INCORPORATION OF ENGINEERING ANALYSIS WITHIN DESIGN SYNTHESIS

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Abstract

The conventional product development process consists of several stages of design and review by which a set of product specifications are converted to engineered designs, hard tooling, and finished goods. Unfortunately, most engineers are uncomfortable with applying even simple equations, let alone deriving custom solutions to estimate design performance [1]. As a result, designers frequently fail to acquire any intuition regarding the performance of the design and permit continued development of poor design concepts. The purpose of this research is to develop a design environment which reveals the first order effects which drive the design performance, enabling the designer to better internalize the causality between critical design decisions and the product's performance. The research requires development of not only a design framework capable of incorporating engineering analysis, but also the development of analyses that are amenable to incorporation.

Objective

> *The goal of "intelligent" computer-aided-design (CAD) systems is to provide greater support for the process of design, as distinguished from drafting and analysis. More supportive design systems should provide a quick and simple means of creating and modifying design configurations, automating evaluation procedures (e.g. manufacturing), and automating interfaces to analysis procedures - Dixon (Cunningham, 1988)*

This quote indicates an accepted view of the design process, which many researchers have pursued. The goal is inadequate given the competitive pressure in modern product development projects and the current interdisciplinary role of design engineers. Rather, the long term vision of this research is to integrate analysis within the process of design thereby automating many evaluation procedures and enabling parallel design development and understanding of design behavior.

Advanced analysis techniques have been developed to provide many estimates of design performance. Typical types of analyses used in molded part design include structural (stiffness, impact, creep, fatigue), manufacturability (pressure distribution, cooling, shrinkage, fiber orientation), and economic (ammortized tooling cost, material costs, machine costs). However, these numerical simulations require complex meshes and boundary conditions to be built on top of detailed geometry. As such, advanced analyses tend to be performed at the end of the design cycle, after the majority of critical design decisions have been completed.

This research should result in an excellent compromise between manual calculations and numerical simulation. The performance estimates will be considerably more accurate than manual calculations yet be available without a finished design or complex mesh. Moreover, these results will be provided real-time as the design is synthesized and stored with the model in the design environment, allowing the designer, colleagues, and other analysis methods access to previous analysis results and assumptions.

Approach

Design Representation:

Engineering performance analysis is presently achieved by two main approaches. One is to use the physical formulae to calculate the engineering parameter [3]. The significance of this traditional approach is obvious and tremendous classical research efforts had been contributed to this area as the cornerstone of the modern engineering. However, in the view of today's computer-aided designer, this approach involves too much human interference and is only suitable for the parts with the relatively simple shape. The method is potentially very difficult, if not impossible, to be applied for generalized complex geometries in modern CAD systems.

The second approach, involving Finite Element Methods, is defined as a computer-aided mathematical technique for obtaining approximate numerical solutions to the abstract equations of calculus that predict the response of physical systems subjected to external influences. It applies the basic stress and deflection functions to the meshed elements, which composed of the complex part, and generates a low-power assembled equation matrix. It can be implemented and solved by computer software. There are three critical drawbacks to FEM. First, FEM is a time-consuming procedure involving pre-processing, process calculation and post-processing which may distract the attention of the designer. Second, the analysis is generally performed after the detailed design, when it is hard to overturn the whole design concept [4]. Third, the selection of proper FEM boundary conditions, FEM approach, or even the correct FEM analysis may not always be obvious to the designer.

Different to two above approaches, Feature Based Analysis uses the generic feature as the unit of consideration. Just like the generic primitive in Constructive Solid Geometry (CSG), we assemble the whole model with the generic features. The physical formulae are applied to each of the generic features. The total system equation results from the interactivity between the generic features. Feature Based Analysis will be able to handle the interactive modeling with the engineering analysis with a target accuracy of approximately 80%. The goal of the research intends to provide a CAD environment with the injection molding analysis and other engineering analyses. With the powerful modeling tool and the manifold engineering analysis, the designer will be able to adjust his/her design through all design stages, from concept development to detailing. Of course, Feature Based Analysis has its own weak point, which is the difficulty to define the feature model [5,6]. This is one key goal of the research program.

