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Calculation Management

Improving Engineering Quality and Productivity by Managing Calculations

Allen Razdow
Chief Technology Officer
Mathsoft Engineering & Education, Inc.

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Math calculations are the backbone of engineering

Calculations are the lifeblood of engineering. They are the basis for design decisions at nearly every stage of the product or project lifecycle. Over the past several decades, the process of making calculations has dramatically improved through the use of specialized software that allows engineers to interact with calculations formatted like an engineering report and automatically manages units. These tools have substantially increased the productivity of the individual engineer. But the resulting worksheets are typically scattered throughout the organization and are often repeated time and time again. They can be inconsistent with each other and difficult or impossible to find when required, such as to verify a design feature. Now, the engineering function is on the verge of another major improvement that promises to substantially improve quality and productivity. New tools are appearing that capture, organize, and manage the myriad of calculations generated throughout an organization. This will make it possible to enforce engineering best practices, make it much easier to verify accuracy, and encourage re-use of calculations.

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Traditional methods of performing calculations

At the foundation of the design of virtually every engineering product or project is a large number of mathematical calculations that underpin the decisions that make up the design. Applied math calculations are the backbone of engineering-computing critical product parameters, analyzing test data, and predicting product performance. When Ben Rich of the legendary Lockheed Skunk Works recalled his early days there as a thermodynamicist, he said, "We were the analytical experts, the elite of the plant, who decreed sizes and shapes and told the draftsmen what to draw."

Calculation Matters: the Tay Bridge Collapse

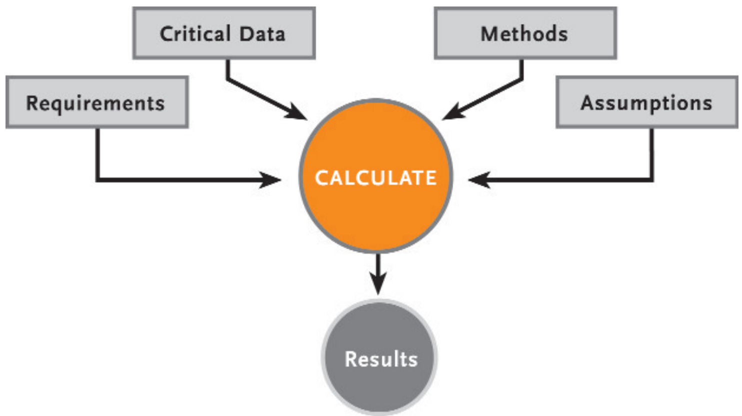
The collapse of the Tay Bridge in a howling gale on December 28, 1879, less than two years after it was completed, is one of the most famous bridge collapses. Its designer, Thomas Bouch, was knighted when it was completed, but the glory was fleeting. A Court of Inquiry held him responsible for the collapse by using an inadequate wind loading assumption of 10 lbsf/sq ft.

Source: Tom Martin's Tay Bridge disaster page [http://www.tts1.demon.co.uk/tay.html]

The calculation process — advancing over the course of a project — is fundamentally what elevates engineering from trial-and-error and guesswork.

The ABET (Accreditation Board for Engineering & Technology, Inc.) defines design engineering as "the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative), in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective."

Mathematics and analysis follow an iterative decision-making process, in accordance with the schematic below:



Individual calculations are concoctions of raw data, practical know-how, mathematical laws, and scientific principles that answer the mundane but vital questions, such as "How thick will this wall need to be to handle the required load?" The calculation process—advancing over the course of a project—is fundamentally what elevates engineering from trial-and-error and guesswork.

Calculation Matters: the Chaparral 2E

As reported in the Competition Press on October 8, 1966, "The spoiler on the new Chaparral 2E more than lived up to its name in [the] second round of the Can Am series." Twice, on different cars, rods that supported the spoiler broke and ultimately blew out a tire each. The spoiler was brand new and very nifty, allowing the driver to adjust its angle to increase drag for braking or cornering. The car's famous designer, Jim Hall, ascribed the failure to fatigue, and a mistaken assumption in his original design. He calculated the main force acting on the link using a maximum lateral acceleration of 1G.

