White Paper

Behavioral Modeling

The Next Generation of Mechanical Design Automation

Executive Overview

To respond competitively to the unprecedented challenges of today's markets, organizations must take a smarter, more objective-driven and process-wide approach to product development. This approach makes it easier to deliver products that take advantage of rapidly changing technology, that hit the market earlier, that achieve a leadership position in existing markets, and that allow more effective entry to new markets. Behavioral Modeling is the next-generation mechanical design automation technology that finally makes this approach possible.

Advancing customer expectations require more from product design than ever before.

Behavioral Modeling gives designers more efficient, adaptable ways of solving engineering problems. It promotes the creation of well designed products by synthesizing required functional behaviors, design context, and geometry. Through an intelligent process of knowledge capture and iterative solving, Behavioral Modeling allows engineers to pursue highly innovative designs that exhibit desired behaviors and robustness in the face of ongoing requirement changes.

Behavioral Modeling is the next-generation mechanical design automation technology that meets these challenges.

The Behavioral Modeling process involves:

The cornerstones of Behavioral Modeling are…

- '*Smart-models' that encapsulate engineering intelligence.* Designs are created using next-generation feature-based modeling techniques, which capture geometry, specifications, design intent and process knowledge — all at the feature level.

…smart models

- *Engineering objective driven design.* Design tools use the feature-based specifications within the smart model to drive and adapt the product design. Using objective-driven solving functions, engineers can determine an optimal solution, even in designs with many variables, constraints, and criteria. This technology makes it easy to meet requirements, optimize to objectives, and assess the effects of change on product performance.

…objective-driven design

- *Open extensible environment for integrating different engineering tools.* An open, extensible environment facilitates associative bi-directional communication among any external applications, such as analysis, engineering, or manufacturing, at the feature information level of the design model, ensuring that the design model reflects the results of other applications automatically.

… and an open extensible environment

Manufacturers that apply Behavioral Modeling technology will be leaders in their respective markets. Because smart models capture so much information with the design, they facilitate early design exploration, resulting in products that are more creative, differentiable, and responsive to customer requirements. With an objective-driven design process engineers can focus on key design issues and optimal solutions for better product performance and functionality. In addition, this open, extensible environment encourages the use of existing external applications — by either re-implementing them directly in the design model or via live data exchange — to drive design requirements and optimization. This results in more reliable and validated, cost-effective products.

Behavioral Modeling enables convenient exploration of new ideas, strategic focus, optimized solutions, and easy interface with external applications to yield *design excellence*: more creative, functional, differentiated, reliable, and customer responsive products.

In order for companies to lead in their competitive markets, design excellence is paramount. PTC's Pro/ENGINEER delivers this next-generation mechanical design automation productivity with Behavioral Modeling capabilities that address real-world needs, providing engineers with the technology they need to solve engineering problems in completely new ways or reach new levels of design excellence. Behavioral Modeling technology changes what engineers expect from a mechanical design automation system.

Design excellence enables market leadership.

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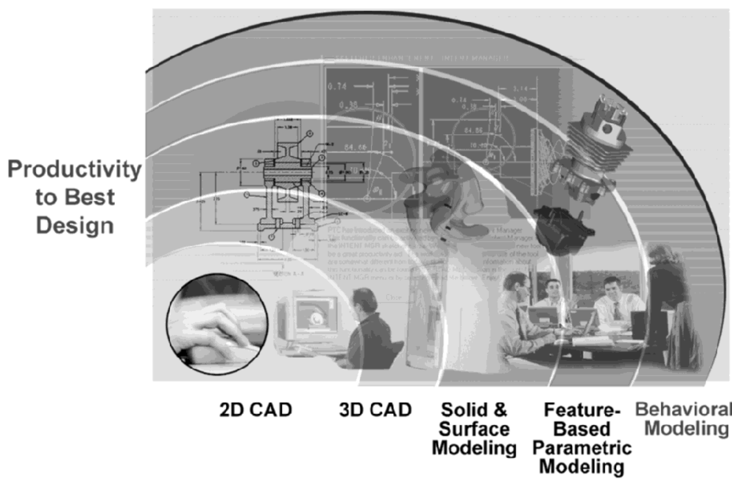
Introducing Behavioral Modeling

