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Moving beyond the Limitations of Spreadsheets

How the Simultaneous Design and Documentation of Calculations Promote Engineering Excellence

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Contents

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 manage 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 put their business-critical calculations under management. 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 diapers, applied math calculations form the backbone of design engineering projects. Numerous calculations inform virtually every design decision during each step of product development.

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.

The failure to manage 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.

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 Mathsoft for many of his engineering calculations. Mathcad earned the highest marks of 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.

Calculations are valuable to technical enterprises, not only because of the end results, but also because of the assumptions, methods and values behind these results.

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 idea of *calculation management*, a 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 choosing "the right tool for the job"—moving beyond the spreadsheet to a *solution expressly designed to better create and manage calculations.* Calculations are valuable to technical enterprises, not only because of the end results, but also because of the assumptions, methods and values behind these results. By implementing successful calculation management, the engineering-driven organization can make valuable engineering information visible to the rest of the organization and manageable 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

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 with more than 150 rows contained errors.[2]
- KPMG found 91% of 22 spreadsheets in an industry sample contained errors.[3]
- Olson & Nilsen found a 21% cell error rate with experienced spreadsheet users.[4]
- The University of Michigan found a 11.3% cell error rate with 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"*

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:

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.[1] 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.

Rick Butler, an auditor who writes and speaks widely on spreadsheets, asserts that controlled experiments show that 40% to 80% of spreadsheets contain errors at their inception.

The Trouble with Spreadsheets

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

Rick Butler, an auditor who writes and speaks widely on spreadsheets, asserts that controlled experiments show that 40% to 80% of spreadsheets contain errors at their inception. Spreadsheet developers miss more than 80% of their own errors, and outside testers miss over 50% of design logic and 34% of application errors.

In 1987, Davies and Ikin inspected 19 spreadsheets that were in use and deemed correct from 10 developers in 10 different firms. Four contained serious quantitative errors, and three-quarters of them included quantitative or qualitative errors. One error involved a $7 million funds transfer between divisions. In another case, inconsistent currency conversion numbers showed up in different parts of the spreadsheet.

Sources: Raymond R. Panko, "What We Know About Spreadsheet Errors," Summer 2000 from the Spreadsheet Research Web site; Rick Butler, "The Subversive Spreadsheet," European Spreadsheet Risks Interest Group.

[1]Rick Butler, "The Subversive Spreadsheet," European Spreadsheet Risks Interest Group Web site www.eusprig.org, November 2002.

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, sharable document.

Spreadsheets require much testing for "mission-critical" usage.

As a personal productivity application (i.e. one 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 to use 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"[2]—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.

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, sharable 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 objectives of the organization.

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

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)."

Source: "Software Support for Metrology Best Practice Guide No. 7: Development and Testing of Spreadsheet Applicaitons

[2]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.

- 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 projects

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

- Improving innovation and product quality
- Maximizing productivity
- Preserving 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 managing engineering calculations as a valuable corporate asset?

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 managing engineering calculations as a valuable corporate asset?

Spotlight on Bechtel

"One company that has signed on to the notion of calculation management is Bechtel, the Houston-based engineering company. Since the late 1990s, the company 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.' Hence, says Sakkal, finding errors and fixing them is a relatively straightforward process of going over just the inputs."

Source: CIO Magazine, July 2003

Unlike spreadsheets, Mathcad calculation software employs real mathematical notation and captures the assumptions, methods and critical data behind every calculation.

