on the footprint size with the change of spatial orientation of the media path and the use of foldable input paper rack. The output tray was removed because initial marketing feedback showed that users could accept this idea in contrast to the stringent footprint specification. The product architects spent a great deal of time debating the trade-offs associated with the various media paths possible. This is because the media path chosen affects the product footprint, customer interface, ability to handle different types of media and functionality of the product. Figure 3 shows the media feeding system designs in the early reference printer and the mobile printer developed.

Figure 3 Media path designs before and after the innovation



An inkjet printer is a complex mechatronic system; its design requires a multidisciplinary team of professionals. Typically, the product architects establish the boundaries of the product, provide a path to successful development of the product and define the product's fundamental feature set. Figure 4 shows the major aspects defined by the product architect of this mobile printer. Some of these aspects include the mechanical system, the electrical system and the firmware system. Product architects also define the layout of the machine by identifying the subsystem boundaries and component locations and by defining how the various design modules integrate. For example, in this project, the mobile printer architect addressed issues such as user interfaces. Some of these are the following: how the paper is loaded, manufacturing processes for individual parts, manufacturing assembly of the whole product and servicing of the product by company service representatives.

Figure 4 Multidisciplinary engineering views from different disciplines



With this mobile printer example, the organisation of a working team for an ODM company can be typically described. Engineers in the design phase of product development were organised functionally around either the parts of the product or the types of analysis. Design engineers were assigned a part or a group of parts. They were then responsible for completing the design of those parts. They were in charge of the technical requirements of these parts during the later phases of product development.

The design engineers were organised around the following subsystems of the printer:

- The printing system. In this system, ink cartridges sweep across the paper as they cross the platen. A cartridge contains many micro-nozzles, which selectively eject the ink.
- The media handling system. The media path is the part of a printer that moves media past the cartridges. It also stops and locates accurately the media for printing.
- The chassis structure that supports the mechanisms and the enclosure, which houses the mechanisms and provides the user interfaces.

Except when working internally with the engineers who were responsible for the parts adjacent to his, each engineer was required to work with many other external groups. For example, design engineers who were working on the carriage system worked closely with the following persons:

- an OEM engineer from the ink cartridge group because he provided the ink cartridge shapes
- the tool and die designers, who were usually from external vendors, to ensure that the parts can be built for a reasonable cost
- one or more testing groups, who were responsible for completing the necessary critical printer performance tests
- manufacturing engineers, who ensured that the assembly process were carried out with appropriate jigs and fixtures in a reasonable time
- other groups, such as the OEM's market and customer service groups, which were occasionally involved.

The engineer in charge of a part had to balance the demands of different partners. Such demands include the cost and weight of each design alternative as well as his own constraints. Eventually the engineer in charge had to ensure that the product worked, and that it was durable, maintainable or producible. Sometimes, certain parts had to be redesigned, necessitating changes undesirable to some or all groups.

One of the jobs of the overall design engineer was balancing conflicting requirements from different perspectives. Unfortunately, this was done by incorporating each perspective sequentially and iteratively in order to converge on a solution. Many of the design engineers, when asked to describe their jobs, used the term 'project manager'. They described their jobs as coordinating a group of people who carry out the bulk of work of design and analysis. Most of the design engineers' time was spent on the coordinating efforts between the different groups.

Design engineers also performed design and analysis work on their own. The analyses performed by them were largely described as 'quick and dirty', so as to understand the feasibility of new ideas and to check the accuracy of results generated by the testing groups. The design engineers were involved to generate new design possibilities. However, this was a smaller part of their work compared to project coordination.