With the advent of mechanical design automation, design engineers began to transfer the product development process from paper to electronic-based models, using the first three generations of technology — initially, two-dimensional drafting, then three-dimensional wireframe modeling, and finally three-dimensional solid modeling. The current 4th generation of mechanical design automation is the most significant to date, and takes advantage of associative, parametric feature-based modeling to improve design efficiency and expand the advantages of electronic-based design throughout the engineering process.

However, as product requirements become more volatile and exhaustive and products more highly focused and tailored for additional markets, engineers require a different type of mechanical design automation technology. The approach that addresses these expanded needs has recently been solidified and consolidated in the industry as the 5th generation of Behavioral Modeling.



The Evolution of Mechanical Design Automation Technology

"We believe that Behavioral Modeling will be the next follow-on technology to re-energize the MCAD business."

Gartner Group Cape Update, October 1998

Behavioral Modeling promotes the creation of well designed products through the synthesis of requirements, desired functional behavior, design context and geometry through an open, extensible environment. Built on the solid foundation of an associative, feature-based, parametric modeling kernel, Behavioral Modeling raises the level of mechanical design automation from simple geometry creation to fully engineering a solution.

The Cornerstones of Behavioral Modeling

The power of Behavioral Modeling eminates from three forces: smart models, objective-driven design capabilities and an open extensible environment. *Smart models* capture design and process intelligence and the range of engineering specifications required to define a product. *Objective-driven design* capabilities optimize each product design to satisfy multiple objectives and changing market needs. An *open extensible environment* enables organizations to integrate diverse tools across unique engineering processes.

The cornerstones of Behavioral Modeling include smart models, objective-driven design, and an open, extensible environment all based on a parametric, feature-based modeling architecture.

Smart Models

Smart models are intelligent designs that contain all the specification and process information they need to adapt to their environment. Because smart models are "aware" of their context and purpose, they enable organizations to develop more innovative, differentiated, and customer-responsive products.

Capturing Design Information in Features

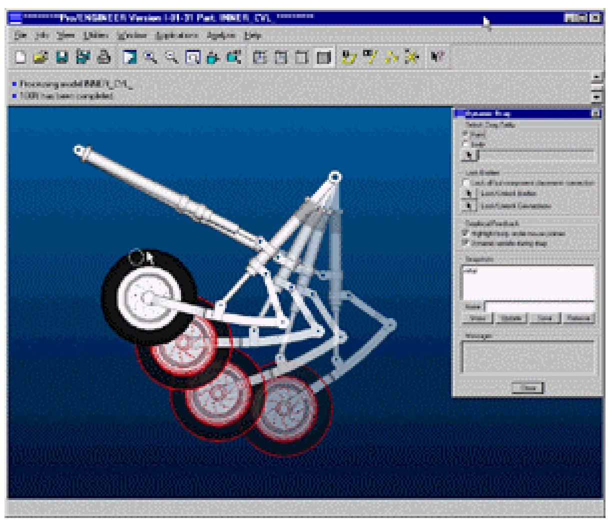
Smart models capture this intelligence within features. Originally, feature-based modeling, which was first introduced to the market with Pro/ENGINEER, only described the geometry and form of a design, such as protrusions, holes, rounds and blends. A Behavioral Modeling strategy advances feature-based modeling to accommodate a set of *adaptive process features* that go beyond the traditional core geometric features. These next-generation extended features accommodate a variety of information that further specifies the intent and performance of the design. Like the traditional geometric features, these other features are an integral part of the product model and perform like any other design object in the system.

There are two distinct categories of adaptive process features. *Application features* describe process information. *Behavioral features* contain engineering and functional specifications.

