Moving Beyond the Limitations of Spreadsheets

How the Simultaneous Design and Documentation of Calculations Promotes Engineering Excellence

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Executive Summary

For a wide range of global organizations in today's competitive marketplace, faster time-to-market, improved product quality and continuous regulatory compliance remain primary objectives–all while fostering continuous innovation. Engineering-driven organizations–from aerospace to automotive to pharmaceutical companies–also share these objectives, but the stakes are arguably much higher as they strive to successfully manage their business-critical information. The failure to capture and document engineering calculation information poses a tremendous risk, as a single mistake can bring down an entire multi-million dollar project–and even jeopardize lives and property.

With engineering driving the success of so many Global 1000 companies today in an increasingly technical economy, organizations are waking up to the need to standardize and document their business-critical engineering calculations. Standardizing the methods of solving and documenting engineering calculations drives consistency in global product development processes.

Whether computing critical product parameters to gauge the impact of obtaining steel from a new supplier, analyzing test data to verify circuitry for a new semiconductor, or predicting product performance to determine the elasticity of plastics, applied math calculations form the backbone of design engineering projects. Numerous calculations inform virtually every design decision during each step of product development. Calculations are an important part of the product development process and should be captured and shared as intellectual property (IP).

Engineers today perform calculations by hand, on calculators, by writing customized programs, and frequently–by using spreadsheets. For certain, the appeal of the spreadsheet lies in its ubiquity as a productivity application that resides on virtually every PC shipped today. However, ubiquity does not equal reliability or auditability, which can be especially problematic in engineering organizations, where the cost of an error can go far beyond dollars and cents.

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Spotlight on Rolls-Royce

"Talented engineers are using Excel and getting serious errors of which they're simply not aware. And errors build up more rapidly than you might expect."

- Dr. Alan Stevens, Specialist, Mathematical Modelling & Simulation, Rolls-Royce

Dr. Stevens uses Mathcad software from PTC for many of his engineering calculations. Mathcad earned the highest marks among four engineering calculation tools studied by Rolls-Royce's. Math Tools for Engineering special interest group. Panelists cited its ease of use, intuitive interface, and ability to handle complex equations.

With calculations as the heart of engineering information, engineering enterprises are finding that their best interests lie beyond the information or data management that spreadsheets provide, and more within the best practice that treats calculations as key business assets rather than incidental tasks.

This white paper discusses how engineering organizations can consistently achieve engineering excellence by standardizing on a tool that is optimized for engineering, moving beyond the spreadsheet to a solution expressly designed to better create, document, and share calculations. Calculations are valuable to engineering organizations, not only because of the end results, but also because of the assumptions, methods, and values behind these results. By standardizing the way calculations are solved and documented, the engineering-driven organization can make valuable engineering information visible to the rest of the organization and accessible by key people–ultimately securing a strong return on their investments and achieving the engineering excellence they desire.

The Attractions and Limitations of Spreadsheets

Spreadsheets have provided fast, accurate computation since the advent of VisiCalc and Lotus 1-2-3, the seminal application that put PCs on corporate desktops. Spreadsheets became ubiquitous in large part because of their programmability, and the success of Microsoft Office means that a spreadsheet is available on virtually every desktop. However, spreadsheets can prevent the engineering organization from achieving its large-scale business objectives by failing to provide the "big picture" when it comes to business-critical calculations:

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Spreadsheets: The Hard Facts

- The University of Hawaii found 20% to 40% of all spreadsheets contain errors.[1]
- Coopers and Lybrand found 90% of all spreadsheets comprised of more than150 rows contained errors.[2]
- KPMG found 91% of 22 spreadsheets taken from an industry sample contained errors.[3]
- Olson & Nilsen found a 21% cell error rate among experienced spreadsheet users.[4]
- The University of Michigan found an 11.3% cell error rate among inexperienced spreadsheet users.[5]

[1] University of Hawaii studies

[2] Journal of Accountancy, "How to Make Spreadsheets Error-Proof"

[3] KPMG Management Consulting, "Supporting the Decision Maker: A Guide to the Value of Business Modeling"

[4] Human-Computer Interaction, "Analysis of the Cognition Involved in Spreadsheet Interaction"

[5] University of Michigan, "Computerized Financial Planning: Discovering Cognitive Difficulties in Knowledge Building"

Spreadsheets show answers but omit context.
A spreadsheet provides the results of a critical engineering calculation, but the methods, assumptions, values, and logic that spawned these results remain invisible. Instead of seeing calculations laid out in conventional math notation, users see machine-readable text buried in formulas. While spreadsheet cell structure hints at the logic behind the cells, that logic is not explicit. Embedded equations and hidden macros are often difficult to decrypt. And though today's spreadsheet software can trace relationships between cells, retracing the steps is likely to be agonizing.