Source: Engineering Case Studies (ECL 79), Carleton University, Ottawa, Canada. [http://www.civeng.carleton.ca/ECL/reports/ECL79/ecl79d.html]

Imagine a flow-chart of the engineering process for a large project. It would be enormous, with loops and branches among sub-projects. The decision stream would have numerous tributaries, including the flow of calculations. Indeed, it is safe to say that the history of the calculation process—inputs, assumptions, methods and results—is among the most important records of an engineering project. Any unusual successes or failures are likely to be reflected conclusively within it.

A complicated component, for example, might have dozens of dimensions, and each of the decisions represents an engineering decision. How thick should the wall of the boiler be to ensure that it doesn't burst when operating at full capacity? Many of these decisions, especially the most important ones, were determined by an engineer who pulled a formula out of a reference manual or memory and selected a formula that applied to the task at hand. A decade or two ago, engineers would typically use hand calculators to solve these problems. The process of crunching through a complicated formula on a calculator takes a lot of time. Even worse, it's not easy to document the calculations so they often had to be repeated multiple times to be sure they were done correctly. Managing the multiple units involved in most calculations is also time-consuming because it's so easy to make mistakes in this area.

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

Multimillion dollar, even billion dollar, errors are regularly made by simple errors in inputting data into spreadsheets or programs written with proprietary programming languages.

Although spreadsheets were originally designed for financial applications, they have found wide use in performing engineering calculations. The advantage of spreadsheets is that they allow engineers to organize the calculations in cells and provide the ability to format the cells in a way that makes the calculations self-documenting. But spreadsheets only partially solve the engineering calculation problem. Being designed for financial applications, they provide no intuitive method of representing an engineering equation and force engineers to continue to manually address the problem of dealing with units. The result is that, like hand calculations, important calculations done on spreadsheets or using programs written with proprietary programming languages must be checked time and time again. The alternative is facing the risk that errors caused by incorrectly entered formulas or data or links might generate incorrect results that could, in a worst-case scenario, propagate through a design and run the risk of poor performance or failure. Multimillion dollar, even billion dollar, errors are regularly made by simple errors in inputting data into spreadsheets or programs written with proprietary programming languages.

Consider a group of engineers brainstorming the redesign of an axle in a conference room. After the meeting breaks up, Fred and Mary work up calculations on two key components. Mary creates a spreadsheet to forecast the type and number of bearings to be used, while Fred writes a program to calculate stresses on a modified u-joint for off-road use. Mary's spreadsheet and Fred's code are essentially the only enterprise records of that brainstorming session. The whiteboard was erased. Fred's notes were on the legal pad he took to the meeting, and Mary's notes are in a spiral notebook on her desk. As the axle design proceeds, the answers produced by the spreadsheet and the program form the basis for ensuing calculations. Mary's bearings spreadsheet is eventually adapted for calculations of other assemblies. A random audit later uncovers errors in 5 percent of the cells. The company has been overspending on bearings as a result, but at least the over design poses no danger to customers. Meanwhile, the new u-joint has failed repeatedly when driven over logs. A recall may be necessary, and a government investigator wants to know what assumptions were used for flexing of the axle on uneven terrain. Fred's program is still in the project document management system, but Fred himself has trouble reverse-engineering his code. Scenarios like this are unnervingly common in engineering-based organizations, with varying degrees of impact.

