Advanced Machine Engineering

Transforming the Machine Building Industry

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As machines grow in complexity machine and equipment builders often struggle to meet cost, quality, timing, and functionality requirements demanded by their customers. Machine applications run the gamut of industries from machine tools and industrial production equipment to food processing, material processing and handling, robotics, and many others. Machinery complexity is increased by the broad range of domains needed to design these complicated devices: mechanical, hydraulic, pneumatic, electrical, electronic, and software; the interactions among domains; and the variety of business models employed by machine builders to satisfy the needs of their customers: including BTS, CTO, and ETO.

To completely support products throughout their lifecycles requires a digital thread to connect the data across the lifecycle from concept to retirement. This is especially true as complexity increases; ensuring the data is properly configured and its integrity is guaranteed. With clear, concise, and valid data, advanced business processes such as product simulation and virtual commissioning can validate products before they are built, reducing costs and risks during physical commissioning and improving profitability for the machine builder and the customer.

Introduction

Today's products are amazing. The level of product choice, convenience, performance, and cost available today was unimaginable 20 years ago, providing many more useful features at an affordable price. The availability of choice and capability in today's consumer goods is supported by more and more complex, and in many ways more flexible, industrial machinery used to manufacture them. The challenges for companies delivering machines and equipment for the factory floor get even more complex as demands change.[1]

Today's more capable and complex products are produced by much more flexible and complex manufacturing systems. Developing the machines that support BTS, CTO, and ETO is a challenge that can be mitigated through the use of new digital enterprise processes and capabilities.

Companies that purchase industrial machinery are making an investment and expect a return. To achieve that return their machines need to operate to produce products at a high level of speed, quality, and up time. To satisfy these expectations and requirements, industrial machines are becoming more complex with more electronic and software elements. A variety of business models ranging from Build-to-Stock (BTS) to Configure-to-Order (CTO) to Engineer-to-Order (ETO) are commonly used to create machines. Elements of all three approaches are often used. Complex machines produced via CTO and ETO rarely ship with identical configurations and are enhanced over time and while in service, so each instance of a machine has a unique configuration. The latest trend within industrial machinery is the product-as-a-service (PaaS) approach where the machine builder leases the machine to its user with a service contract that guarantees service levels as well as maintenance and support.

[1] Research for this paper was partially supported by Siemens Digital Industries Software.

An aggravating issue for both PaaS and customer-owned machines is that when customers order parts for planned, or worse, unplanned maintenance, they expect the correct part be delivered and installed so their uniquely configured machine can get back into production as quickly as possible. While the expectation is easy to identify, it is not so easy to deliver when the machine builder does not have a way to "know" the current state of a machine—a digital twin is needed that is kept up-to-date with each machine's current, as-maintained configuration. Delivering the wrong part can have much higher consequences, such as negative financial impact, unplanned downtime, customer dissatisfaction, and perhaps the worst, a safety issue. For the producers of these products and their replacement parts, this is the outcome of poor management of the product development, manufacturing, and distribution lifecycles and maintenance of a consistent, evolving digital thread of information and processes throughout.

The tools required to get products developed and produced vary widely in discipline, deployment, and integration. While there are some large solution providers with broad, deep portfolios there is no single source for all of the tools that a machine builder needs to flexibly and efficiently produce complex industrial machines. Even within solution suites from a single supplier, differences in how organizations operate, including their enterprise supply chains and disparities in people, processes, and technology virtually ensure that solutions from multiple providers will be employed—product development takes place in a heterogeneous world. There are always best of breed tools, unique processes, and creative tool users that cause breaks in the digital thread of product information required to overcome suboptimization.

Complex machines have been common for centuries, well before the industrial revolution. The development of Industry 4.0 where machine usage information can be accessed more easily and in which design creation and simulation software are the primary tools used and result in 3D models that describe a part's shape and other characteristics such as material and tolerances. But just being able to design more complex machines is not enough to satisfy today's need for customization and more efficient operation of massively complex machines. A digital thread that supports digital twins of products that include all domains, especially software, throughout their lifecycles has become necessary.