Application features encapsulate product and process information. For example, a pocket feature can contain NC part programming intelligence, including the tools and toolpaths necessary to manufacture itself. Routed-system features, such as cable segments and spools, simplify cable routing to point and click, because they hold all the necessary information to capture connectivity data, and to self-determine appropriate paths to avoid violating minimum bend radii.

Behavioral features contain information about design specifications, such as desired weights, angles of reflection, mass properties, or other measurements. They can also include spatial allocation information, including external static envelopes (shrinkwraps) and working envelopes (swept solids/movement evaluations). Moreover, when product definitions require the use of a customer's proprietary design application (for instance, one that designs turbine blade profiles), a behavioral feature can reference that external application as part of the product model definition.

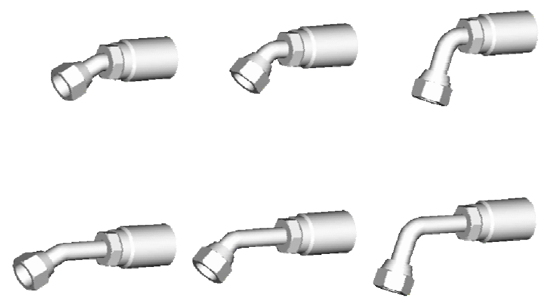
Behavioral features can also define the way that components in an assembly connect, using welds or pin, ball, and slider joints. When behavioral features consist of assembly connection information, including any assembly constraints, the assembly design process automatically implements that information to execute the functional behavior and purpose. By capturing original design intent, behavioral features ensure that product designs retain their integrity, robustness, and performance while adapting to market and engineering changes.



In one application, behavioral features can define the way that components in an assembly connect

Flexible Evaluation

At the heart of Behavioral Modeling, adaptive process features make smart models highly flexible. As engineers make changes to smart models, the models regenerate to accommodate all their features and satisfy objectives and context. This regeneration may be fluid and dynamic, with a click-and-drag movement of a mechanism, for example. The regeneration may also be automated based on table-driven input; for instance, the process may select specific models from a generic family of parts or interchange alternate assemblies from an on-line parts catalog. Finally, the regeneration can occur as a result of program logic or driven by routines referenced in the feature itself. In all cases, this highly flexible adaptation allows smart models to respond to changes in their environment.



Change may be automatic and based on table-driven input

Benefits of Smart Models

Because smart models encapsulate the key characteristics of a product, engineers no longer need to manage these aspects of the design; they are just part of the inherent intelligence of the model. For example, when application features such as joints and connections embody required constraints, they prohibit inconsistent behavior. Thus smart models allow engineers to focus on product differentiation and enhancement.

Since smart models facilitate design iteration, they promote design innovation. In the past, design iteration was often unachievable due to being too cumbersome, complex, or time consuming. For example, smart models make it easy to verify functional behaviors with click-and-drag operations or to check in-service interference after changes have been made. Such ease of iteration is critical, since many times innovative ideas are the result of investigating or validating something altogether different.

Organizations can also use smart models to increase their responsiveness to customer requirements. Using adaptive process features, engineers can create a springboard from which to perform custom product development. They can build intelligent products and then quickly and easily adapt those designs to new requirements.

Objective-Driven Design

An objective-driven design approach automatically optimizes designs to meet any number of objectives captured in the smart model by adaptive process features. It can simultaneously resolve conflicting objectives, a task that was often impossible using traditional approaches. Because the specifications are inherent in the features of the smart model, engineers can quickly and easily regenerate and revalidate the design’s conformance to specifications as often as the model changes.