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.

```
=U15+1/(1-C$8)*((1+C$8)*H15*1000/(2*(AF15+AG15)*CA15)-
C$8*J15*1000/(AG15*BZ15))
```

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

A Mathcad worksheet, by contrast, enables engineers to document the design calculation process effectively. Unlike spreadsheets, Mathcad calculation software employs real mathematical notation and captures the assumptions, methods and critical data behind every calculation (Figure 1b). The foundation of the Calculation Management Suite™, Mathcad offers a 100-percent "white-board" 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.

$$U_{16} := U_{15} + \frac{1}{\left(1 - C_8\right)} \cdot \left[\frac{\left(1 + C_8\right) \cdot H_{15} \cdot 1000}{2 \cdot \left(AF_{15} + AG_{15}\right) \cdot CA_{15} - \frac{C_8 J_{15} \cdot 1000}{AG_{15} \cdot BZ_{15}}} \right]$$

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

Because the Mathcad interface is live, a single keystroke returns a result. Changing a variable instantly recalculates the answer or redraws any 2-D or 3-D 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.

Mathcad vs. Spreadsheets - Finding the Right Tool for the Job

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 counterintuitive 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

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.

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.

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

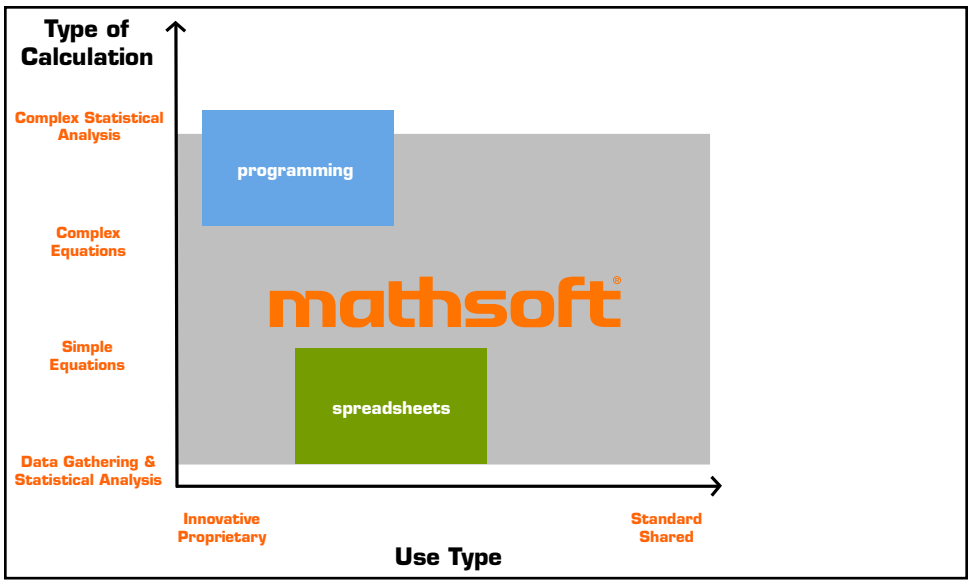


Figure 2. Various engineering projects require different tools, depending on the type of calculations involved as well as the use type.

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.

Will your calculations be reused by others in your organization for different projects?

As mentioned earlier in the 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.

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 maintain consistently high product quality. Spreadsheets lack the controls and documentation capabilities needed for proper traceability. "The use of macros and multiple spreadsheets which are linked together allows users to build very complicated—and sometimes convoluted—models and other business functions with minimal or no documentation."[3] Mathcad simplifies and streamlines documentation, critical to communicating and to meeting business and quality assurance standards (Figure 3). All engineering information is in one place with appropriate annotations, and calculations, methods and values can be shared as the company sees fit with a wide variety of parties outside the engineering division.

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.

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

$$C := 0.5959 + .0312\cdot\beta^{2.1} - 0.1840\cdot\beta^{8} + 0.0029\cdot\beta^{2.5}\cdot\left(\frac{10^6}{Re_D}\right)^{0.75} \ldots$$

$$+0.0900\cdot L_1\cdot\left(\frac{\beta^4}{1-\beta^4}\right) - 0.0337\cdot L_2\cdot\beta^3$$