The world of machinery development has evolved from one of hand-built, completely bespoke, relatively simple machines, to standard machines with only minor variations, to a point where every aspect of a machine may be customized to support a customer's needs.

Multi-Disciplinary Design

Machinery design has historically been driven by mechanical parts and assemblies and modern CAD tools do a good job of representing that type of data. Another issue for today's machine developers is that the world of power and control systems has evolved from waterwheels, linkages, simple cams, and other mechanical devices to include a number of other disciplines. In most cases today the energy to run a machine is provided by electrical power, but within machines hydraulics and pneumatics are often used for power or force transmission and an abundance of software driven electronic systems are used in combinations to control very complex and variable processes.

Flexibility in industrial machines arises from multi-disciplinary physics that allows more accommodating, refined control systems. However, success in designing these systems requires much better data and process management supported by a lifecycle digital thread.

Electric motors and electronic control devices are at the heart of virtually all modern machines and becoming more popular due to their efficiency and sustainability. Electronic controllers manage motors teamed with actuators and sensors that provide feedback to ensure the machine works properly. Sophisticated machines use microprocessors and computer software to manage more complex equipment that may contain many controllers and sensors. For machinery applications most hydraulic, pneumatic, vacuum, and electrical systems are configured from commercial off the shelf (COTS) components. Schematic diagramming software is used to create the logical design and the physical design is created with a CAD application.

Software is used in several different contexts. Embedded software runs on machine controllers in real-time directly interfacing and controlling physical operation. Desktop or edge computers oversee machine modules, and production lines, providing local reporting and analysis, as well as feeding data to the factory or enterprise level applications via sensors and the internet of things (IoT).

With the use of more electronic controls comes an increase in the use of software to facilitate refined control linked to machine-based sensor feedback. This has become a critical part of industrial machinery design that must be supported in the machine's digital twin—it is critical to know which version of software is embedded in each machine.

Machine Design Issues

Ask any engineer about the problems he faces getting his work done, and the complaints will usually revolve around tools, data, and processes. Probe a bit further and difficulties in collaboration get mentioned. Interfaces or boundaries are where most problems occur—they happen across functional domains such as mechanical, electronics, and software and across organizational domains such as engineering, validation and test, manufacturing, installation, and service. In the case of data interoperability, issues arise due to the various types of software used in each domain. At the process level, the handoffs of data from one domain or department to the next cause additional issues. Transferring the right data to the right people and tools at the right time is complex when a project team is larger than a handful of people.

- These issues are made much more difficult because modern machines are complex, flexible, and leverage a variety of technology domains to meet their requirements.

Machine Design Business Processes

To maximize profitability many machine building companies, use a modular design strategy. At its most basic level modular design involves ensuring interface or connection points between modules are consistent so modules that increase capability or capacity can be easily added. Within the mechanical or physical domain connection points need to match. The input and output of one module needs to meet the requirements of the modules with which it connects. On the electrical side wiring harnesses need to connect, and the electronic signals and power conductors need to align. Hydraulics, pneumatics, and vacuum devices have similar issues to electrical and electronics. Software is where it starts to get very complex. Ensuring that embedded controllers can be managed as a single unit across modules without customizing each installation's software is critical to smooth operation.