Proliferation of specialized software for engineering calculations

These difficulties with spreadsheets help explain the popularity of software specially designed for the task of facilitating engineering calculations that was first introduced about two decades ago. As exemplified by Mathcad®, this software formats engineering calculations in exactly the same way that they appear in a reference handbook or engineering report. The key difference is that the formulas are interactive. An engineer can change the formula or data value and the calculation will automatically be updated in the same way as a spreadsheet. A very important feature is that the software intelligently keeps track of units. Engineers can enter data in whatever units it is available in and the software will make the appropriate conversion. A key advantage is that this approach makes engineering calculations self-documenting. The formulas and the data are self-contained so there's no possibility of errors in, for example, typing the formula into a calculator. As opposed to a spreadsheet or other tools, formulas are maintained in a format understood by every engineer that makes them easy to check or share with others. Normally, for example, in an engineering report you have to have faith that the calculations and graphs correspond to the formulas in the document. With engineering calculation software, the doubt goes away because the document itself produced the results.

As a result of these advantages, engineering calculation software has proliferated through most important engineering organizations. 1.7 million engineers in more than 50 countries are using Mathcad software, by far the leading product in this category. Mathcad is used by 90 percent of the Fortune 1000 companies, more than 500 government agencies and more than 2,000 colleges and universities. Customers include: 3M, Alliant Defense Electronics Systems, BAE Systems, Bechtel Corp., Boeing, Caterpillar, Delphi Delco, Dupont, Excalibur Systems, Exxon, Fujitsu, General Dynamics, General Electric Aircraft, Hershey Foods Corp., Honeywell, IBM, Lockheed Martin (LMCO), Los Alamos National Lab, Moog Inc., Northrop Grumman Corp., Ohio State University, Raytheon, Rolls Royce, Siemens Westinghouse, Universal Studios, USDA Forest Service. These companies have discovered that software can substantially improve the productivity of the individual engineers by providing an intuitive, interactive, self-documenting method of performing engineering calculations.

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The challenge of managing these calculations

As a result of the wide use of this software, many engineers are obtaining the increased productivity and accuracy that comes documenting formulas and performing calculations within a single environment and automating the calculating of units. This presents an enormous opportunity. Up to now, engineers have essentially worked on their own, generating huge numbers of calculations as part of the design process that are very difficult to verify. For example, is every engineer involved in a major road construction project using the same number for the density of concrete 320, or any one of the hundreds of other constants that play a critical role in the project? Are engineers using the same formulas to perform similar engineering calculations and where did those formulas come from?

It can take a considerable amount of time to answer these types of questions during the design phase of a large project. You need to identify the engineers involved in the decisions and ask them to call up their spreadsheets or Mathcad worksheets. But what if the questions come up after the project has been completed and the people involved have headed off to other projects or even left the company? Chances are that it will be difficult or impossible to understand their decision-making process. For example, during the design review, someone will probably want to check the calculations used to set the thickness of the boiler walls in the example mentioned above. They will have to call the engineer that was involved and ask him to either fax his notebook or Mathcad worksheet. Or imagine the situation where the determination was made in the middle of the project that the concrete being used actually had a different density than what was used in the design calculations. The question then arises, in which areas of the design were the earlier numbers used and what needs to be changed? Potentially, it could become necessary to contact every single engineer involved in the project, assuming they could be located, and ask them to go back through all of their calculations, assuming they still have them, for the older density values. Even after this enormous effort, there would be no way to ascertain that certain parts of the design did not rely upon the old number.

XML-based solution emerges

Very recently, a solution called Calculation Management has begun to address this problem. The basic idea is to provide organizations with a framework to standardize their calculations and methods so that they can be managed and tracked as the valuable intellectual property that they are. The key obstacle that had to be overcome was developing a structure to capture and manage the myriad of engineering worksheets into a single well-organized repository. This has been accomplished with the widespread utilization of XML, a technology that offers simple schemas that elicit meaning from otherwise unstructured data, enabling information to flow easily, coherently throughout the organization and to external partners as well when needed. XML provides the ability to standardize and share calculations and also imparts meaning and traceability to engineering calculations. XML makes it possible to store and trace the calculations as well as their assumptions, constants, reference materials, etc. that back them up.