Basically, there are two ways to get the feature information. The first approach is called feature-based design (FBD, also known as design with feature), wherein the predefined feature library is used to create the product model. The physical information exists as the system starts the engineering property analysis. The second approach, feature recognition, extracts the higher level engineering properties from the lower level geometric object, which is well known as being represented by Constructive Solid Geometry or Boundary Representation. It turns out both methods have advantages and disadvantages. We will try to combine two approaches in our system. Since artificial intelligence, the main tool of feature recognition, is not yet fully developed, we will spend more time on FBD exploring the robust feature model.

Due to its open data structure and PC based performance, SolidWorks has been choses as the development platform of our CAD system, called PlasticWorks. According to the notification mechanism of SolidWorks API, the engineering analysis can be running transparently through the whole design procedure. So the designer can refer the analysis result, which is exhibited in the specific colors or with the information dialog in real time. To maintain the best efficiency, the designer is also able to turn on/off specific engineering analysis.

The attribute sets, which are defined by PlasticWorks, combined with SolidWorks feature model, sets up the groundwork for the injection molding performance analysis. Feature information, shown as the attributes in the database, provides the data source to the real-time analysis. On the other hand, the real-time analysis adds estimates of the performance attributes. The integrated database of geometric and engineering feature provides a robust system to the developer and the designer.

Figure 1 shows the structure of PlasticWorks. Based on SolidWorks, PlasticWorks main module, which has been created utilizing Microsoft Visual C++, will manage the interface and the communication between SolidWorks and PlasticWorks. The different module in PlasticWorks, which is developed by Visual Basic or Visual C++, handles the different engineering analysis respectively. It is obvious that the feature definition of SolidWorks is not enough for the engineering analysis. We will define our own feature and set up the specific Feature Manager window. The whole idea is to give the designer an enterprise-level CAD system with the professional engineering analysis, more specifically, the injection molding analysis at this stage.

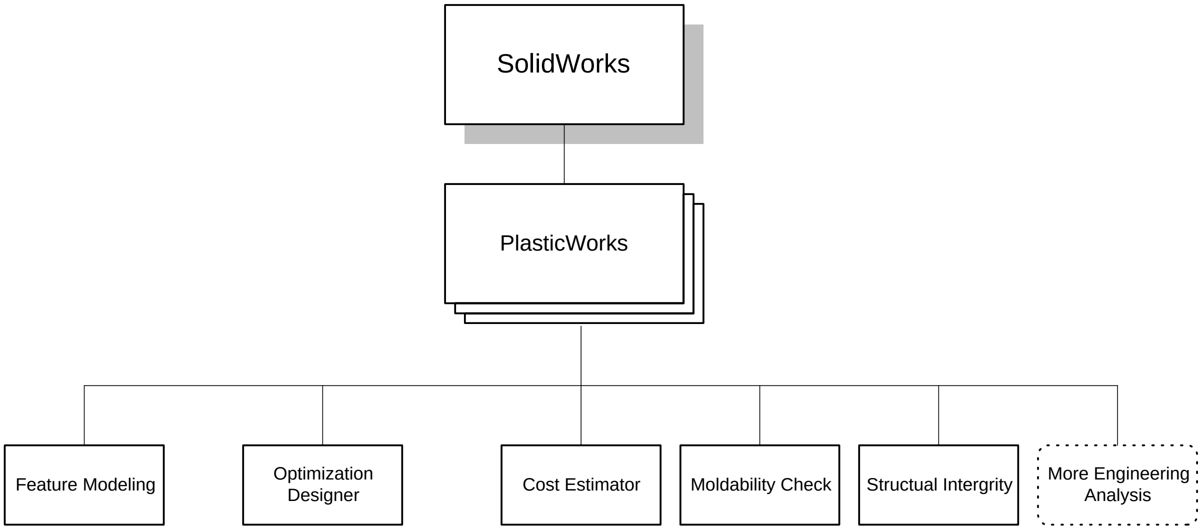


Figure 1. PlasticWorks System Diagram

Cooling Analysis:

The cooling time of an injection molded part directly affects the production cost and efficiency. As such, cooling time estimation is a critical cost driver that should be modeled early in the design stage. For cooling time estimation, several possible methods will be considered.