Spreadsheets are inherently error-prone.
Rick Butler, an auditor who writes and speaks widely on spreadsheets, asserts that controlled experiments show that 40 to 80 percent of spreadsheets contain errors at their inception.[6] In today's global economy, engineering calculations must be free of errors, and demand validation, verification, documentation, and traceability, all of which spreadsheets fail to provide.

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The Trouble with Spreadsheets

Spreadsheet expert Raymond Panko of the University of Hawaii has written "Every study that has attempted to measure errors, without exception, has found them at rates that would be unacceptable in any organization."[7]

Rick Butler, an auditor who writes and speaks widely on spreadsheets, asserts that spreadsheet developers miss more than 80% of their own errors, and outside testers miss over 50% of design logic and 34% of application errors.[8]

In 1987, Davies and Ikin inspected 19 spreadsheets that were then in use and deemed correct by 10 developers in 10 different firms. Four spreadsheets contained serious quantitative errors, and three-quarters of them included quantitative or qualitative errors.

[7] Raymond R. Panko, "What We Know About Spreadsheet Errors," Summer 2000 from the Spreadsheet Research Web site

[8] Rick Butler, "The Subversive Spreadsheet," European Spreadsheet Risks Interest Group.

[6] Rick Butler, "The Subversive Spreadsheet," European Spreadsheet Risks Interest Group Website, www.eusprig.org, November 2002.

Spreadsheets require much testing for "mission-critical" usage. As a personal productivity application (i.e., where a user creates a spreadsheet solely for his or her own purposes), the spreadsheet has proven to be quite useful. However, the process of engineering design is more often than not a collaborative process, requiring many different users of the same application. When this happens, it is crucial that the spreadsheet be tested and validated or verified–the later users may use the spreadsheet application for 'mission-critical' purposes, and may assume that the spreadsheet application is suitable for such use, when in fact, it may not be.

Although spreadsheets have many viable uses in engineering organizations, they are unsuited to the task of modeling, analyzing, and documenting engineering designs. Spreadsheets are general purpose tools and are not designed to handle the language of engineers. Engineers need documents that explain all one needs to know about the design process–including text, interactive math calculations, graphs, and actual drawings and models–in a single, share-able document. The other necessary piece is a system for viewing, searching, reporting, and publishing these documents–and their components as well.

Finding a Single Solution for Achieving the Objectives of the Engineer and the Engineering Organization

Throughout the computerized revolution in engineering, one of the primary challenges for engineering enterprises has been the struggle to support both the everyday computational needs of engineers, as well as the long-term business or engineering process objectives of the organization. The calculation methods that are available for simply solving calculations are not always the best tools for capturing IP, sharing best practices, supporting standards compliance, or optimizing process productivity.

From a fundamental, task-based perspective, engineers should be able to:

- Perform the computational work in the same language that they do the design–using math notation
- Document the actual methods and assumptions and capture the processes behind calculation results
- Efficiently perform all phases of their work and reduce errors
- Reuse calculations for future projectsEngineers need documents that explain all one needs to know about the design process–including text, interactive math calculations, graphs, and actual drawings and models–in a single, share-able document. The other necessary piece is a system for viewing, searching, reporting, and publishing these documents–and their components as well.

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Spreadsheets: A Risky Proposition

"The greater the criticality of the intended usage, the higher the software integrity required. Spreadsheet packages and spreadsheet applications are not capable of providing the highest levels of software integrity required for safety-critical applications (e.g. where software failures can be damaging to human health)."[9]

[9] R.M. Barker, P.M. Harris, and G.I. Parkin, "Software Support for Metrology Best Practice Guide No. 7: Development and Testing of Spreadsheet Applications," March 2004.