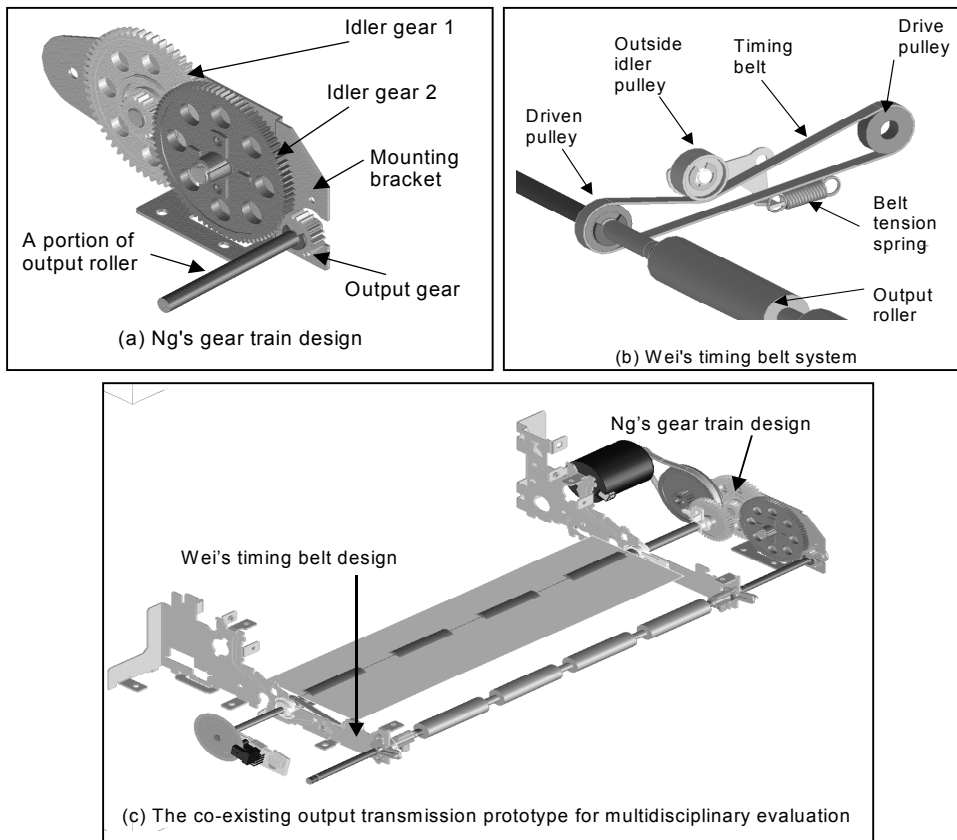
As the ODM had helped to manufacture the previous printer models, it gained substantial know-how and the required technologies. Hence, ODM started the project with an early product model. Many parts were reused with minimal modifications in the form of non-parametric solids. For example the sub-assembly shown in Figure 2 was reused with some shortening in size. In fact, animation was carried out to see the product working envelop and the working processes, such as folding and unfolding media rack, picking up media, media transfer and media ejection out of the printer.

Another major improvement that the team had achieved was the significant reduction of printer width due to the application of the 'printing-on-ramp' mechanism. Since this technology was mainly enabled by the company control software, it only required some size changes to the parts shown in Figure 2 as to the width direction.

4.2 Detailed structural design

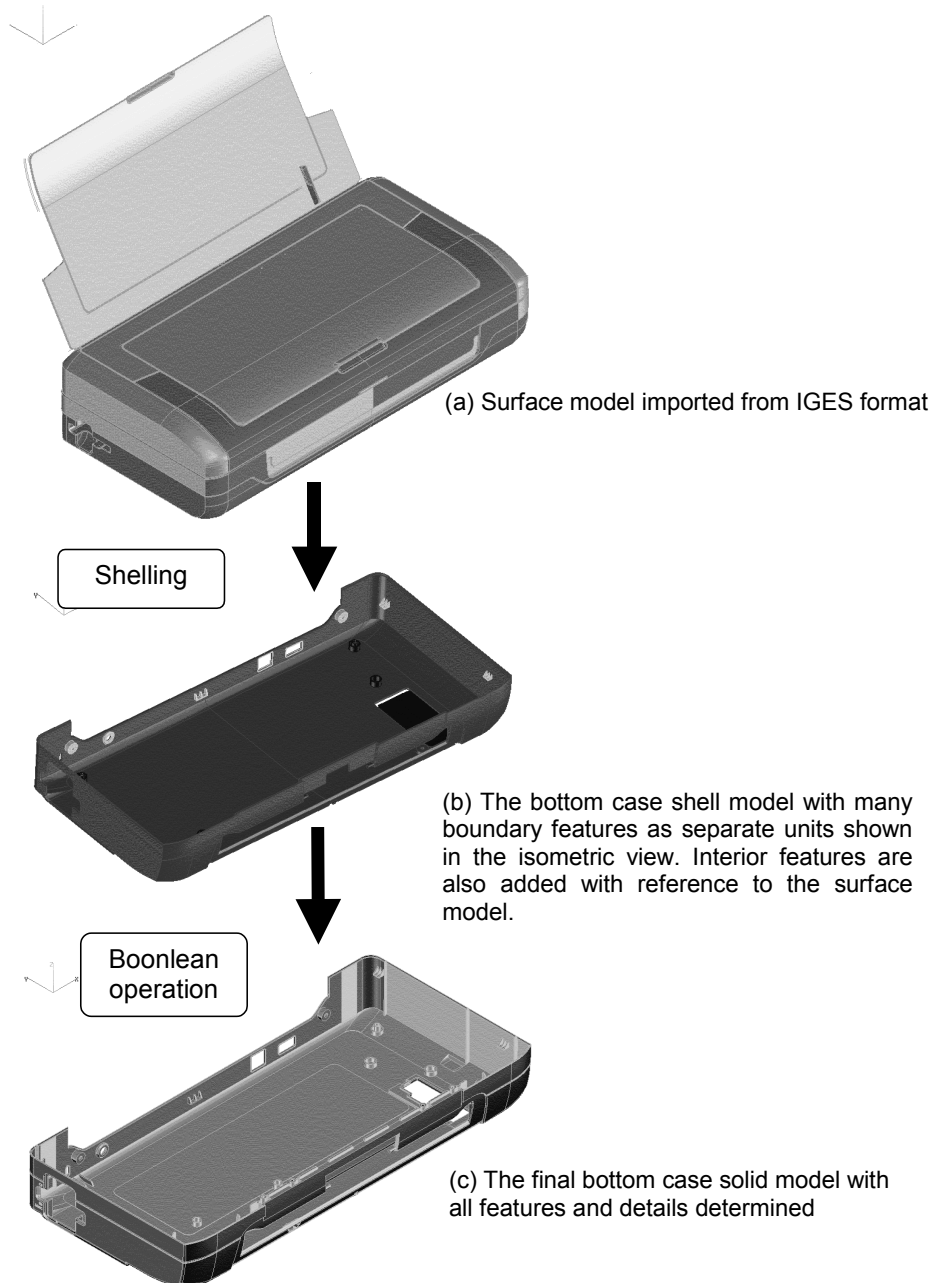
Once the product architects finished the overall conceptual design, design specialists then concurrently carried out the detailed design. Figure 5 shows the evolvement of the design solution for the media driving and output mechanism. It involved several designers (*e.g.*, Mr. Ng and Mr. Wei) as well as supervisors to compare, analyse and compromise the final solution. After designing all the mechanisms, the product functions should have been fully addressed.