Machine companies primarily use three business models, BTS, ETO, and CTO and often blend them. In a BTS business, the strategy is optimized for volume production and machines are designed to meet well defined requirements with predictable sales volumes. In an ETO process, significant elements of the machine are customized or designed from scratch to meet specific customer requirements. In a CTO process, common modules and parts are assembled to meet a customer's requirements. These three business models are often thought of as a continuum, wherein elements of each can be combined to produce a wide range of products. For instance, core product modules may be produced in volume using a BTS strategy, then, these core modules and standard components can be configured to support more complex applications using a CTO strategy. Then, for customers with unique requirements the machine builder configures as much of the product as possible with these core BTS and CTO modules and then custom engineers only what is special. Few machine companies are pure BTS, CTO, or ETO. Adding some configurability to a BTS product is an easy way to grow sales, while fully engineering from scratch is usually too expensive. BTS is usually the lowest cost and most predictable approach, ETO the highest cost (but with the highest potential margins) and least predictable approach, and CTO is in the middle.

A good example of a mixed mode machine is an HVAC system. The system is configured using standard duct and control components, but custom sheet metal may be used to support non-standard building design features. Product configurators can be used in both CTO and ETO processes. Using a configurator, an application engineer or even a customer can input requirements that support a desired process. This is evaluated by an algorithm that understands how modules and parts may be configured to achieve a particular result. This automation approach can dramatically reduce the design and planning time required to produce a machine once its architecture is defined. When reusing existing parts in a configurator, it is easier to forecast cost and profitability as the cost data from previous equipment can be incorporated into the configuration enabling better business decisions for both the machine builder and the customer.

Two areas of innovation within machine engineering companies are IoT and machine learning (ML). IoT uses sensors to report on a machine's environment and performance. The data from IoT is usually reported to enhance operation of the machine, but in the most advanced implementations machine builders are using IoT to provide condition-based and predictive maintenance services. They are also using IoT data to improve product designs. ML, an application of artificial intelligence, has received a lot of attention and is being applied to many problems. Equipment operation optimization is perhaps the most developed use of ML. As sensors drop in cost, they are used more and more and output more and more data. Processing that data is a bottleneck and CIMdata is seeing more case studies on how machine learning is helping transform raw IoT data into actionable information.

IoT and ML allow companies to operate their machines more efficiently. They also provide feedback to machine builders that support predictive maintenance and can influence improvements in machine design.

Configuration Management

Conceptually, configuration management (CM) is often simplified to ensuring that correct part revisions are included in the BOM and the drawings sent to manufacturing and suppliers have the same revision level as those parts. This is a dramatic over-simplification and causes many design, production, and operational issues.

In addition to variations brought about during the machine design process, there is also the need to support machine sales configurators, especially in CTO businesses. In these cases, the configuration needs to identify and manage all of the combinations of machine systems that can be built into a working, saleable solution for a customer—and exclude combinations that will not result in a valid, workable product.

Issues Caused by Poor Configuration Management

CIMdata believes that doing things right the first time is much more efficient than doing them over. During our consulting practice we see many errors that trace back to incorrectly defined or poorly managed configurations. This results in problems such as the wrong version of a part or software causing a malfunction or failure. In the days when the majority of design concentrated on managing the mechanical aspects, a change needed to be documented only when form, fit, or function (FFF) was affected.

Issues related to poor configuration abound. Some have the potential to be quite expensive—such as safety related failures or inability to satisfy regulatory compliance standards.

With the complexity of today's products, the supply chains that produce them, operating condition variability, and the massive increase in design items that come from non-mechanical domains, companies are finding that product configurations are much more complex and more difficult to understand. Configurations have many more interdependencies that have to be managed and understood. Some issues that are common follow.

Regulatory Issues

Machine builders can face many different regulatory requirements often dependent on the industries of their customers and the uses of their machines. For highly regulated industries such as food processing and medical, not only the configuration of the product must be controlled, but the equipment within the manufacturing process must be controlled.

Safety Issues

Many hazards—physical, electrical, chemical, biological, and others—can injure or kill workers or bystanders. Machinery is dangerous and safety is always critical. Evaluating safety issues that may occur in a machine may require ergonomic simulations and analysis combined with machine operational analysis.