For the engineering organization, top-of-mind business objectives include:

- Improving innovation and product quality
- Maximizing productivity
- Preserving and reusing the organization's intellectual property
- Promoting regulatory compliance by tracking, verifying, validating, and reporting activities with key business partners and agencies
- Leveraging existing IT assets

Spreadsheets give organizations the ability to manage large datasets, present tabular data, and perform basic math operations–but what is the ideal solution for creating and documenting engineering calculations as a valuable corporate asset?

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Spotlight on Bechtel

"Since the late 1990s, Bechtel has created engineering calculation templates (using Mathcad) and posted them on its Intranet for use by 70 engineers. We stopped using spreadsheets and macros because of checking issues," says Khaldoon Sakkal, the automation coordinator for civil, structural, and architectural engineering for Bechtel's petroleum and chemicals group. "With 40 calculations centralized for use, all engineers need to do is download the one they need, whether it be for wind loads or anchor bolt analysis, and fill in the variables. While the technology doesn't eliminate mistakes (an engineer can input the wrong data), mistakes won't be in the calculation itself."[9] Hence, says Sakkal, finding errors and fixing them is a relatively straightforward process of going over just the inputs.

[10] CIO Magazine, July 2003

Mathcad® – Enabling the Simultaneous Design and Documentation of Engineering Work

With a spreadsheet or programming language, the logic behind engineering decisions is invisible (Figure 1a). As a result, work cannot be quickly and properly verified. A calculation error will likely only show up downstream in the project, when the costs of rework are multiplied exponentially. Worse, the error may make it into the final product.

A Mathcad worksheet, by contrast, enables engineers to document the design calculation process effectively. Unlike spreadsheets, Mathcad engineering calculation software employs standard mathematical notation and captures the assumptions, methods, and critical data behind every calculation (Figure 1b). Mathcad, PTC's engineering calculation software, offers a 100-percent "whiteboard design" environment that allows engineers to easily capture, apply, and manage their product requirements, critical data, methods, and assumptions for rapid calculations. With Mathcad, the original concepts, underlying assumptions, mathematical formulas, illustrative graphs, explanatory text, annotations, sketches, and results are all plainly visible in the worksheet. Knowledge is captured in a shareable form and clearly documented.

Because the Mathcad interface is 'live', a single keystroke returns a result. Changing a variable instantly recalculates the answer or redraws any 2D or 3D graphs–eliminating any manual recalculation work. The calculations and results are documented in reusable worksheets, which can be saved in several formats, including Word, PDF, HTML, and XML. These flexible formats enable engineers to share the fully documented design, including the concept and implementation–not just the code. The XML format makes it easy to share worksheets, methods, or values with other users and systems, including document management applications, computer-aided design (CAD) programs, and product data management (PDM) solutions.

> "Unlike spreadsheets, Mathcad engineering calculation software employs standard mathematical notation and captures the assumptions, methods and critical data behind every calculation."

```
((pi*D1*h)/2)*(SQRT(1+((D1^2)/(4*h^2))+((pi*D1^2)/4)))
```

Figure 1a. A sample equation in Excel in which the logic is invisible because of the linear expression buried in the cell.

$$\frac{\pi \cdot D \cdot h}{2} \cdot \sqrt{1 + \frac{D^2}{4h^2} + \frac{\pi D^2}{4}}$$

Figure 1b. The same equation as in Figure 1a, this time represented in Mathcad using standard math notation.

Mathcad vs. Spreadsheets–Standardizing on the Right Tool for Engineers

How do you know whether a particular project will benefit more from the features and capabilities of a spreadsheet or Mathcad? While the needs, parameters, and objectives of every engineering design project differ, the following questions prove useful when deciding which tool is truly the "right tool for the job."

What types of calculations and equations are you looking to perform?

Historically, users have employed spreadsheet applications such as Microsoft Excel to handle large data tables and simple calculations and equations. However, the more complex or advanced a calculation, the more convoluted its representation becomes in Excel, often resulting in a counter-intuitive jumble of numerals, letters, and parentheses.