Mathsoft® developed and published the first comprehensive XML-based schema for engineering, the Mathcad XML Information Architecture. Although XML schemas for math had previously existed, this is the first that accounts for the special nature of applied math and engineering information, including parameters, units and results. It is an open and nonproprietary data model that is readable by human engineers and their software, including Mathcad and other packaged and custom software. Mathcad XML supports Calculation Management by making engineering information traceable throughout the enterprise via a central database or repository.

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New version of engineering calculation software

Calculation Management is enabled by the Mathsoft Calculation Management Suite™. The first product in the suite, Mathcad 12, is a new version of the popular engineering calculation software that supports XML, enabling calculations to be managed and shared in the enterprise repository and making it possible to store and track not only the calculations themselves but also a wide range of information about them. While there's no limit to the type of information that a particular company can choose to track, some of the most common and obvious is who created the worksheet, when was it created, when was it modified and by whom, has it been approved for use within the company or on a particular project, what type of problems does it apply to, and so on.

Importantly, the provenance or source of formulas, constants, and data can be included in worksheets, and worksheets can be established that force engineers to enter the original source of key values. For example, you could establish the history of a formula by stating that it came from page 149 of *Roark's Formulas for Stress and Strain*. Or you could establish the origin of the constant for the density of concrete by stating that it was provided by a key supplier. Use of XML as its native file format rather than a closed binary format means that the information in the calculations can be accessed by other software packages or even read by an engineer with a browser or text editor. It's also important from a regulatory standpoint because some industries are required by regulatory bodies to store engineering information for long periods of time in a format that is readable without access to a particular software program.

Mathcad worksheets can be used to go one step further by customizing them to enforce the use of best practices within the organization.

Mathcad worksheets can be used to go one step further by customizing them to enforce the use of best practices within the organization. The organization can create a set of standard templates that serve as building blocks for calculations and ensure that engineers use consistent and proven methods. Of course, managers can quickly audit the project and ensure that engineers have used approved templates, established provenance for design information, etc.

A tool for managing calculations throughout the organization

Designate™ is the second component of the Calculation Management Suite. It is targeted largely at engineering managers, who don't even need to be Mathcad users to take advantage of its functionality. Designate makes it possible to search Mathcad and other XML documents throughout the organization based on the calculations themselves as well as the metadata incorporated in them. In the example above where the decision was made to use a new figure for the density of concrete, a manager could search the project or the entire organization for every calculation that used the old number to evaluate the impact of making the change. Engineering reviews are dramatically simplified by making it straight-forward for the reviewers to understand what formulas were used, where they came from, and a clear identification of the source of the various parameters of the calculation. All of this information, it's important to note, is contained within the worksheets themselves and no longer depends upon the availability of the person that originally performed the calculation. These same features also make it possible to re-use designs that have been created within the organization. Engineers can copy worksheets or parts of worksheets while maintaining the history of the information contained within them.

Mathsoft is offering Mathcad XML as an open standard that can be used by other engineering software vendors to store auditable engineering information. For example, design information in product lifecycle management (PLM) systems could potentially be linked to the engineering calculations upon which they are based. The inputs to engineering analysis programs could be tied to calculations performed on Mathcad worksheets or other sources and their outputs could serve as provenance for other calculations. Many of the leading engineering software vendors have already expressed interest in this approach. As it takes root, the manageability and traceability that is provided by the new Calculation Management Suite could extend across an organization's entire engineering operations. Potentially, the engineering decision-making process throughout an entire product development program or project could be documented and linked so that managers could investigate any decision simply by pointing and clicking with their mouse.