Defining the Problem to be Solved

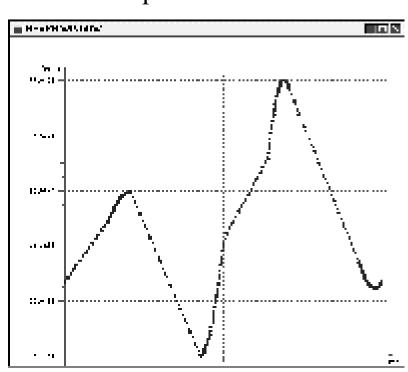
Traditionally engineers have maintained engineering and functional specifications in their heads, as notes on sketches, or in formal requirements documents. However, with Behavioral Modeling, specifications and requirements are captured and defined within the smart model. Rather than iterate through small changes to transform an initial design into a solution that meets specifications, the specifications can be used to actually drive the design. For example, perhaps an engineer wants to place a hole coincident with the axis of the center of gravity of a design. Capturing the center of gravity in a behavioral feature and parametrically tying it to the hole will ensure that the features remain coincident, even as other design changes are made and the center of gravity moves to reflect these changes. Moreover, this can be undertaken to meet any number of objectives.

In addition to defining the problem with standard types of measurements such as the center of gravity or an edge length, more complex requirements can be captured in behavioral features. For example, when designing the pattern of reflected light on a surface, not only is construction geometry required to accurately define the travel of the light from the source, to the reflector and onto the surface, but it is also needed to create surface normals and reflection angles. Other examples of nonstandard measurements could include mathematical equations that define the shrinkage of gas in a pipe as it cools. In Behavioral Modeling, these more complex requirements are captured in such a way that they can be shared among engineers in a library of features for reuse when needed.

Understanding the Impacts of Change

The objective-driven design approach supports sensitivity studies, which give engineers multiple ways to assess and understand the impact of change on product design and performance. Sensitivity studies demonstrate how changes in design variables affect performance. For example, given a behavioral feature that specifies the volume of an automobile gas tank, a sensitivity study can illustrate the affect of modifications to the tank on its volume.

Design evaluations are easier when engineers can view results of their efforts in graphical displays that reside directly within the design environment. For instance, an engineer may want to click-and-drag a mechanism through its range of motion and visually detect potential interferences right on the screen. Or when studying the clearance between two loosely interfacing parts, an engineer may want to refer to an XY graph of position versus clearance to quickly understand the effect of a change in relative position.



Graphs residing directly within the design environment communicate the impacts of change to the engineer

Synthesizing Multi-Objective Designs

Objective-driven design identifies feasible and optimal solutions for complex problems by synthesizing multiple objectives. It accomplishes this goal by automatically searching the realm of all solutions to yield a set of feasible solutions. Through this automated design exploration, engineers can ascertain that a design meets all its engineering requirements. Moreover, engineers can use objective-driven design to find the single design that optimizes one or more goals, such as desired mass, minimum surface area, or maximum tolerance. Traditionally, engineers would need to manually try out as many of these iterations as they could within the time and resource constraints of the project.

For complex product designs, objective-driven design technology searches the range of possible solutions to determine the feasible ones and then searches the feasible solutions to produce the optimal product design.

Benefits of Objective Driven Design

Because objective-driven design satisfies engineering specifications automatically, engineers can concentrate on designing higher performance, more functional products. Assured of a solution that meets basic design goals, engineers are free to use creativity and skill to improve the design.

Open Extensible Environment

An open extensible environment is the third cornerstone of Behavioral Modeling. To maximize the benefits of the Behavioral Modeling approach, technology must be in place that allows engineers to take advantage of external systems, applications, information, and processes already in use within an organization. These external resources can contribute to the process of solving for design objectives and can return the results so that they become part of the final design. By providing connectivity throughout unique engineering processes, an open extensible environment increases design flexibility and results in more reliable designs.

Connecting Applications

At the design level, smart models accommodate features that link to information in other applications. These *external features* make the design solution infinitely extensible. External features reside within the smart models and link to other applications, for example, the generation of turbine blade profiles by an external system during the modeling of a jet engine. External features permit engineers to regenerate and re-use designs built on live information created in many disparate systems. Each time an engineer regenerates the model, the Behavioral Modeling system will reference and execute the external features as part of the process.

At the process level, this universal regeneration technology embeds closed-loop communication with external applications. It pushes attributes, parameters, and geometry from the model to the external routines and accepts the results as features native to the product model.

Behavioral Modeling extends the power of object-driven design regeneration through closed-loop communication with external applications.