With Mathcad, there is no difficult syntax to learn; you simply type in your equations, then the results are displayed. Mathcad employs real mathematical notation and captures the assumptions, methods, and critical data behind every calculation–whether simple or complex. If you require more mathematical horsepower and greater flexibility than simple numeric calculations can provide, Mathcad enables you to perform symbolic calculations or other types of higher-level computations. In addition, Mathcad QuickSheets offer ready-made Mathcad templates that you can customize to perform a wide range of mathematical tasks, from solving equations to graphing and calculus.

Will you need to derive a model equation or solution?

For engineers and their organizations, the need to derive equations to model or describe a specific process or behavior is quintessential. Mathcad is ideal for creating model equations expressed in natural math notation, and enabling users to switch out different variables with ease.

"If you require more mathematical horsepower and greater flexibility than what simple numeric calculations can provide, Mathcad enables you to perform symbolic calculations or other types of higher-level computations."

Do you need to document the model in a report?

Readability is essential when documenting findings in a report. While spreadsheets such as Excel provide the ability to input text, the cell and tabular format is far from ideal for lengthy or detailed descriptions. In contrast, Mathcad enables users to combine equations, text, and graphics in a single worksheet. In addition, Mathcad's XML architecture allows users to save worksheets in XML format, reuse the information in other text-based systems, or search and report on worksheets without needing to reopen them in Mathcad.

Is unit conversion essential to the task?

While spreadsheets such as Excel allow you to convert measurements, the process involves inputting complex formulas to perform a simple conversion. Mathcad provides built-in unit conversion and unit intelligence, allowing users to mix and convert between unit systems with ease. Mathcad also catches unit mistakes by checking worksheets for dimensional consistency.

Do your calculations drive the design dimensions and parameters in CAD models?

Results from spreadsheet calculations can be used as inputs to CAD model dimensions, but they do not document the complete reasoning behind the CAD model design. Mathcad can be used early in the design process to determine the appropriate physical design dimensions and parameters used in CAD models and provide more comprehensive documentation of the key assumptions and calculation methods.

Engineers can now leverage a direct integration with Pro/ENGINEER® to directly drive the geometry of the design. The Mathcad-Pro/ENGINEER integration is a bi-directional link between the two applications. Users can easily associate any Mathcad file with a Pro/ENGINEER part or assembly. Critical values calculated in Mathcad can be mapped to parameters and dimensions in the CAD model to drive the geometric design. Parameters from a Pro/ENGINEER model can also be input into Mathcad for downstream engineering design calculations. The integration offers dynamic updates to calculations and the CAD drawing when parameters are changed.

Do you need to reduce the number of design iterations performed between CAD modeling and analysis phases of the design?

By using Mathcad to predict the performance of designs before modeling the physical geometry, engineers can optimize designs early in the process, predict functional performance, and thus decrease the number of design iterations required. "Predictive engineering" is a product development process capability enabled by using Mathcad early in the product design and development process. Mathcad can be used to apply scientific and mathematical principles to engineering design problems at the beginning of the design process in order to determine the critical dimensions and parameters used downstream in the CAD model. By calculating the parameters required and "predicting" the performance of the design up front, instead of guessing key dimensions and parameters, product designers can produce an optimized design more rapidly and with less iteration than by applying the traditional methods used today.

Will your calculations be shared and reused by others in your organization, by geographically dispersed teams, contractors, supply chain partners, or others for different projects?

As mentioned earlier in this white paper, many spreadsheet solutions are designed by a single developer for his or her own use. Although the spreadsheet thrives as a personal productivity application, this presents a problem when other users throughout the organization want to reuse the solution, and assume that it fits their requirements, when in fact it does not. The XML architecture of Mathcad delivers an open engineering data model enabling publishing, collaboration, integration, and search capabilities, especially when deployed as an organizational standard.

"Mathcad provides built-in unit conversion and unit intelligence, allowing users to mix and convert between unit systems with ease."