Application server provides broad access via web

The third element of the new Calculation Management Suite is the Mathcad Application Server, which lets companies create and distribute fully interactive Mathcad documents over the Internet and intranets. Design engineers can easily deploy Mathcad content over the Internet without programming. Users can view and interact with Mathcad documents through their Internet browser, eliminating the need for learning Mathcad or installing it on client systems. The documents can be configured to allow users to enter different parameters using HTML form fields. The server then recalculates the worksheet and updates the web page with the new results. This makes it possible for organizations to distribute interactive Mathcad document to users that do not run Mathcad yet still have the ability to perform calculations. The designer can limit the amount of content on the web pages in order to protect the company's intellectual property. IT administrators have full control over security and access because the application is built on top of Internet Information Services.

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Calculation Management can dramatically improve the performance of engineering organizations

Basic principles of calculation management

Principle 1: Managing calculations includes managing underlying assumptions

While many tools, such as spreadsheets and programs, can successfully automate calculations, the assumptions and data underlying those calculations are effectively obscured by most of them. And without the information behind the answers in some readable and manageable form, how much is a company willing to risk reusing those answers in the future?

Assumptions don't record themselves, but companies can provide a calculating environment (through technology and training) that is conducive to thorough documentation.

Principle 2: Liberate calculations from particular media and applications

Math is a particularly challenging datatype. Often when equations are represented most accessibly (as in printed materials and handwritten notes), they don't work; they're just pictures. Meanwhile, working formulas in most applications are forbidding to the eye.

Here's an example of an engineering equation in standard math notation, as rendered by Mathcad:

the equivalent RMS noise current is approximately

$$I_n := \sqrt{\left(\frac{4 \cdot k \cdot T}{R_p} + \frac{\varepsilon_n^{\,2}}{R_p^{\,2}}\right)\Delta f_v + \frac{4}{3} \cdot \pi^2 \, C_S^{\,2} \cdot \varepsilon_n^{\,2} \cdot \Delta f_v^{\,3}}$$

Here's how the same equation would appear in a spreadsheet:

	A
1	=SQRT(0.0000000000324645*B1+1002.4356*B1^3)
2	
3	

We all know the frustration of entering the same information into an array of databases or other sprawling applications that are intended to save labor. Your calculation management tools should offer a user-friendly display, produce hard copy that is easy to work with, and interface neatly with relevant software.

Principle 3: Establish rules and procedures for calculation management

Successful calculation management strategies are a logical and natural outgrowth of current practices. These systems should improve the enterprise's control over valuable intellectual capital and make it easier for engineers to do their jobs by:

- *Promoting reuse* and creating libraries of in-house standards and methods.
- *Centralizing key parameters.* Certain variables, such as material properties, find their way into most calculations. Keeping these key parameters under centralized management ensures that all calculations use the most reliable values. Moreover, the impact of changing those numbers can be assessed and minimized.
- *Making calculations and standards available online.* The Internet is the eye-level shelf for the information consumer, and remote access is essential for many engineering firms whose employees are frequently out in the field.

Process improvement trumps task automation

It is common sense and well-known in the business world that automating a business process offers a much higher return on the technology investment than automating discrete tasks. In the late-1980s, the consulting firm Nolan, Norton & Co. put some numbers on the phenomenon, citing modest (10 to 20 percent) ROI for task automation and impressive returns of up to 300 percent for business process automation. Today's leading expert on IT investment as it relates to worker productivity is Erik Brynjolfsson, a professor at the Center for eBusiness at the Massachusetts Institute of Technology's Sloan School of Management. He has spent years studying the business process changes, small and large, that are precipitated by new technologies, and which he believes account for the really impressive productivity gains.

Brynjolfsson's study of 1,167 large companies in 41 industries concluded that productivity growth arises from the combination of new technologies and new business processes. Addressing an eBusiness conference in Cambridge, Massachusetts in 2002, Brynjolfsson said companies' productivity and market value were not as closely linked with IT spending as with "how they used technology. It was what they were doing with it. And it was their corporate culture, their attitudes towards a whole set of information-related decisions."

