PTC®

Best practices in product development: Design Studies & Trade-Off Analyses

This white paper examines the use of Design Studies & Trade-Off Analyses as a best practice in optimizing design decisions early in the product development lifecycle.

From this paper you will gain a better understanding of the benefits that Design Studies & Trade-Off Analyses offer in meeting specific Electrical, Mechanical and Civil Engineering challenges. A different scenario is presented for each of these engineering disciplines, in which the capabilities provided by PTC® Mathcad® streamline the performance of Design Studies & Trade-Off Analyses.

By following this best practice, Engineering can make faster design choices, with the confidence knowing they have evaluated all the best options. Making better design selections early in the product development lifecycle:

- Shortens time-to-market, with less risk;
- Enhances engineering creativity through exploration of more product designs, faster;
- Achieves desired real-world performance through optimized product designs;
- And ultimately lowers product, warranty and development costs.

Design studies & trade-off analyses: A best practice in improving early design decisions

Design Studies & Trade-Off Analyses is a best practice that improves early design decisions that, in turn, help reduce costs later in the product development process. Engineers establish performance envelopes and trade-off curves using mathematical models to quickly identify the design solution that most efficiently meets product requirements. A well-documented study or analysis should make it clear why the proposed design offers the best tradeoff between performance and cost–and give reviewers a high degree of confidence that a better solution has not been overlooked.

However, there are daunting challenges to achieving the full benefits of following this best practice.

Many new products are, in fact, variants of existing designs, but because the original analysis tied to these products is neither captured nor organized for others to find, there frequently is significant re-work. This leads to longer development lead times, ties up valuable resources, and limits the number of conceptual designs that can be effectively evaluated. This process is especially time-consuming for new staff or new team members without any legacy information to draw upon.

When an analysis is not documented and tied to the particular design, engineers in the modeling group, for example, have to make assumptions about why certain design decisions were made. If this analysis was better annotated with the assumptions, engineers could move more quickly and confidently to the solution phase. Better design annotation and organization allows more efficient communication with management for early approval and the sharing of work across multiple disciplines or the global enterprise.

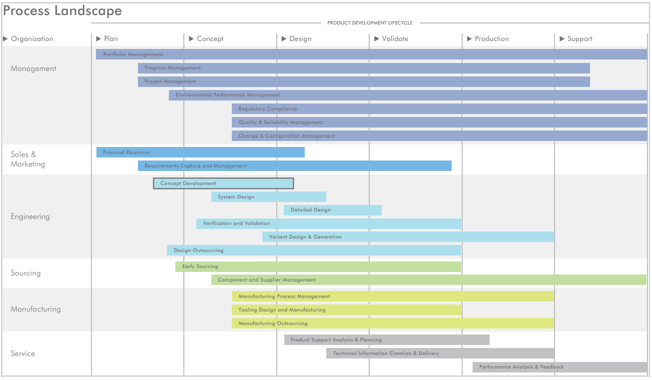

Figure A: PTC Mathcad provides best practices across the Engineering stages of the Product Development Chart.

To overcome these challenges and fully realize the benefits of conducting Design Studies & Trade-Off Analyses, engineers need key capabilities that allow them to:

- Quickly generate design studies crossing multiple functional areas–and analyze and document them;
- Be comprehensive in considering all design requirements, to produce optimal design choices;
- Efficiently and confidently assess different models' sensitivity to understand and quantify the effects of change on design objectives (iterating quickly through alternatives);
- Integrate results with external applications and clearly communicate them up and down the organization as well as across distinct groups.

Design studies and trade-off analyses across engineering disciplines

Electrical, Mechanical and Civil Engineering all benefit from using Design Studies & Trade-Off Analyses. However, each discipline faces some unique challenges, as illustrated in the three scenarios presented below.

In our first scenario, an electrical engineer is charged with redesigning a poorly performing circuit in a video game controller and meeting specific requirements for improved reliability, lower power consumption, and greater interoperability with existing devices. Next, a mechanical engineering team tries to determine which material optimally meets the maximum gripping force of a robotic arm component while remaining within design parameters such as thickness and weight as well as within cost constraints. Finally, an experienced civil engineering firm is tasked with presenting the cost/benefit trade-offs for three different types of bridge designs, while looking ahead to safety regulations from the Department of Transportation.