Dimensional analysis produces a model that can be used as a “simple thumbnail cooling predictor”. This model makes use the material’s thermal diffusivity to describe how quickly heat will flow out of a part area of a given thickness. It allows for the use of single-point melt data to describe a material’s propensity toward heat transfer and takes into account both conductive movement of heat through the plastic and convection to the mold surface. It produces results which are “average cooling times” [3].

$$cooling \quad time \quad = \quad \frac{(thickness)^2}{4\alpha}, \tag{1}$$

where α is the thermal diffusivity of the material. While this model will usually produce reasonable predictions about cooling in many cases, it does not take into account the temperature gradient that exists between the temperature of the melt and the temperature of the mold surface. Experience with this model has shown that it tends to overpredict cooling times in parts with thicker nominal walls and it is not particularly useful with some types of polymers.

Our research in cooling analysis has two main goals. First, we are developing more valid criterion to predict the ejection requirements of an injection molded part. Second, we are creating new thermal analysis approaches which are well suited to performing cooling analysis based on design features, and is computationally feasible within a design framework.

1. Ejection Criterion:

One common criterion for part ejection is when the mean or maximal temperature is equal or less than an estimated ejection temperature, T_e. But in industrial practice, the ejection condition is determined by the part’s deformation or warpage due to ejection forces and subsequent cooling. This research uses a combination of experimental, analytical, and statistical methods to discuss different ejection criteria and their rationality, thereby developing a more effective criterion based on part stiffness [7,8]. This stiffness criterion facilitates more accurate estimation of cooling time at early stages of product development. This knowledge can help the designer to improve the design and reduce the cost by increasing the production efficiency while simultaneously ensuring injection molded part quality. Matlab® is being used in this investigation for analysis development.

2. Analysis Development:

To be amenable to real time design synthesis, the cooling analysis can not develop a global model such as is currently being utilized in Boundary Element approaches. Rather, the cooling analysis must locally inspect the feature geometry and established a mostly-valid lumped parameter model while identifying significant thermal interactions with adjacent features. Since injection molded part is relatively thin, it is possible to perform one-dimensional heat analysis in the thickness direction. With this approach, the key is to establish the representative thickness and boundary conditions that are physically correct and will yield good approximate result for complex three-dimensional geometry. Unfortunately, the complex part geometry may significantly affect the cooling time as shown in Figure 2. In the example shown, a rib will produce more thermal mass than the nominal wall. One technique is to add the thickness described by the included radius of the rib to the nominal wall to provide a more realistic measure of the necessary amount of cooling. Such approaches are currently being developed, validated, and incorporated.

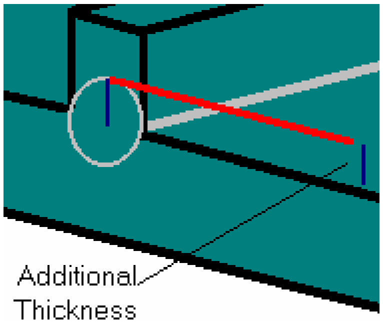


Figure 2. Typical Part Cross-Section

After the representative thickness and boundary conditions have been developed, the implicit finite difference methods will used. The instantaneous heat transfer for a controlled volume in the part and mold is:

$$\frac{kA}{\Delta x}(T_{i+1}{}^{p+1} - T_i{}^{p+1}) + \frac{kA}{\Delta x}(T_{i-1}{}^{p+1} - T_i{}^{p+1}) = \rho c_p A \frac{\Delta x}{2} \frac{T_i{}^{p+1} - T_i{}^{p}}{\Delta t}. \qquad (2)$$