Cost Issues

While satisfied customers are critical, keeping them happy while meeting business requirements is critical for a successful machine builder. Poor CM leads to duplicate parts, overly complex products and product lines, excess inventory, more scrap, more rework, and incorrect machines and repair parts being shipped to customers. All items that have significant impact on margins. Without good solutions to support CM, more people are required to manage configuration data, adding cost, and inevitably increasing mistakes.

ETO machine builders often need to be very creative in their solutions to meet specific customer requirements. This often means developing innovations. These can be very profitable if captured and aggressively pursued. Without strong configuration management, even if the engineering work is not patentable, the innovation can be lost to history, becoming tribal knowledge, and must be re-created or re-invented for future opportunities.

Cost of Late Changes

It is well understood that the cost of a change goes up by an order of magnitude as a product progresses through each phase of the product lifecycle. A change that costs $1,000 in the design phase, costs $10,000 in the manufacturing phase, and costs $100,000 in service.

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Once product manufacturing starts, investments in raw materials and tooling dwarf the early development costs. Field changes are worse because of the cost of travel to the machine's location, time to audit the current state of a machine in service, time to discover which parts and subsystems can be replaced or repaired, getting the parts and equipment to the location, and executing the repair. Furthermore, changes later in the product lifecycle impact delivery time which damages customer credibility and may negatively impact repeat business.

Virtual Commissioning

Virtual commissioning enables testing to be done in less time, much earlier in the product development lifecycle, and avoiding the use of potentially destructive or hard to execute tests. Virtual commissioning may also include the use of pre-existing hardware components and humans to further validate and understand how to commission the real machine.

The machine commissioning process is common across many industries. Historically this has been done by building a physical version of a machine and all of its controls, then testing the system manually to assure that everything works as specified. This can be time consuming and very expensive. When flaws are found, it is almost always late in the development process, typically with deadlines and penalty clauses looming. Virtual commissioning uses product models, simulations, and physical components to verify how a machine will operate, and how it will be controlled before all of the physical machine is built. Later, the same virtual-physical model can be used for operator training.

Early implementations of virtual commissioning focused on physical fit and function. However, in recent years, the technology has expanded to support validation and verification (V&V) combining hardware-in-the-loop (HiL), software-in-the-loop (SiL), and human-in-the-loop (HITL).

Beyond V&V, virtual commissioning also enables early training as well as remote training, a useful capability in our current work from home situation caused by COVID-19. Operators and technicians can test software and control concepts in a virtual or mixed virtual and real environment using a physical control to drive a virtual machine or a virtual control to drive a physical machine. This flexibility allows ideas to be tested early, improving products, and training to be done before the machine is production-ready, so when it is, the startup will be quicker and more productive.

Installation and Commissioning Issues

Machinery installations are often complex and costly. Machines are usually large and heavy, cost a lot to ship, often have to be assembled on location, require specialists (riggers) to position the equipment, and need many specialists (electricians, mechanics, and others) to assemble and test. Often this is the first time the whole machine has been assembled and surprises happen. Modules don't mate together, interfaces don't connect. The installation team is stressed and the design office scrambles to verify issues in the design and develop fixes and workarounds. It's usually a high-pressure event resulting in a lot of anxiety.

Beyond mechanically fitting together, electrical and electronic functions constitute another level of issues. Sensors and controllers have to manage real world physical problems with raw material inconsistences, signal issues from sensors, and timing issues. Because operators may have only had cursory training, basic setup and operation is more time consuming, delaying productive use of the machine.

Software is a difficult issue because it is not often managed in parallel with the hardware and electronics definitions and its integration typically happens late in the machine's development lifecycle. Also, machinery usually has lifecycles measured in years if not decades so software updates have to be managed and documented throughout. As code is modified and extended over the years it has to be tested to assure it is bug free.

Within a virtual commissioning environment, the software is part of the configuration. So, multi-domain configuration management capabilities must include embedded software as part of the as-built configuration, and keep track of field updates via the as-maintained configuration. When IoT is included machines can "phone home" or be accessed remotely to report status to the machine builder and the machine builder can often send code updates on-line.