In each scenario, the capabilities required to quickly select a best concept design are provided. Also supported are the unique requirements of Electrical, Mechanical and Civil Engineering, while allowing each team to:

- Easily and intuitively create mathematical model design options;
- Use this model to efficiently iterate on design options;
- Clearly share and review design options with management and global team members.

Scenario 1: Circuitry redesign for improved gaming performance

A manufacturing company tasks an engineer with redesigning a client's video game controller circuitry. The new design must meet specific requirements for improved reliability, lower power consumption and greater interoperability with existing devices. Cost constraints suggest the use of cheaper, off-the-shelf components wherever possible.

Using this tool, the engineer quickly creates design component models in worksheets. One component model focuses on the trade-off analysis of impedance given different off-the-shelf resistors and capacitors. The intuitive whiteboard interface and built-in equation editor lets the engineer express component solutions and constraints in familiar, natural math notation (Figure B). She can zero-in on the design experiments and analysis itself, rather than laboring to "program in" hard-to-read formulas.

In fact, she has access to over 600 math functions and standard electrical equation libraries, enabling her to create component models quickly and easily before committing them to a design.

Frequency	$f := 3000\ Hz$
Resistance	$R := 8\ \Omega$
Capacitance	$C := 6.63\ \mu F$
Inductance	$L := 0.424\ mH$
Angular frequency	$\omega := 2\ \pi \cdot f$
Reactance XL	$X_L := \omega \cdot L = 7.992\ \Omega$
Reactance XC	$X_C := \dfrac{1}{\omega \cdot C} = 8.002\ \Omega$
LF Impedance	$Z_{LF} := R + 1i \cdot X_L = (8 + 7.992i)\ \Omega$
HF Impedance	$Z_{HF} := R - 1i \cdot X_C = (8 - 8.002i)\ \Omega$
Total Impedance	$Z_T := \dfrac{Z_{LF} \cdot Z_{HF}}{Z_{LF} + Z_{HF}} = (7.997 - 1.8i \cdot 10^{-6})\ \Omega$

Figure B: PTC Mathcad worksheet showing total impedance calculations for first order RLC circuit.

To evaluate the impact of any component change, the engineer can easily "swap out" the Resistance, for instance, value from "8" to "30". These component values are likely already available from a library of off-the-shelf components. Because the product's natural math notation is "live," changing in real time, the change in low-frequency, high-frequency, and total-impedance values is reflected immediately throughout the model. As the engineer works, dynamic units-checking reduces errors and increases the accuracy of results. Natural math notation, unit checking accuracy, and live equations allow for more precise communication between engineers, which improves process efficiency and reduces the likelihood of costly errors.

The software automatically calls upon previously defined impedance calculations and a table of frequencies to generate a first-order crossover impedance trade-off plot (Figure D). Any change made on the whiteboard or in the supporting tables dynamically updates the plot display. Just as with changing the resistance component above, if the capacitance is revised, the plotlines for higher frequency impedance and total impedance will update automatically. This enables the engineer to quickly evaluate, and easily communicate, component choices.

Anyone, anywhere, viewing the results of this trade-off analysis can clearly understand the formulas, with the entire set of assumptions and calculations clearly presented–whether it's for a review of the design study with management, for auditing by a regulatory agency, or for communicating with team members across the globe.

$$
\begin{aligned}
ImpedanceVals := \ & a \leftarrow 0 \\
& \text{for } i \in 0 \,..\, 12 \\
& \quad \omega_i \leftarrow 2\ \pi \cdot freq_i \\
& \quad X_{L_i} \leftarrow \omega_i \cdot L \\
& \quad X_{C_i} \leftarrow \frac{1}{\omega_i \cdot C} \\
& \quad Z_{LF_i} \leftarrow \left| R + 1i \cdot X_{L_i} \right| \\
& \quad Z_{HF_i} \leftarrow \left| R - 1i \cdot X_{C_i} \right| \\
& \quad Z_{T_i} \leftarrow \left| \frac{Z_{LF_i} \cdot Z_{HF_i}}{Z_{LF_i} + Z_{HF_i}} \right| \\
& \text{return } \left[Z_{LF}\ Z_{HF}\ Z_T \right]
\end{aligned}
$$

$$Z_{Low} := ImpedanceVals_{0,0}$$

$$Z_{High} := ImpedanceVals_{0,1}$$

$$Z_{Total} := ImpedanceVals_{0,2}$$

Figure C: PTC Mathcad loops through impedances.