Figure 5 Evolvement of the media feeding mechanism design



Concurrently, the industrial designer was involved and the product surface model was developed as shown in Figure 6. Such a surface product model was then converted into a solid model. It was then decomposed into parts with the considerations of aesthetic requirements, product maintainability and manufacturability for each part.

Figure 6 External enclosure design phase

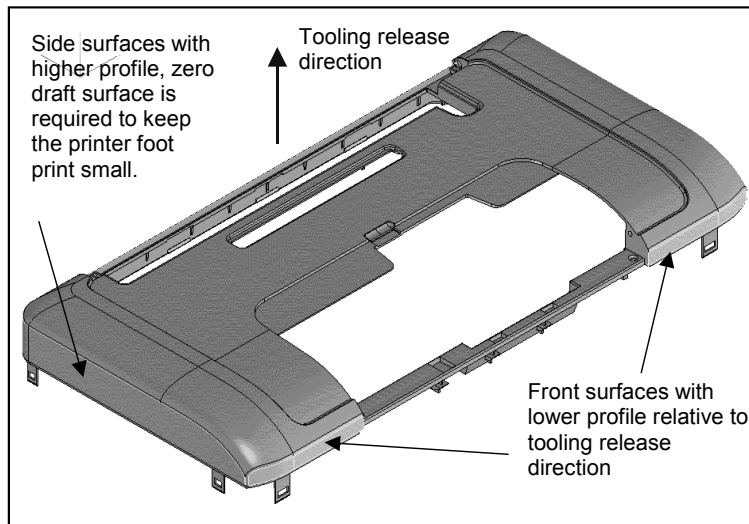


4.3 Tooling design

After the design team obtained the draft product model, it then used solid models to communicate with the toolmakers that produce the injection moulds for the production of plastic parts (*e.g.*, enclosure parts). Non-parametric modelling facilitates this communication process by allowing the reuse of the design solutions generated by the toolmakers. Here is an example which shows how a last-minute change initiated by a toolmaker was incorporated into the product model.

Figure 7 shows the initial *Top Case* model which required additional two sliders for the two front surfaces because of the zero draft angles. This was due to the paramount requirement to keep the printer size as small as possible. The ODM industrial designer defined these surfaces based on a consensus that no draft was allowed. The team did not realise this fact until the toolmaker made a suggestion of adding a draft angle to the front vertical faces because these two front surface regions had lower profiles than the rest – the left, right and rear surfaces.

Figure 7 The initial top case model that requires two additional sliders due to the zero draft angles on highlighted surfaces