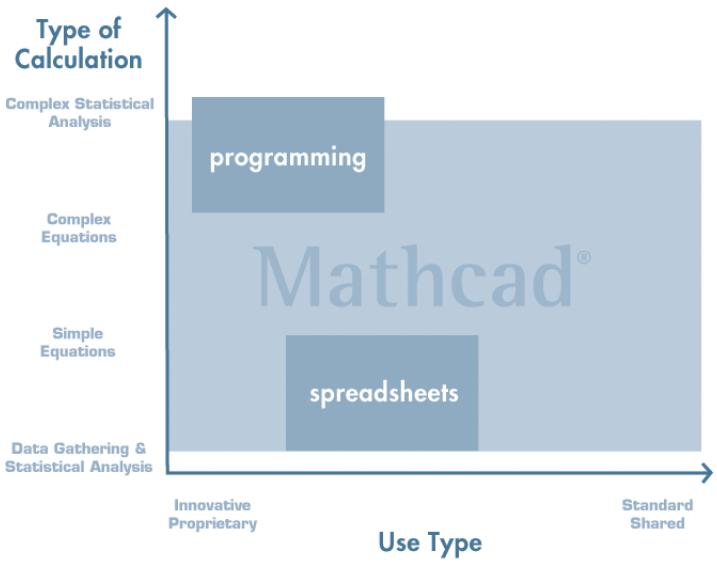

Figure 2. Various engineering projects require different tools, depending on the type of calculations involved as well as the use type.

Will your calculations need to be audited or debugged?

In today's business environment, regulatory compliance is a top priority. Moreover, an organization's ability to track and trace its calculations for debugging and troubleshooting is essential to maintaining consistently high product quality. Spreadsheets lack the controls and documentation capabilities needed for proper traceability. The use of macros and multiple spreadsheets that are linked together allows users to build very complicated–and sometimes convoluted–models and other business functions with minimal or no documentation.

Mathcad simplifies and streamlines documentation that's critical to communicating and to meeting business and quality assurance standards (Figure 3). All engineering information is in one place with appropriate annotations. Calculations, methods, and values can be shared as the company sees fit with a wide variety of parties outside the engineering division.

Spreadsheet

	A	B	C	D
64	beta	0.25		
65	beta^4	3.91E-03		
66	E	1.002		
67	Re term	1.70E-03		
68	L1 & L2 terms	-1.10E-04		
69	C Stolz equation	0.599		
70	omega/delta p	0.928		
71	delta p/p1 < 0.25	1.72E-01		
72	epsilon	9.50E-01		
73	area orifice m2	1.23E-04		
74	delta p Pa	21000		

Mathcad

$$\beta := \frac{d}{D} \qquad E := \frac{1}{\sqrt{1-\beta^4}}$$

Stolz equation for the discharge coefficient C

$$C := 0.5959 + .0312\cdot\beta^{2.1} - 0.1840\cdot\beta^{8} + 0.0029\cdot\beta^{2.5}\cdot\left(\frac{10^6}{Re_D}\right)^{0.75} + 0.0900\cdot L_1\cdot\left(\frac{\beta^4}{1-\beta^4}\right) - 0.0337\cdot L_2\cdot\beta^3$$

$$C = 0.599$$

Figure 3. In this example, the Stolz equation is hidden within the spreadsheet cell, making it difficult to document the methods, assumptions, and data behind the equation. With Mathcad, the mathematical formulas and explanatory text are plainly visible and auditable.

PricewaterhouseCoopers, "The Use of Spreadsheets: Considerations for Section 404 of the Sarbanes-Oxley Act," 2004.

"The XML architecture of Mathcad delivers an open engineering data model, enabling publishing, collaboration, integration, and search capabilities, especially when deployed as an organizational standard."

Transitioning from Spreadsheets to Mathcad–Integration and Migration Options

For those organizations that have already invested heavily in a spreadsheet solution to document their engineering calculation information, Mathcad easily integrates with a variety of data sources and third-party products, including Excel. Users can imbed Excel data into Mathcad, or enable information exchange through dynamic linking, exporting, or even a simple cut-and-paste. Available with Mathcad out-of-the-box, the Excel Component, through "in-place activation," allows users to run Excel within Mathcad, inserting existing Excel worksheets or creating new ones (Figure 4).