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Making the most out of math

IDC analyst Gisela D. Wilson wrote the following about Calculation Management in *"Calculation Management - Making the Most Out of Math"* in March 2004:

When thinking about discrete product development and even more so about product life-cycle management, we generally focus on electronic product drawings or virtual product prototypes. Engineering calculations per se are often ignored. And yet, mathematical calculations and their underlying thought processes and assumptions play a fundamental role in product development. They are far too important to languish in desk drawers or in spreadsheets on desktop PCs. This study describes the emerging transition in managing engineering calculations from paper-based notebooks to electronic calculation management systems. This transition is fraught with hurdles that have to be overcome, ranging from winning buy-in from engineers who generally don't like to share their work with others to overcoming security concerns and extracting funding by demonstrating return on investment. IDC's recommendations to promote the successful introduction of calculation management into a manufacturer's product life-cycle management process include the following:

- Encourage a culture of collaboration, information sharing, and team learning within your company's engineering department.
- Make calculation management part of your team collaboration applications, such as Web conferencing, email, and discussion forums.
- Establish ROI information to prove out the benefits of calculation management practices and then share these learnings with the rest of your extended organization and its business partners.
- Make sure that the calculation management application you plan to implement is easy to learn, does not require a lot of time to use, and fits into your existing IT infrastructure.

Calculation Managements' Key Benefits

On-Time Product Developement	• Automate the reusability of engineering work. • Design and document engineering work simultaneous. • Enable faster collaboration. • Access design information instantly for improved decision-making.
Product Quality	• Reduce calculation and design errors. • Ensure innovation design.
Regulation Compliance	• Capture engineering intellectual property, design intent, and methods. • Meet national and local regulations. • Comply with regulatory standards, such as Sarbanes-Oxley.
Easy Integration with Existing Engineering Applications	• XML information architecture is a standards-based, structured data model. • Fits into your organization's existing product development process. • Integrates with third-party applications. • Compliant with information technology standards.

This new approach to Calculation Management has the potential to dramatically improve the productivity and quality of the engineering process. Giving engineers the ability to quickly search for and copy engineering calculations throughout the organization will save large amounts of time by making it much easier to re-use engineering information as opposed to re-inventing the wheel. It will be possible to locate previous calculations that apply to the job at hand and their origin can easily be determined. The use of custom templates will help ensure quality by promoting proven best practices throughout the organization. Further productivity improvements will come from manager's ability to instantly access calculations so that, for example, if a new grade of aluminum becomes available at a lower price, managers can very quickly evaluate the affected projects and determine if it will cause any problems. Finally, the intellectual property that serves as a valuable asset of any engineering-based organization will become more valuable through its ability to be easily leveraged and preserved regardless of personnel changes.

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mathsoft®

With 20 years of experience, Mathsoft Engineering & Education, Inc. provides comprehensive solutions that streamline the engineering process in a way that can be documented, verified and reused, enabling engineering and product innovation.

www.mathsoft.com

HEADQUARTERS

{North & South America}

101 Main Street
Cambridge, MA
02142-1521
USA

T 617 444-8000
F 617 444-8001

sales-info@mathsoft.com

GERMAN OFFICE

{Germany and Austria}

Steinstrasse 56
81667 München
Germany

T +49 (0) 89 666 103-0
F +49 (0) 89 666 103-13

germany@mathsoft.com

JAPAN OFFICE

{Japan, Korea & China}

Level 11, Aoyama Palacio Tower
3-6-7 Kita-Aoyama, Minato-ku
Tokyo, Japan 107-0061

T +81 3 5778 7684
F +81 3 5778 7676

asia-info@mathsoft.com

NETHERLANDS OFFICE

{Benelux}

Rotterdamseweg 183c
2629 HD Delft
Netherlands

T +31 15 268 2640
F +31 15 268 2629

netherlands@mathsoft.com

UK OFFICE

{All other locations}

Knightway House
Park Street
Bagshot, Surrey
GU19 5AQ
United Kingdom

T +44(0) 1276 450850
F +44(0) 1276 475552

int-info@mathsoft.co.uk