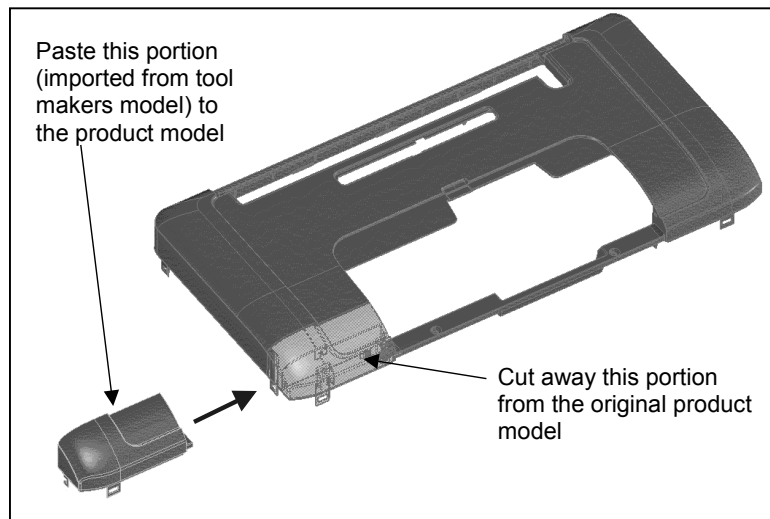


The ODM industrial designer quickly approved a secondary (2°) draft surface requested by the toolmaker. By doing this, there would be no parting line on the front surfaces of the final part which would otherwise occur due to the intersection of the main cavity insert and those slider inserts. Nevertheless, parting lines are always not favoured for the appearance parts.

However, the challenge was really on identifying who would carry out the change. The ODM industrial designer was supposed to perform the change as it should have been done before the stage of detail design. At that time, however, he was occupied on another project. The part designer was also tied up with other part releases for tooling according to the project schedule. In such a circumstance, the toolmaker was the ideal expert to perform the change since their concern was to simplify the tooling structure.

The toolmaker took the challenge and changed it. Subsequently, the change was propagated back to the designer's product model with the non-parametric solid model as shown in Figure 8. The part designer cut off the affected respective surfaces and pasted the toolmaker's suggested structure onto the current part model. If a parametric modelling method is used, this change would require tremendous amount of work to rebuild the model because the *shelling* process is always the very first step in part modelling.

Figure 8 Change propagated back to the original part with 'cut and paste' operations

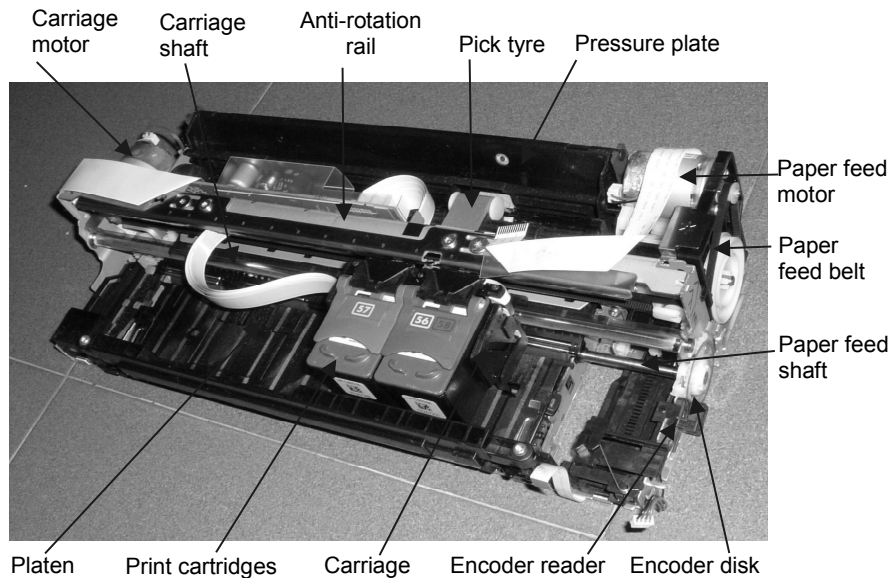


4.4 Rapid prototyping

Physical rapid prototyping technology was used frequently in the development of the mobile printer project because it allows a multidisciplinary evaluation. Several conceptual designs were realised with this technology. As pointed out by Dragoi *et al.* (2004), in the context of a mechatronic system (a printer), the idea is to find the best overall product system solution, but not the best mechanical solution, not the best electronics solution, not the best control solution and not the best software solution. Figure 4 also shows how the function of the physical prototype is evaluated from the multidisciplinary views.

Finally, Figure 9 shows the finished mobile printer with its top cover removed and the critical components labelled.

Based on this case study, it can be appreciated that the ODM information management requires different tools in comparison to the OEM in-house product development systems. Then, the question is, "Do we have the right engineering approach to address such challenging collaboration requirements?" In this end, reviewing an early work on CAD methodologies (Robertson and Allen, 1992) is useful. The essential values added by commercial tools must be re-evaluated.