In addition to using the built-in Excel component, organizations can leverage the expertise provided in a services engagement. Consultants can quickly convert Excel spreadsheets into Mathcad worksheets, enabling organizations to retain and use their valuable library of product calculations and formulae. This service helps reduce data migration errors, and enables engineering calculations to be preserved as a corporate asset or intellectual capital.

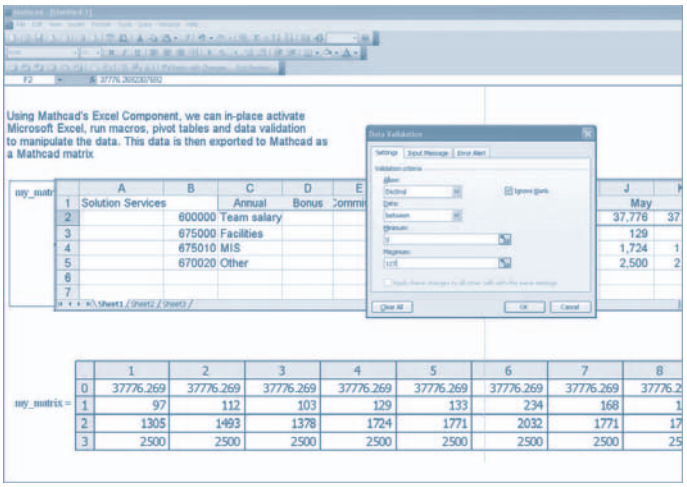

Figure 4. Through in-place activation, the Mathcad Excel Component enables users to manipulate Excel data within Mathcad.

PTC Mathcad – Answering the Needs of the Engineering Enterprise

To leverage and share the power of Mathcad across the enterprise, organizations can choose to standardize on Mathcad, building on the value of Mathcad worksheets by sharing them as best practices. Calculations can be retrieved at any time for reuse, validation, refinement, reporting, and publishing, along with effective audit tracing (provenance) of every calculation. Mathcad incorporates elements of knowledge management to create, and capture an organization's most valuable engineering information. The powerful knowledge capture capabilities of the Mathcad Product Family can help engineering organizations achieve their business objectives with accuracy and efficiency:

Mathcad enables collaboration and fosters on-time product development and maximum productivity by letting organizations reuse proven, verified engineering information with confidence. Engineers save time both in the initial design and by avoiding time-consuming error correction down the line. And compared to complicated number-crunching software or programming tools, less time is spent in training.

Mathcad improves product quality by documenting and enforcing best practices, thus setting a solid foundation for continuous improvement. Organizations can share fully documented designs as professionally formatted Word files, PDF documents, Web pages, or as Web services . For example, if an engineer needs to calculate the wall thickness of an oil pipeline two miles below the surface on a deep-sea reef, she can retrieve the appropriate worksheet from the organization's online repository of standard calculations, thus making an investment in design a permanent corporate asset.

Mathcad promotes easy reporting to regulatory agencies and clients who are auditing their vendors' quality processes. All engineering information is in one place with appropriate annotations, so that calculations, methods, and values can be shared with a wide variety of parties.

Mathcad has minimal impact on IT departments since it operates on open, standard, highly reliable, and easily integrated technologies such as the Microsoft .NET framework and XML. By using the XML data exchange standard, the suite makes it easy to integrate calculations into automated business processes across teams and among discipline "silos."

> "PTC Mathcad incorporates elements of knowledge management to create, document, and exploit an organization's most valuable engineering calculation information."

Conclusion

While general purpose spreadsheets have found their place in organizations as a way to handle tabular data and basic math operations, they fail to fulfill the more advanced computational needs of engineers as well as the larger business objectives of the engineering organization.

To truly standardize on the right tool for engineering calculations, organizations must fully examine their needs within the context of both the engineer and the engineering organization. Mathcad moves beyond the capabilities of the spreadsheet, providing a solution that is expressly designed to better solve and document calculations. Mathcad not only speaks in the language of the engineers–using standard math notation–but also captures the assumptions, methods, and critical data behind every calculation. Furthermore, organizations can leverage Mathcad's calculation capabilities within a larger, more comprehensive enterprise product development process. The engineering organization can harness the full power of their calculations–enjoying faster time-to-market, higher product quality, painless regulatory compliance, and easy integration with enterprise applications.