At the interface between the mold and the coolant, the heat transfer is given by,

$$hA(T_\infty{}^{p+1} - T_i{}^{p+1}) + \frac{k_m A}{\Delta x}(T_{i\pm1}{}^{p+1} - T_i{}^{p+1}) = \rho c_{pm} A \frac{\Delta x}{2} \frac{T_i{}^{p+1} - T_i{}^{p}}{\Delta t}. \qquad (3)$$

At the interface between the mold steel and polymer melt, the heat transfer can be represented as,

$$\begin{aligned} &2F_p T_{i-1}{}^{p+1} + [1 + 2F_p + \frac{2\Delta x_p}{F_p}\frac{k_m}{k_p}\frac{F_m}{2\Delta x_m}(1+2F_p)]T_i{}^{p+1} + 2F_p \Delta x_p \frac{k_m}{k_p}\frac{1}{\Delta x_m} T_{i+1}{}^{p+1} \\ &= (1 + \frac{2\Delta x_p}{F_m}\frac{k_m}{k_p}\frac{F_p}{2\Delta x_m})T_i{}^{p}, \end{aligned} \quad , \qquad (4)$$

where $F_m = (\alpha_m \Delta t) / \Delta x_m{}^2$ for the mold and $F_p = (\alpha_p \Delta t) / \Delta x_p{}^2$ for the polymer.

Comparison will be made for these two methods. The analysis of the heat transfer of the complex part will try to estimate the cooling time quickly with appropriate accuracy. With combination with SolidWorks®, this is useful in early stage of design. All the above proposed research is aim to predict the cooling time accurately and quickly. This research will help designer quickly get an approximate cooling time estimates at the early design stage, then make any revision to increase production rate and reduce cost with acceptable quality.

Costing Analysis:

The application of Design for Manufacture (DFM) guidelines in the design of mechanical systems often results in systems with fewer but more complex components that are most often injection molded. Significant savings in assembly costs and product quality have been reported from the application of DFM in many industries [11]. However, in spite of these savings in assembly costs, development times (which include design and tooling lead-times) are definitely greater for complex components. Time is of the essence in product development in many leading edge companies. According to a McKinsey and Company study, “a high tech product that reaches the market six months late, even on budget, will earn 33% less profit over five years. On the other hand, finishing on time but 50% over budget will reduce a company’s profit by only 4%” [12]. In addition to the increased development times for complex components, manufacturing yield could be significantly lower for a consolidated complex component in comparison to the equivalent total yield of the individual parts. The need for a system view of component consolidation is thus apparent.

The effects of complexity on the manufacturing cost and time-to-market of discrete mechanical systems are difficult to predict. The current research uses the injection molding process to characterize the effects of part and system complexity on their life cycle costs and time-market. Models for predicting the effects of part and system complexity on development and total life cycle costs as well as tooling lead-time are being developed. The injection molding process has been chosen as the subject of the research because of its complexity and its increasing usage in the manufacture of complex net-shaped domestic and industrial products.

Design cost analysis has the greatest impact when done at the early design stages before a considerable detailing of design, and the resulting difficulty and costly nature of late design changes. In addition, life cycle cost analysis is considered the most appropriate means for comparing the cost efficiency of design alternatives. Hence, the complexity metrices that drive the cost of the design for every stage of its life cycle are first identified through literature review and interview of mold makers and molders. Quantitative metrics that can be evaluated from CAD product data are preferred to qualitative metrics that require the subjective judgement of the designer.

Complex systems consist of finite variety of interacting elements. According to Scurcini [13] the complexity of a technological system is driven by the number, variety, and types of elementary components in the system, as well as the organization of the components. Form and shape features constitute the building blocks hence the elementary components of a discrete product. Hence, it is hypothesized that an enumeration of the number, variety, types, and organization of features in a designed part could be functionally related to the complexity at every stage of its life cycle. It is also hypothesized that the difficulty of manufacturing a designed feature correlates, among other factors to the number of dimensions required to completely define the feature, its feature points.