Figure 9 The finished mobile printer with the cover removed

5 Two solid design methodologies

5.1 The parametric design methodology

Parametric design methodology utilises special-case searching and solution techniques to provide dimension-driven capability applied primarily to geometry constraints. These constraints could be coupled or uncoupled (Singh, 1996). Geometric constraints are specified relations between geometric entities such as parallelism, tangency and linear and angular dimensions. Parametric modelling provides constraint-driven capability. Constraints can be solved simultaneously to arrive at a design configuration that satisfies all the design criteria specified by the designer. Parametric design systems require the user to work within a fairly rigid modelling process. For example, in Pro-Engineer, the user first has to create a fully constrained 2-D sketch. This sketch is then converted into a 3-D object using one of several modelling operators such 'extrude' or 'spin'. This first feature of the model is usually referred to as the base feature. The user then repeats this process to add additional features onto the existing features with the requirement that each new feature has to be positioned and size-constrained relative to one of the features created. This condition is called as a parent-child constraint relationship (Murphy, 2003). This concept of parent-child constraint relationships is not just used for part creation, but also used as the foundation upon which all parametric functions operate. So it affects all areas of the software such as assembly creation, construction and datum plane placement, and dimensioning. The result of this process is a model wherein a change of any parent feature can cause a number of child features to change, very often, unexpectedly. Although different parametric CAD tools have different approaches for product modelling, implicit constraints are commonly used as a basic means to maintain geometric relations such as features and design patterns.

5.2 Non-parametric modelling

Non-parametric modelling is based on a ‘cut and paste’ solid modelling method (Ranta *et al.*, 1993). The main distinction of non-parametric design systems is that they do not maintain a feature history or require constraints such as parent-child constraints among its features (Murphy, 2003). For example, if you place a cylindrical hole through a block in a Boolean modeller, the only way to move that hole is to first fill up the original hole and then create your new one. In the case of a B-rep modeller, you may have added a cylindrical hole initially; in a subsequent editing step, it does not recognise it as a hole but as a face belonging to a single B-rep model. You can move it as an independent face. However, if that hole intersects with other features of the part, each remaining segment of that cylinder becomes a separate B-rep face with no information indicating that all the faces that originally belonged to the cylinder should be associated. Since non-parametric modellers do not have a history tree, there is no question of feature re-ordering which is a common modelling practice in parametric modellers. The ODM studied in this paper has implemented a non-parametric modelling methodology. In this project, the collaboration tool used was OneSpace from CoCreate Inc. (CoCreate, 2005).

6 Observations and interview results

The ODM company studied used a parametric solution before adopting the current non-parametric solution. This is because it requires a collaborative system that has good interoperability among different applications. When reviewing the product development cycle, the information flow among the extended team members is identified to be an essential factor for the design methodology to be effective.

First, when a new design team inherits an existing product model, the model has to be easily understood, decomposed, evaluated, reused (with or without modifications) and reassembled into the new product model without the limitations of embedded constraints.

Second, model sharing and co-modelling are critical for team collaboration. It is very common that when different design ideas are being discussed, multiple solutions need to be easily modelled and dynamically adjusted or modified. This will the assembly results to be evaluated by the members from other disciplines. Since the extended team members are likely to use different CAD systems, then the interoperability here is essential (*i.e.*, the data interchange among different CAD solutions have to be warranted with a high successful rate). In addition, job hand-over from one to another is common in real practices. In this study, we had observed that half-finished jobs were passed over from senior engineers to junior engineers and from design engineers to specialist engineers. These specialised members should understand the modelling principles easily and try out some necessary simulation or manipulation. Such transparency of close collaboration in a geographically distributed team is even more critical. This practice does not give problems when using non-parametric modelling. It would be difficult if a parametric approach were used.

Third, incorporation of design models from different participating sources into the master product design is frequently required. The design system should facilitate such activities effectively. In this presented case, after the industrial designer completes a product model with surfaces, the surface model has to be easily converted into the

detailed design; the internal fittings and the external panels should be considered. Design for Manufacturing (DFM) is another important aspect to be considered, and DFM suggestions (in the form of suggested changes with modified part geometry, in this case) should be incorporated into the current design as much as possible. Again, efficient cooperation can only be enabled with the effective model sharing and integration. It was noted that in the process of DFX evaluation, any additional constraint would make the specialist designers hesitate to touch the product model. Hence they would rely on the design engineers to show them different scenarios which again is a task that the design engineers may not be comfortable with. Such interactions from one partner to another require an effective, simple and reusable model representation.

Fourth, through many interviews with the project team members, the following point had been highlighted: parametric modelling systems require a great deal of forethought prior to the start of the design of an individual part or assembly. However, innovative design is rarely well structured in its beginning. The concept is divided into subsystems or modules that can be mapped with sub-functions (a one-to-one mapping will not always be possible). With non-parametric modelling, project team members are free to work on any subsystem, although every subsystem had an assigned design engineer. This setup allows design engineers working on different concepts to fulfil the same function or sub-function. On the later embodiment design stage, the conceptual designer could easily check the essentials, drawbacks and characteristics of the chosen concept. He is the best person to guard the concept during the embodiment and other detailing phases. Finally, the owner of a subsystem does not need to deal with a complex history tree when integrating a new conceptual model into his model.