At the architecture level, a rich, concise, and easy-to-use protocol connects the applications seamlessly. This protocol also permits engineers to redefine proprietary programs so that they reside directly within a product model. For example, an engineer can re-implement a routine that aligns the center of mass to an axis of rotation into a model of a motor.

Benefits of an Open Extensible Environment

The seamless engineering process afforded by an open extensible environment protects the product from loss of design intent. It avoids distractions brought about by cumbersome, disconnected communications and ensures the integrity of design information by directly connecting the 3D design definition to information that drives it.

Real-World Applications

Behavioral Modeling is more than a theoretical concept. PTC's Pro/ENGINEER Behavioral Modeler delivers real-world advantages that apply across multiple manufacturing industries.

Gaining Design Performance Insight: Headlamp Design

A key aspect of headlamp design is control of the pattern of light reflected from the curved surface of the lamp housing. Specifically, the angle of the light reflected from straight ahead must remain within a specified range.

Without Behavioral Modeling, the options for designing a headlamp have drawbacks. If engineers evaluate the design by measuring the reflected angle at various points along the surface of the model, the manual nature of the process limits the number of measurements that are made. If engineers use a proprietary application external to the model, they will have to translate the data to the other application and back every time there is a change to the model, reducing the efficiency of design exploration. If engineers build and test a prototype, they will incur significant costs and delays.

On the other hand, with Behavioral Modeling, an engineer can evaluate the reflection pattern over the entire surface of the headlamp at any time. In this scenario, the smart model includes a behavioral feature that captures the desired angle of reflection at a single point on the surface. It also includes a special point, called a field point, which represents the entire surface. During objective-driven design, the engineer groups this feature and the field point, along with any other construction features that will change as a result of optimization, in a user-defined behavioral analysis. The analysis returns results for the entire surface based on this information.

Since Behavioral Modeling simplifies the critical aspect of headlamp design, the angle of reflected light, the engineer can explore many more design concepts. As the engineer modifies the model, the system automatically updates the reflection analysis, ensuring performance of the design to specification and design intent is maintained for right-first-time product development.

Determining the Impacts of Change: Landing Gear

One challenge of mechanism design is to maintain design integrity throughout all assembly positions within the allowable range of motion. Engineers have to validate designs across the full range of motion every time a change is made.

Without Behavioral Modeling, such design validation requires engineers to use a CAD system to re-create the mechanism at interim positions or to export the design to an external motion simulation and analysis system for review by a design analyst. Unfortunately, this tedious process discourages extensive design exploration.

Because Behavioral Modeling supports click-and-drag visualization of the mechanism's motion, it can significantly facilitate design exploration. Since the joints and connections of the assembly "understand" their context within the model, the model accurately represents the behavior of the mechanism throughout design modification.

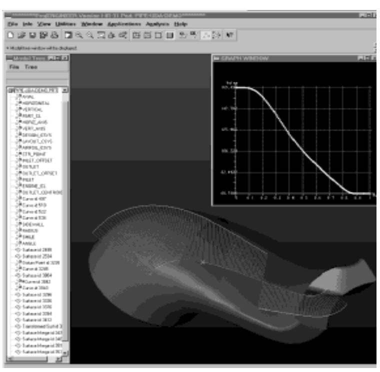
In addition, engineers can further characterize the behavior of the landing gear mechanism to capture its full range of motion. The output of that process can be a solid model that defines the total working envelope of the mechanism for use in assembly design. Of course, it will be easy to regenerate the solid model, as often as the mechanism design changes.

Behavioral Modeling is particularly useful for mechanism design. Because engineers can explore designs more easily, they can evaluate a larger number of variations to produce better products.

Driving Design by Engineering Objectives: Duct Design

In most duct design applications it is important to control the cross-sectional area. In fact, in some high performance applications, it is important to make the cross sectional area conform to a prescribed variation along its length.