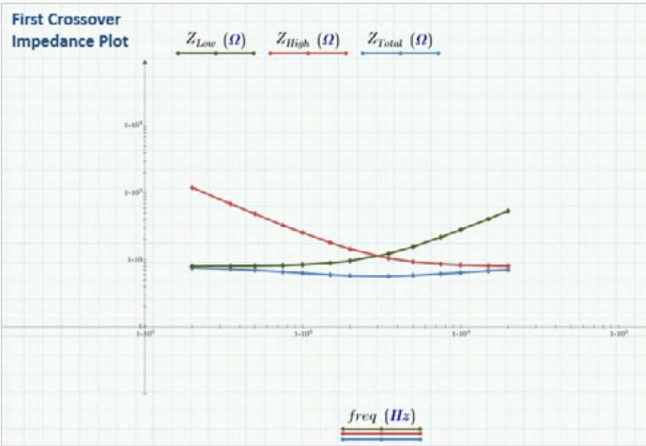

Figure D: PTC Mathcad plot showing first order crossover impedance trade-offs.

Scenario 2: Evaluating yield strength in candidate materials for robotic armature

The Engineering team at an industrial equipment manufacturer is asked to evaluate the yield strength and cost trade-offs for robotic 'fingers' materials under different gripping forces. The materials evaluated include steels like ASTM A36, ASTM 514, stainless steel ANSI 302, and high-density polyethylene (HDPE). The material has to maintain yield and tensile strength requirements to safely meet the maximum gripping force, as well as fit within existing design parameters such as thickness and weight, as well as cost constraints.

Using the intuitive whiteboard interface, engineers quickly formulate a series of visual trade-off equations and plots to calculate the area moment of inertia for bending about the x-axis of the armature model. The built-in equation editor lets the team express component solutions in familiar, natural math notation, with automatic unit checking for accuracy. The team can focus on the design experiments and analysis itself, rather than laboring to "program in" formulas that are hard to read and difficult to communicate.

Evaluating maximum stress as a function of material thickness is given a jumpstart with an open architecture. Collected in an earlier project, the yield strength, ultimate strength, and density values for the materials under evaluation were imported from an Excel® spreadsheet to a library of proprietary worksheets.

The Engineering team can now easily incorporate this information into the worksheet armature model they are using to conduct their trade-off analysis (Figure E).

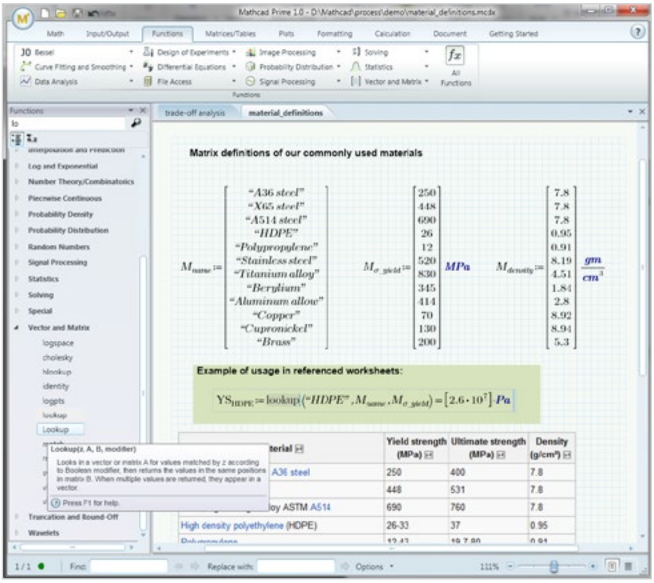

Figure E: PTC Mathcad table showing yield strength, ultimate strength and density of different materials.

The team minimizes the thickness for each material within a safety factor of yield strength, then PTC Mathcad generates a graph that visually displays the trade-off between using HDPE and ASTM A36 steel (Figure F).