7 Comparative analysis

Table 1 gives a summary of the advantages and disadvantages of these two solid modelling approaches based on the author's observations and the input from Murphy (2003). To make a more systematic comparison, the author uses the CAD functions commonly used in the practice of ODM as a reference frame. The strengths and weaknesses are discussed accordingly.

Table 1 Strengths and weaknesses of parametric and non-parametric systems

<i>CAD functionalities</i>	<i>Parametric CAD</i>	<i>Non-parametric CAD</i>
Modelling design intent	Excellent	Poor
Supporting concurrent and collaborative design process		
Conceptual design	Poor	Excellent
Design reusability	Poor	Excellent
Interoperability	Poor	Excellent
File size	Large	Small
IP protection	Poor	Excellent
Multi-applications	Moderate	Excellent
Team work	Poor	Excellent
Mobility	Poor	Excellent

Table 1 Strengths and weaknesses of parametric and non-parametric systems (continued)

<i>CAD functionalities</i>	<i>Parametric CAD</i>	<i>Non-parametric CAD</i>
Change management	Good in an integrated engineering environment; Poor in heterogeneous collaborative design	Excellent with flexibility
Family part design	Excellent in capturing design knowledge and generating variations	Poor
Constraints of design	Implicit constraints	No constraints
CAD knowledge and technical understanding requirements to the users	Very high	Moderate

7.1 Modelling design intent

The associative dimensions and feature patterns are useful for capturing the design intent in a systematic approach. Design intent can be defined as the set of relations the designer requires such that it reflects engineering rules and semantics. To capture the design intent requires the ability of the CAD software to capture form, fit and functional requirements of a design during the modelling process. This capturing is usually accomplished using various types of constraints. Since parametric systems allow an entity (*e.g.*, a vertex, a face or a feature) to be dependent on another entity, they are ideal for capturing the design intent. Feature-based design is developed based on parametric solid modelling approach, which is excellent in modelling the design intent. Maintaining feature identity allows faster editing to be performed especially in cases where several features may intersect. Take, for instance, a cylinder that may intersect several slots cut into a block. In a parametric system you would be able to move the cylinder to a new location conveniently; all the faces belonging to the old hole would follow the new location. All the entities belonging to a feature can be manipulated in a group; their parameters, dimensions and constraints are managed properly. So far, feature as an object type (defined with many varieties and derivatives) is recognised as the viable intermediate information format to interface tedious geometrical entities with a high-level semantic application. Very often, the designer would like to capture the design intent while building the model. Such design intent can be feature-based templates with engineering knowledge rules embedded in the design models. This function comes naturally in a parametric system. However, the design intent can be a fuzzy concept that requires very advanced understanding of engineering rules involved and methods to realise it in the CAD system used. After which, conflicts among rules have to be resolved before including them into the model.

In contrast, non-parametric approach is rather poor in modelling the design intent. It is unable to maintain relations among entities, not to mention individual feature identities and feature history. When editing the shape of a solid, such as a cylindrical hole, in a direct B-rep modeller, the user would be responsible for selecting all the faces that belonged to the original cylinder and for performing the modification on the selected set. Since the product model does not have the constraints built into the database, associative relations among entities are not preserved. This is a major drawback for non-parametric design. Although it is possible to convert the non-parametric model into a parametric one

via feature recognition, due to the diversity of feature definitions such algorithms seldom work in real design applications. Instead, according to the author's view, the interactive approach is more practical. However, due to the lack of an underlying standard of unified feature definitions, this approach needs much theoretical research before any realistic system appears in the market. Furthermore, engineering semantics in the product model is not preserved with this approach. Hence, design intent has to be captured in a secondary step, which is specifying attributes in the non-parametric systems. In many cases this might not even be possible, because the inconsistency of entity identification. For example, if feature intersection has broken the faces of an original feature into several separate faces, then it would be difficult for the system to relate these faces together, apply attributes and form consistent and valid constraints. Generally speaking, non-parametric modelling is not fit to embed design semantics in the product model.

7.2 Supporting collaborative and concurrent design processes

When applying parametric modelling in collaborative product development, major problems occur. This is due to the rigid requirement of parent-child relationships, upfront knowledge of design intent and increased model size.

7.2.1 Conceptual design

In order to support the ODM business model, collaborative conceptual design is the most common activity. 'Show me your idea' is often requested by peers in the project. In the parametric approach, the ability of innovation decreases when the model complexity increases. With the non-parametric approach, the model complexity does not increase when the conceptual model evolves.

7.2.2 Team work

With the parametric method, because the project team usually consists of engineers with different level of skills in CAD and product knowledge, understanding the embedded design intent becomes a major hurdle. This difficulty limits the in-context editing by the team members except by the original CAD engineer. On the other hand, with the non-parametric solids, its operations are unified and can be easily made available by each partner company. Since everyone can get hands-on operations, everyone can take charge of the changes. Such synergy is precisely what collaboration is for.