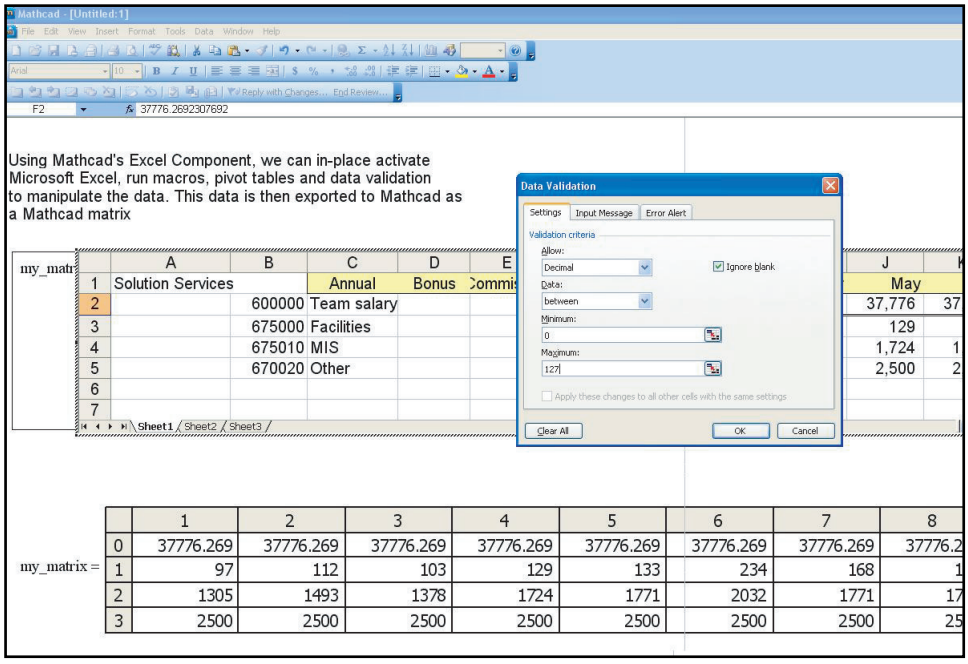
$$C = 0.599$$

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.

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

Transitioning from Spreadsheets to Mathcad - Integration and Migration Options

For those organizations that have already invested heavily in a spreadsheet solution to manage their engineering 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).



	1	2	3	4	5	6	7	8
0	37776.269	37776.269	37776.269	37776.269	37776.269	37776.269	37776.269	37776.2
1	97	112	103	129	133	234	168	1
2	1305	1493	1378	1724	1771	2032	1771	17
3	2500	2500	2500	2500	2500	2500	2500	25

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

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 manages engineering calculations as a corporate asset or intellectual capital.

Calculation Management - Answering the Needs of the Engineering Enterprise

To leverage and share the power of Mathcad across the enterprise, organizations can choose to implement the Calculation Management Suite, building on the value of Mathcad worksheets by organizing, tracking, controlling and sharing them. Calculations can be retrieved at any time for reuse, validation, refinement, reporting and publishing, along with effective audit tracing (provenance) of every calculation. Calculation Management incorporates elements of knowledge management, document management and product data management to create, manage and exploit an organization's most valuable engineering information. With Mathcad as its foundation, the Calculation Management Suite can help engineering organizations achieve their business objectives with accuracy and efficiency:

Calculation Management 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.

Calculation Management improves product quality by documenting and enforcing best practices, 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.

Calculation Management 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.

Calculation Management 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."

Calculation Management incorporates elements of knowledge management, document management and product data management to create, manage and exploit an organization's most valuable engineering information.

Conclusion

While 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 find the "right tool for the job," engineering enterprises 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 manage calculations. Mathcad not only speaks in the language of the engineers—using real math notation—but also captures the assumptions, methods and critical data behind every calculation. Furthermore, by using Mathcad as a part of the Calculation Management Suite, organizations can leverage Mathcad's calculation capabilities within a larger, more comprehensive enterprise framework. By implementing calculation management, the engineering organization can harness the full power of their calculations—enjoying on-time product development, higher product quality, painless regulatory compliance and easy integration with enterprise applications.

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