Managing the Digital Thread

A digital thread and digital twins are critical components for managing a machine's product lifecycle from concept to retirement. The digital thread must provide a continuous oath of information and processes through the lifecycle—updating the digital twin and maintaining its relationship to the physical twin of the machine at all critical junctures.

To improve effectiveness and efficiency industrial companies and PLM solution providers are collaborating to create a complete digital representation of products. This manifests itself in a complete end-to-end virtual representation of the product's configuration and related information throughout its lifecycle. This representation is also known as the digital thread which allows the creation and maintenance of a digital twin of a product. A digital twin is a physics-based description of a system resulting from the generation, management, and application of data, models, and information from authoritative sources across the system's lifecycle. The Digital Twin must be more than just a descriptive model or collection of related digital information (e.g., a SysML model). It is a complete physical description included all behaviors.

To maintain a robust end-to-end digital thread, the minimum structures required include the EBOM (as-designed), MBOM (as-planned), MBOM (as-built), and SBOM (as-maintained). When these different BOMs are available a company can establish a robust digital thread that can maintain the data required for a set of digital and physical twins.

Traceability

Traceability across product information is a fundamental capability that impacts cost, quality, and time to market. As a product progresses from design to manufacturing to operation, there are always questions that need to be addressed. Understanding the interdependencies among the MBOM, the EBOM, the bill of process (BOP), and related documents for a particular item needs to be understood, which is a straightforward process when enabled by traceability. Questions about a particular component in the field could relate to how it was manufactured, (e.g., were there any issues in quality control) or understanding when a component is worn so much that it is out of tolerance.

IoT, one of the recent technology additions to many machines provides machine builders with two fundamental digital thread capabilities. IoT enables improved product performance monitoring and support. Operational data can be used to support condition-based and predictive maintenance when combined with artificial intelligence or machine learning. Furthermore, operational data can be used to provide machine builders with insights that drive requirements to improve the next version of the product closing the product lifecycle loop. As companies start to adopt new technologies like IoT, the need to have traceability and impact analysis further increases.

Impact Analysis

From an innovation viewpoint, impact analysis is perhaps the most useful capability enabled by the digital thread. Change impact analysis is painful in most companies because data is not fully connected in a digital thread. This lack of connection forces the change team to search manually to identify issues and reduce risk, a time consuming and error prone process. Once a digital thread is created and a comprehensive digital twin is established, change processes improve dramatically in speed and quality. People are more confident that their decisions are accurate and won't have unintended consequences.

Siemens Advanced Machine Engineering Solution

CIMdata continues to be impressed with Siemens progress in supporting the machine industry. Siemens has invested heavily in acquiring technology and has consolidated many software teams and products in their Digital Industries division. The TIA portal shown in Figure 1 leverages comprehensive digital twins and enables virtual commissioning. The Siemens Xcelerator portfolio has the tools to create the models that describe the product, NX for mechanical, hydraulic, and pneumatic systems; Capital to define electrical and electronic systems; Polarion to manage software development; and Teamcenter to tie the authoring tools and their data together with development processes into a comprehensive digital thread. Simatic controller models can be integrated to support control systems simulation. Simcenter supports simulation of all the physical domains necessary to predict machine performance.