On the other hand, the non-parametric solid model can be conveniently incorporated into other CAD systems. Usually, the solid model has a much smaller data size than a parametric one; the regeneration time, therefore, is faster. Technical rules are not embedded in the product CAD models. Hence, they are controllable by different companies involved.

7.2.3 Design reusability

So far, there are no standards for feature definitions, semantics and constraints. Once the current design project has been dropped, its resulting models, especially those with the complex references and constraints, become difficult to be reused. Even in a single company, the ability to innovate the legacy model knowledge requires very much in-depth knowledge and CAD skills. Of course, parametric design can export solids and

use them in the same way as the non-parametric method. The question then is “What about the changes made on those solids?” Should the changes have to be made in the original parametric manner, the user then must re-learn the rules and links that have been implemented. If such changes are made on those exported ones, then a hybrid approach becomes necessary. Then is it really worthwhile to create the parametric models in the first place? The only exceptional application is for standard family parts or products, which are to be discussed later in this section. Clearly, the resulting designs with the non-parametric approach, even legacy ones, can be easily reused.

7.2.4 Interoperability

Most CAD applications can handle solid geometry very effectively.

7.2.5 File size

Non-parametric solid files are usually much smaller.

7.2.6 IP protection

In parametric models, technical rules are embedded in the product CAD models. They can be easily interpreted and learned by other participating companies. This may cause the dispute over intellectual property. In contrast, the non-parametric method supports model sharing on a ‘need-to-know’ basis.

7.2.7 Multi-applications

In the non-parametric approach, a solid model can be manipulated with many different applications. Simple operations include viewing, editing, analysis, marking up, and drawing generation among others. Many other operations can be integrated such as CAPP and CAM systems. Since most geometry passed between systems goes through a neutral format, which is a unified representation, this enables most acceptable geometry data standards such as STEP files. Parametric approach, on the other hand, requires fully integrated application which can access and accept CAD feature definitions. Otherwise, it may need to rely on feature recognition which often fails. Again, exported solids from parametric system can be used; their use, however, is limited to one-way integration. To reflect the feedback from different aspects due to complicated constraints, links and relationships, only the original designer who created the model can make the changes. This makes other application engineers dependent upon a few original design engineers. Effective collaboration, therefore, is limited.

7.2.8 Mobility

Before any commercial, distributed and parametric system appears, parametric product modelling will be most likely centralised in the OEM. It does not have mobility; the designed product models do not allow transferring from one company to another. This is due to the technical difficulties in ensuring consistent high quality of design or the high technical requirements of the CAD engineers. Non-parametric models can be mobile because solids can be easily decomposed into any pieces of sub-blocks. Such blocks can be modified by partners in context. The results can be easily united together as a single part.

7.3 Change management

The parametric approach can manage changes effectively in an integrated engineering environment. However, it is rather poor in heterogeneous collaborative design. The 'master model' can only be modified by the OEM. The requirement of reapplying created features to enable changes is double sided. On the one side, a parametric system's ability to change the order in which features are applied gives the user a way for changing the final geometry outcome quickly. Take for instance a boss that was added to a previously shelled body. The boss would be solid because it came after the shell. To make the boss shelled, the user simply has to move the boss feature in front of the shell feature in the history tree. Comparatively, this simple operation cannot be performed in a non-parametric modeller. The user would have to apply a more complex alternative method (*e.g.*, adding the boss and then reapplying the shell based on the last modelling step). On the other hand, since a parametric system creates a sequential relationship between each feature, every feature depending on this node in the history tree has to be reapplied for a user to effect any change at a node. It involves tedious mapping from the previous modelling constraint scheme to the new feature entities. Sometimes, feature mapping is not feasible, and then the down-stream features have to be remodelled.

The non-parametric design is excellent to effect changes with much flexibility. Changes can be made by different players in a collaborative manner. The model can be bi-directionally transferred from one to another. The non-parametric model regeneration is more directly related to the solid kernel methods to update the solid. Hence, regeneration functions are highly reliable and compact. Compared to the parametric approach, non-parametric modellers do not have to replay the entire feature history in order to view the latest model change; they tend to be faster when editing large models.

7.4 Family part design

The parametric approach is excellent in capturing design knowledge and generating variations. Parametric systems are very effective at converting existing well known designs into 3-D models. It is also an effective and efficient approach to create reusable design libraries for both components and assemblies. Usually, the changing parameters in the existing designs are well established and are not prone to changes (Ma and Tong, 2003; Ma *et al.*, 2004). With the feature-based design approach, parametric systems are a perfect fit for family parts or assemblies, where in each case the geometry just varies in size, position and visibility (Ma *et al.*, 2003; 2004). However, parametric systems are not strong in those cases where input parameters lead to the creation of new additional geometry. Non-parametric approach is poor in automatic generation of variations. Explicit editing or even reconstruction is required.