Three approaches are frequently used for product design with features: interactive feature recognition, feature extraction, and feature-based design. Of the three, only feature-based design is easily amenable to easy and automatic enumeration of all the features in a part from its CAD data. Feature extraction requires complex algorithms that have only been successfully implemented in the recognition of simple feature profiles. However, even with feature-based design, standardization of feature categories, that does not limit designers creativity, is required for portability of data across platforms. Efforts to meet this need are on going with development of the Standard for the Exchange of Product Data (STEP). A form feature classification of features for injection molding that conforms to STEP is shown in Figure 3.

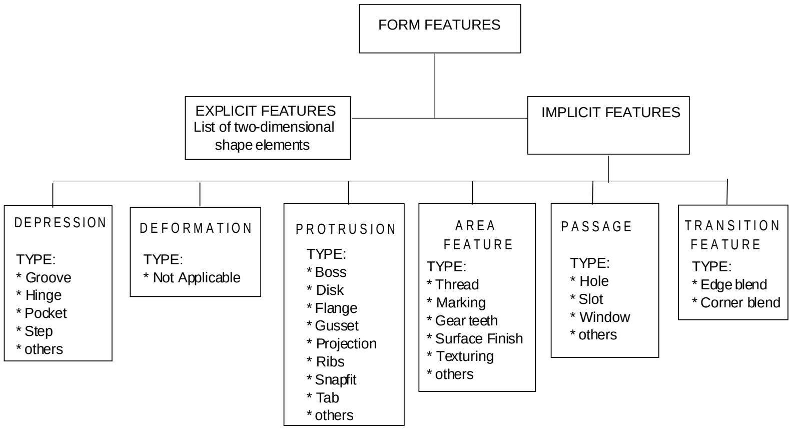


Figure 3: A STEP Classification of Injection Molding Form Features

However, the designer has the freedom to define application type features, as long as they fall within the above classification. A large library of features that renders any model built on a fixed number of features obsolete is soon created. A surrogate that correlates to both the number and types of features in a CAD model is the *total number of dimensions* or total number of feature points required to completely define the model. This is particularly true in constrained-based type modelers, which includes most 3-D modelers, where for example a solid block would require three dimensions, its height, base, and width to uniquely define it. The block is then said to have three feature points.

Manufacturing cost data for 25 injection molded parts of varying complexities, were collected from a custom injection molder. The data collected for each part included its detailed blueprints, two to four mold quotes submitted for each part, and the injection-molding yield. The number of dimensions required to completely define each part was enumerated. Functional relationships are being investigated between the average mold manufacturing costs, and the number of dimensions that constitute cavity detail, internal and external undercut features, and the basic envelope size. Other factors that will be considered include projected part size, and mold parting line complexity. These factors can be evaluated from the CAD data at the design configuration stage. As the design becomes further detailed, the inclusion of part tolerances, fillet and chamfer radii tightness, and surface finishes, will further constrain the model. Thus, the accuracy of cost estimates made at the early stages of design is expected to improve at the detailing stage.

A close correlation, $R^2 = 0.85$, was found between the average quotes submitted for each part and a linear function of the total number of dimensions and basic envelope volume of the parts, at 95% confidence:

$$Cost_{Tooling} = 21{,}800 + 92 \cdot \#\_Dimensions + 0.75 \cdot Part\_Volume \tag{5}$$

A plot of the results is shown in Figure 4. These results show that an accurate model can be obtained with further tweaking of the feature points and metrics obtainable from CAD data.

Further analysis is being done to refine and validate the relationships with additional independent data. Since each feature has certain number of feature points, it will be possible to determine the cost of every additional feature to tooling cost as the design progresses. Moreover, the relationships between complexity and process yield, process capability, assembly costs, maintenance cost, and total life cycle costs will be determined. Guidelines for optimum consolidation of parts will thereafter be established.