Without Behavioral Modeling, engineers usually achieve the cross-sectional area objectives at several discrete points along the length of the duct but only approximate the area at intervals between these points. It takes an unreasonable investment of time to fine-tune the duct manually.



In the case of duct design, Behavioral Modeling makes the impossible possible, allowing engineers to achieve the desired cross-sectional area along the entire length of the duct. To accomplish this, the smart model includes a behavioral feature that contains the constructed analysis calculations for measuring cross-sectional area. As the design process advances, the engineer can regenerate the model, driven by an objective that minimizes the difference between the desired and actual cross-sectional areas at every point along the length of the duct. The solution meets the design objective without compromise, resulting in a more functional, higher performance design.

Design Optimization: Crankshaft Design

A basic requirement in crankshaft design is to align the center of gravity with the axis of rotation to avoid susceptibility to wear, which compromises product performance and life. Another design goal is minimum weight, and a third ensures there is enough material around the shaft. By optimizing a model across all these goals, engineers can produce a crankshaft that delivers the best performance.

Without Behavioral Modeling, engineers approximate coincidence of the center of mass with the axis of rotation by adding or removing material strategically and then checking the resulting location of the center of mass. However, this method is inefficient and inaccurate, and it precludes optimization of weight and materials.

Using Behavioral Modeling technology, engineers can optimize the crankshaft design over multiple engineering objectives. The crankshaft model includes a behavioral feature that measures the distance between the center of gravity and the center of mass. Other features capture special constraints, such as the maximum weight of the part or the minimum thickness of material around the shaft. To solve for all these design intents, the engineer regenerates the model setting the following objectives: the distance between the center of mass and the axis of rotation should be zero, the thickness of material surrounding the shaft should not be less than the minimum, and the entire part should have a minimum weight.

In this manner, the engineer achieves the best possible solution across all objectives and can use saved design time to investigate new alternatives that differentiate the product.

Complex Multivariable Designs: Exhaust Manifold System

Optimizing an exhaust manifold system is an exceedingly complex problem with many parameters and constraints. In particular, the lengths of the pipes must be equal, the pipes must not bend unduly, and there must be enough distance between pipes in the system.

Problems like this are nearly impossible to solve without Behavioral Modeling. In most cases, engineers develop a configuration that seems close, choosing among alternatives that all violate the objectives by varying degrees, and then build a prototype to verify the design.

With Behavioral Modeling, the technology automatically solves for the optimum design across all objectives. The design objectives in the model's behavioral features — such as equal length, minimum bend radii, and minimum distance between pipes — drive the objective-driven design regeneration process.

Exhaust manifold system design is also an ideal application for table-driven customization. For example, a logic table containing information about environmental regulations that differ by geographic location could be tied to the model to produce a single design that is highly responsive to the customer needs.

Conclusion

Design excellence results in a product that is differentiable and responsive to customer requirements, that offers better performance and more functions, and that demonstrates reliability. Behavioral Modeling incorporates smart models, objective-driven design, and an open, extensible architecture, allowing engineers to achieve these key qualities in their product designs.

Smart models contain intelligent features that accommodate information about geometry, process, applications, and desired behaviors. Moreover, organizations can use these feature capabilities to incorporate performance insight and feedback into the design process on a continual basis. As a result, engineers have more time to explore new ideas, resulting in products that are differentiable and responsive to customer requirements.

Objective-driven design capabilities regenerate model geometry to meet engineering specifications. Thus, engineers can focus on solving other critical design problems. In addition, they support design optimization across one or multiple variables to produce models that automatically meet rather than haphazardly approach design objectives. As a result, objective-driven design delivers more high-performance and functional products.

Behavioral Modeling offers an open extensible environment that facilitates interface with analysis, manufacturing, and other applications in the engineering process increasing product reliability. In some cases, external applications can be re-implemented within the design model. In other cases, the Behavioral Modeling application can automatically exchange design information with external applications at the feature level, and incorporate the results within the design model.

Design excellence is crucial to today's manufacturers across all industries. PTC's Behavioral Modeling offers organizations the technology they need to achieve this excellence.