7.5 Constraints of design

In parametric approach, constraints are attached to entities implicitly. Regeneration failures occur if these constraints are not fully satisfied. This approach requires constraint relationships at every stage of the model-building process. Very often, incomplete constrained schemes are not acceptable. This condition forces the user to add more constraints than what would really be required for the design intent. Hence, the user introduces possible design problems down the road. In a particular CAD system, the parametric approach has the power to capture a certain amount of design intent. When the

designer is required to add hundreds of these interdependencies, however, it becomes difficult for the designer to anticipate the cumulative effect that each change or modification would cause. The negative impact of such constraints would be the unanticipated model. Sometimes, the resulted geometric model fails to regenerate due to some constraint conflicts. In such cases, a significant amount of time is usually required to resolve the problem. It then results in a design productivity that is lower than expected. Such implicit constraints become the obstacles for one engineer to pick up another one's work, or one team to work on top of another team's product models. Therefore, they create information flow gaps.

The non-parametric approach guarantees clean, solid representation form with no constraints attached. It uses only straightforward representation of shapes and structures without the complexity of dependencies. Since there are no parent-child relationships to be worried about, editing operations only affect the solids being edited. It is a truly What-You-See-Is-What-You-Get (WYSIWYG) editing paradigm. Therefore, this approach allows decomposing a complex product model into different combinations or groups.

7.6 Technical requirements to the users

The parametric design gives a very high demand to CAD users. The individuals' overall knowledge and in-depth understanding are essential to project success. The challenges are in understanding or recalling the embedded rules and constraints in a project. So far, parametric modelling tools cannot manage constraints in a consistent and unified manner. When a user creates a parametric model, he has to memorise the parametric relationships that he has built into the model in order to effectively perform any required changes. Such a job is stressful and is not friendly to newcomers. Since parent-child relationships are fundamental to all parametric modelling systems (Murphy, 2003), it is vital for the user to have a clear plan on how a model is to be constructed according to its design intent. Without this prior knowledge, it is very easy for users to create a model that restricts the creation process. As mentioned previously, low-level constraint errors occur from time to time. The consequence of whether the whole set of design intent rules can be realised or not depends on the modelling strategies. This involves trials and errors. The worst situation is that some changes require re-modelling of the previous constraint schema. In some cases, the resulting model has to be recreated entirely in order to accomplish a single desired change.

In the non-parametric approach, the requirement for users' knowledge and skills is moderate. Solid modelling functions are less complicated and easy to learn. The most involved engineers need only to know their own domains. Interdependency among different engineers and companies is not a major issue.

8 Discussion and conclusion

This case study has highlighted the industrial requirements for collaborative engineering across heterogeneous platforms. It can be concluded that non-parametric modelling has advantages in interoperability at the solid-model level, which has created tremendous benefits in ODM business model. It is more appropriate than the parametric approach under this collaborative design environment. First, it allows more design alternative

evaluations at the same time. Second, it has a higher rate of success in 3-D data translation across companies. Last but not least, it supports specialist deployment more effectively. This case study suggests that collaboration improvement does not need to finalise an integrated environment but requires a common space to connect resources and to share knowledge about the product, even in a heterogeneous network.

However, the author is not fully satisfied with the complete absence of higher-level engineering entities, such as features and constraints in the non-parametric approach. He believes that, ideally, parametric modelling will enable the sharing of not just solid models but also knowledge and design patterns. To achieve this, the functions of parametric modelling should be made available for different applications in a 'plug-and-play' manner.

The current parametric modelling tools lack the necessary interoperability and mobility for distributed communication. Each CAD tool adds special features and options to increase their system's values compared to its competitors. These added capabilities are beneficial for each user but make the exchange of data between different systems very complicated and, in many cases, not realistic. The market shares of parametric solution could be soon eroded if their collaborative means are not harnessed. This may happen even though they command a larger share of mechanical CAD market than non-parametric ones for the time being. More research should be done to improve dynamic sharing of parametric or non-parametric based product definitions across enterprises. Even though there are some hybrid approaches currently, the author believes that non-parametric design will play a more dominant role in collaborative engineering. The parametric method can be a complement to support family parts or sub-assemblies.

Currently, information sharing across different domain applications has drawn attention (Bidarra and Bronsvoot, 2000). However, the standardisation of engineering information entities (*e.g.*, features), is still in its infancy. Hence, the author suggests that the unification of feature modelling, which is the development of generic mechanisms to associate solid entities and feature objects (Bhandarkar and Nagi, 2000; Chen *et al.*, 2004), should be emphasised in future research. It is one of the preconditions for engineering knowledge/feature mobility over sophisticated computer networks.

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