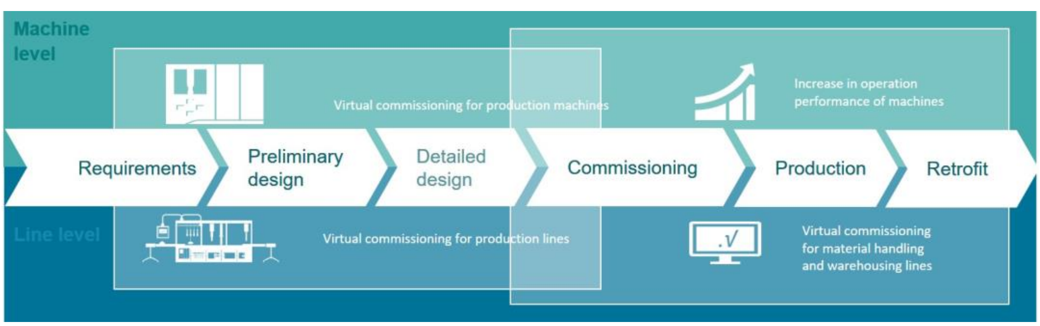

Figure 1–Siemens TIA Portal Enables Virtual Commissioning and More

The Siemens Advanced Machine Engineering solution packages all the appropriate portfolio technologies to support the three capabilities all machine builders need—multi-disciplinary design, configuration management, and virtual commissioning. The business benefits of this are reduced uncertainty in both function and schedule, improved quality leading to satisfied customers, and improved, predictable profitability for the machine builder as well as the customer.

Conclusion

We live in an amazing world, but it was built with good ideas and hard work. Most physical goods including food are created in factories with complex production lines of machines. The competition built into our economy forces product manufacturers to continually improve, and most production improvement results from the implementation of machine and information technology. Machine and equipment builders often struggle to meet cost, quality, timing, and functionality requirements demanded by their customers.

Like most things in today's world complexity has grown in parallel with capability, and new ways of doing business are needed to stay competitive. Complex machines can consist of thousands of commercial and custom parts. Keeping track of them all accurately while ensuring the product can perform as required, on-time is daunting and stressful.

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PLM solutions are a core technical element that helps machine and equipment builders continue to improve. The latest generation of technology can now deliver on the actionable digital twin strategy that has been promised for decades. The digital twin enables engineers to reliably predict machine performance before cutting steel. The technology supports all critical machine domains, mechanical, electrical, electronics, and software. Furthermore, domain silos have been broken down so each domain can do its work within the context of all the other domains, reducing risk and rework, thereby improving cost, timing and quality.

Siemens AG is both a leading provider and major user of advanced machine technology. Beyond the core multi-disciplinary design and configuration management support, Siemens provides support for end-to-end virtual commissioning. The TIA Portal provides support for accurate simulation of controllers and software so virtual commissioning can be supported. All these capabilities combine to improve efficiency so more time is available for innovation ensuring that customers are satisfied and the machine builder is profitable and successful. Machine builders should check out Siemens latest Advanced Machine Engineering solution, adopting it will enable digital transformation and help improve customer satisfaction ensuring business success.

For more information please see Siemens Digital Industries Software at:
siemens.com/plm/advancedmachinery

About CIMdata

CIMdata, a leading independent worldwide firm, provides strategic management consulting to maximize an enterprise's ability to design and deliver innovative products and services through the application of Product Lifecycle Management (PLM) solutions. Since its founding over thirty years ago, CIMdata has delivered world-class knowledge, expertise, and best-practice methods on PLM solutions. These solutions incorporate both business processes and a wide-ranging set of PLM-enabling technologies.

CIMdata works with both industrial organizations and providers of technologies and services seeking competitive advantage in the global economy. CIMdata helps industrial organizations establish effective PLM strategies, assists in the identification of requirements and selection of PLM technologies, helps organizations optimize their operational structure and processes to implement solutions, and assists in the deployment of these solutions. For PLM solution providers, CIMdata helps define business and market strategies, delivers worldwide market information and analyses, provides education and support for internal sales and marketing teams, as well as overall support at all stages of business and product programs to make them optimally effective in their markets.

In addition to consulting, CIMdata conducts research, provides PLM-focused subscription services, and produces several commercial publications. The company also provides industry education through PLM certification programs, seminars, and conferences worldwide. CIMdata serves clients around the world from offices in North America, Europe, and Asia-Pacific.

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