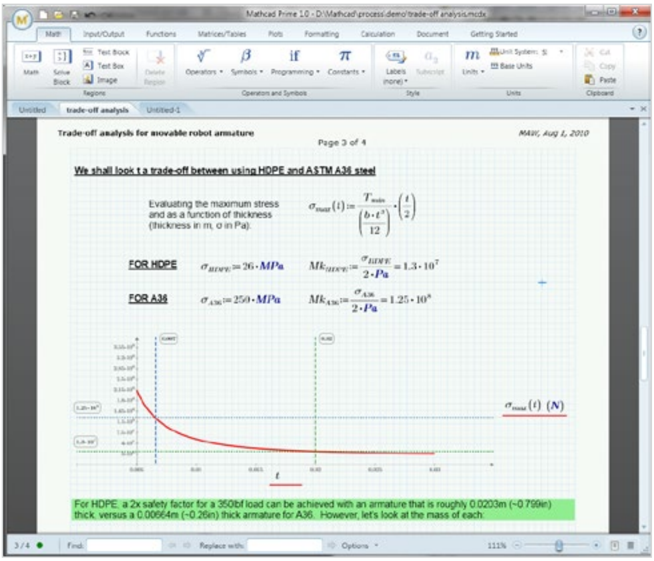

Figure F: Graph showing tradeoff analysis between HDPE and ASTM A36 steel.

The team concludes that, considering all the constraints and stated goals, the optimal material is HDPE. There is ample room in the design envelope to accommodate the thicker armature, which also meets the tensile and yield strength requirements. The resulting mass is 37.5% of the equivalent A36 steel structure, and the cost of HDPE is less than the steel. The process of analysis arriving at the choice of HDPE is automatically documented, step-by-step, in the worksheet, and now can be easily reviewed or reused by subsequent teams on different projects.

The team could also choose to import armature dimensions and gripping geometry directly from a CAD model (such as PTC Creo® Elements/Pro® application) into worksheets, along with a "snapshot" of the CAD model (Figure G). Any changes to the model can dynamically modify the CAD model.

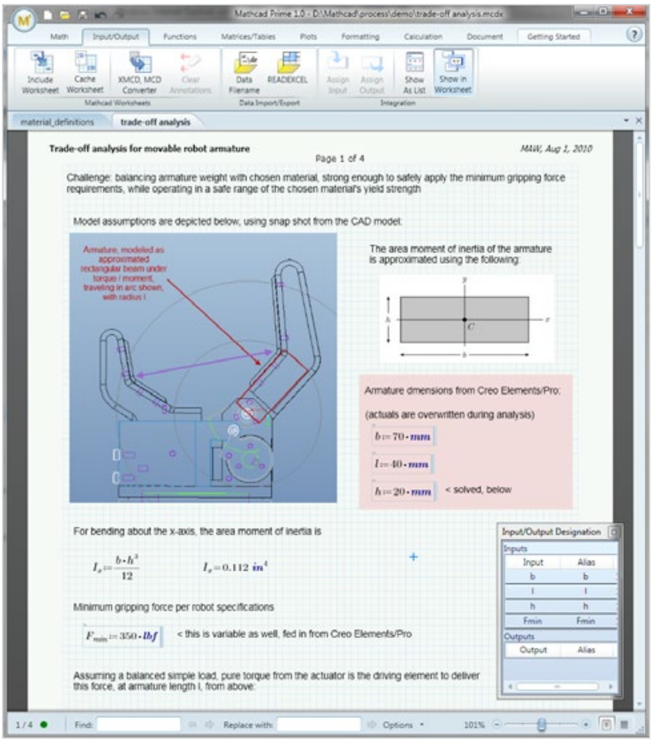

Figure G: Snapshot of CAD model for moveable robot armature.

Scenario 3: Comparing cost/benefit trade-offs in bridge design

An engineering firm with decades of bridge building experience has been asked to determine which of three designs offers the best cost/benefit ratio: cantilevered, suspension, or floating.

There is a large number of variables involved in this design study, including volume of traffic, spans of varying lengths, cost of maintenance, etc. Experience has shown that engineers charged with the project need to show due diligence in anticipating safety requirements for Department of Transportation approval.