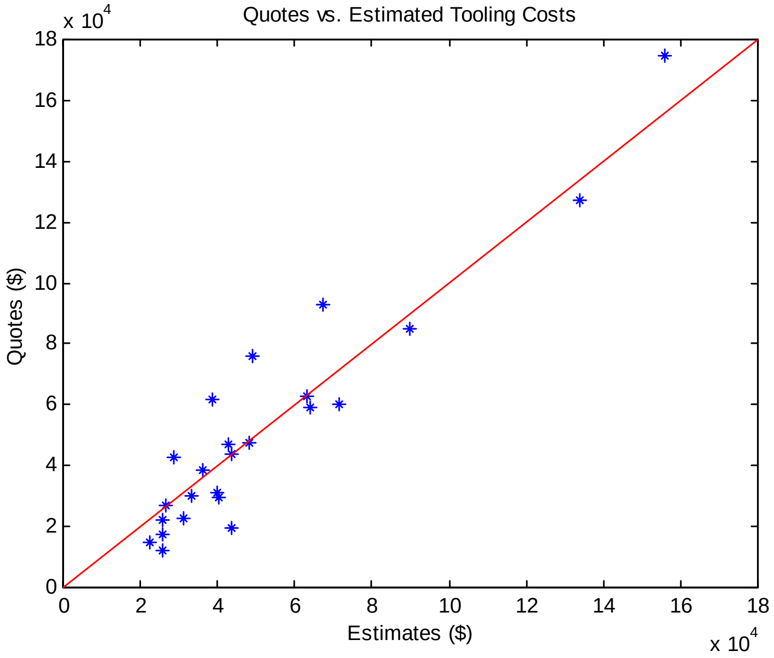


Figure 4: Plot of Quotes and Estimated Mold Costs

Optimization:

Since there are multiple performance goals arising during product development, the research team is also investigating optimization methods and robust design methods. Specifically, it is our goal to ensure that the product specifications are most likely to be met at the lowest possible costs. As such, the overall performance of the product is being analyzed with respect to the specifications. The likelihood of specification satisfaction is represented by the combined yield P_{Joint} as follows

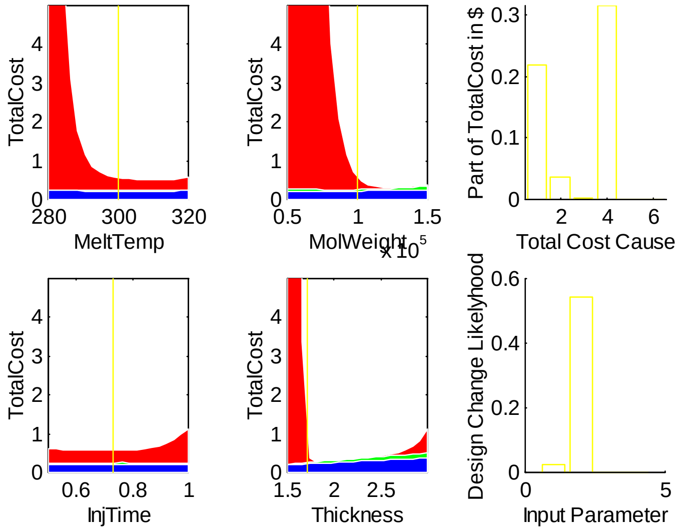
$$P_{Joint} = \prod_{i=1}^{n} P_i \, , \tag{6}$$

where each P_i represents the probability that the *i-th* performance criteria will be met. These probabilities can be estimated by estimating the expected mean and standard deviation according to the performance analyses described above together with variance analysis. The cost of each type of defect, $Cost_j$, can then be assessed as follows:

$$Cost_j = Cost_{Part}\left(1 - \frac{1}{P_{Joint}}\right) \bullet \frac{1 - P_j}{\sum_{i=1}^{n}\left(1 - P_i\right)} \, . \tag{7}$$

These cost elements, too, can then be decomposed into the material cost of the different features, the different causes of the process cost (like cooling time, clamp tonnage and injection time), and the different causes of the defects (like stiffness requirements, flow length or shear rates). This performance decomposition research is currently under progress, and will aid the design engineer in analyzing the cost and performance drivers.