Fortunately, engineers do not have to undertake bridge Design Studies & Trade-Off Analyses from scratch. They can access their library of archived worksheets derived from previous projects. In addition to allowing the engineers to find a best design concept more quickly, the software also allows them to run a proposed approach by management for approval or course-correction much earlier in the design process.

The team begins by selecting the previous design study that is most similar to the current challenge. Choosing the most applicable worksheet is made easier by the fact that calculations are expressed in live, natural math notation. Fundamental assumptions made in the earlier study are also documented on the same worksheet, along with graphs and other visual parameter representations.

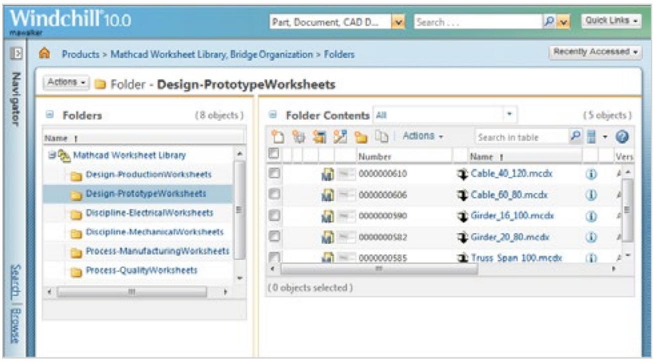

Figure H: Directory of archived PTC Mathcad worksheets used in design studies & trade-off analyses.

The intuitive whiteboard interface and built-in equation editor allows the team to quickly modify the worksheet to fit the current project. Leveraging access to more than 600 math functions and standard equation libraries, the team can quickly iterate on detailed component options. The results of the modifications to the worksheet update in real time–including any visual display elements. Further, any changes made are validated by the dynamic units checking to reduce errors. Annotations are easily added in place with calculations to document key facts and assumptions–showing how results have been derived under what parameters and logic.

Because the use of PTC Mathcad is "self-documenting," there is no need for the engineers to create a separate report for management that repeats details of the original worksheet and their modifications. Management can be confident that due-diligence has been done.

Summary

When applied as a best practice early in the product development process, Design Studies & Trade-Off Analyses enable engineers to more closely align product decisions with defined requirements. PTC Mathcad provides the key capabilities required to efficiently and confidently realize the full benefits of this best practice.

Phase of design studies & trade-off analyses best practice	PTC Mathcad capabilities supporting design studies & trade-off analyses
Quickly implement a mathematical model of the design	• Intuitive whiteboard, task-based interface improves usability while also enabling users to learn unfamiliar functions or features quickly and easily; • WYSIWYG (What You See Is What You Get) equation editor allows users to express problem constraints and solutions in natural math notation, without needing to know programming; • Toolbox of over 600 ready-to-use functions that enable users to tackle any computational problem; • Full support for units throughout all calculations for reduced errors, higher accuracy of results, and more precise communication between engineers and teams.
Use this model to try several options quickly and efficiently	• Live calculation environment allows quick and easy creation of calculations for testing before committing them to a design; • DoE (Design of Experiments) functions help users understand the variable interactions that influence an experiment when there are multiple variables and levels, and provides templates for a smaller number of more intelligent experiments; • Integration with other products like CAD applications establishes increased productivity, improved process efficiency, and better collaboration between individuals and groups.
Review and evaluate several what-if scenarios with global team and pass to management for approval	• The use of standard notation, integrated text and graphical displays automatically generates readable documents that are easily understood up and down the management chain and across diverse, multicultural teams; • Live calculation makes what-if scenarios across teams easy–supported by text annotation and graphical displays; • Archived shared worksheets facilitate knowledge-capture and reuse between teams, for better control over errors, and promotion of engineering-calculation best practices.

By enabling the best practice of Design Studies & Trade-off Analyses, this software helps Engineering contribute to higher- level corporate goals:

- Shorten time-to-market with less risk;
- Enhance engineering creativity through exploration of more product designs, faster;
- Achieve desired real-world performance through optimized product designs;
- And ultimately lower product, warranty and development costs.

Learn more at PTC.com/products/mathcad.

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