The plot below shows the output of a design advisor prototype. The data shows the performance decomposition of a polymer part. The four graphs to the left show how the total cost per part changes with the change of one of the four input variables. This total cost is split up into material cost (the bottom area of each graph), processing cost (the middle area), and cost due to defects (the top area). It is clearly visible how a violation of the constraints affects the total cost due to defect parts. A more detailed analysis of the cost drivers is given in the upper right corner, where for the given point the cost is split up into material cost, process cost and the different defect costs as shown in the legend. In this case, the violation of the deflection constraint increases the price per part about 60%. The bottom right area estimates the likelihood of design change and is explained in more detail below.



Part of total Cost Legend:
1: Material Cost (Blue)
2: Process Cost (Green)
3: Yield Fill Pressure Cost
4: Yield Deflection Cost
5: Yield Shear RateCost
6: Yield MeltFrontTempDev Cost

Design Change Likelyhood Legend:
1:Melt Temperature
2: Molecular Weight
3: Injection Time
4: Thickness

Figure 5: Cost-Quality Trade-Offs for Critical Design Parameters

Long term research includes analysis of the design time, which is crucial in today's fast moving business. This analysis will provide estimated of the time between the start of the design work and the start of the production, and will be based on elements like the time required to cut the mold, and also estimates of the likelihood that the design has to be changed. Design changes may be necessary because the knowledge about the system is incomplete, and the proposed design has not the desired quality or performance. At this point, a design change may be necessary. The design change advisor will analyze the likelihood of design change, and also provide estimates which design parameters have to be changed, as it is usually preferred to change the material or the injection time instead of changing the wall thickness, which would require expensive and time consuming retooling. A plot of the design change estimator is seen in the figure describing the cost drivers above. The bottom right graph of this figure shows a first prototype, where depending on the robustness of the design the likelihood of design change is plotted. For the given point, there is a 60% chance that the molecular weight makes the design unfeasible and has to be changed, and there is also a small possibility that the melt temperature has to be changed.

In summary, the optimization research consists of three main blocks: the decomposition of the cost, quality and performance; advising about the trade off between cost and quality; and the analysis of the likelihood of design change. All three elements are extremely useful to the modern designer, yet the research explores new areas of design.

Conclusions

The fundamental purpose of the research is to feed back the first order effects which drive the design performance during design synthesis. The current approach is not intended to compete with more advanced analysis techniques, but rather provide an estimate of the performance which identifies the need for guided design refinement and/or more sophisticated analysis techniques. There are a myriad of possible analysis types which may be of interest to the engineer in estimating the design's performance, some of which are listed in Table 1.

Table 1: Some Common Design Analysis Methods

End-Use Structural	**Manufacturing**	**Economic**
Tension, Torsion	Moldability	Tooling Cost
Bending, Creep	Cooling, Shrinkage	Material Cost
Impact, etc.	Process Plan	Processing Cost

Many of these analysis types have different physical bases and requisite numerical analysis techniques. While the analyses are unique and require separate development, each analysis is tractable and can be formed in a consistent format for execution and storage. This research is not focusing on developing multiple analysis types. Rather, the approach will be to develop a structure that manages each feature's internal system of equations and boundary conditions. To develop and demonstrate the architecture, cost and cooling analyses are to be developed and implemented. While the premise of the research is that first order analysis will provide design intuition, the interaction between features can change the physical dynamics which are being estimated. To enable the described performance analyses, the current design environment must be extended. As a review of the related research will show, much of the design intent is being captured by storing the objective of the feature design in addition to the traditional geometric and topology data. The research is attempting to transcend this trend by not only capturing design intent, but by providing performance estimation relative to the stated objective.

Our team is making fundamental contributions to both the design research and polymer processing areas. Currently, implementation of the design representation, performance analyses, and performance interpretation tools are being incorporated into SolidWorks. It is intended that this tool will aid the design engineer to optimize the trade off between cost and performance during design synthesis. Many of the research concepts are also being communicated through the University of Massachusetts Amherst Video Instruction Program, which will be offered again in Spring of 1999.

Acknowledgements

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