Title
Enabling Manufacturing Research through Interoperability

Authors
Dornfeld, David
Wright, Paul
Helu, Moneer
et al.

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ENABLING MANUFACTURING RESEARCH THROUGH INTEROPERABILITY

David Dornfeld
Laboratory for Manufacturing and Sustainability
Berkeley Manufacturing Institute
University of California
Berkeley, CA 94720-1740

Paul K. Wright
Ford Prototyping Laboratory
Berkeley Manufacturing Institute
University of California
Berkeley, CA 94720-1740

Athulan Vijayaraghavan and Moneer Helu
Laboratory for Manufacturing and Sustainability
Berkeley Manufacturing Institute
University of California
Berkeley, CA 94720-1740

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ABSTRACT

Interoperability standards, which provide standardized communication and information exchange between machine tools and components, are necessary to bring together the many advances of the manufacturing community and fully address the challenges facing industry. Such a comprehensive approach is necessary due to the growing complexity in manufacturing and the shrinking time scale of manufacturing decision-making. In this paper we discuss the benefits of interoperability in different aspects of manufacturing research including process monitoring, CAD/CAM/CAPP, and flexible and reconfigurable manufacturing systems, as well as the advantages of interoperable systems in fulfilling the growth of sustainability and environmental requirements in manufacturing.

INTRODUCTION

With the increase in complexity of manufacturing systems and processes, there is a growing need to bring together advances from different realms of manufacturing research. This trend is motivated by many reasons including: products are more complex and tolerances tighter, manufacturers need to focus on multiple aspects of the manufacturing process to achieve the required level of quality, and response times are decreasing from design to product. It is no longer adequate for manufacturers to focus on particular aspects of their process for improvement. Rather, they need to use a holistic approach for process improvement. This is especially the case as cost and time requirements for manufactured parts are getting progressively stringent. Lean manufacturing techniques are standard in most manufacturing practices these days, and inefficiencies in the manufacturing process are being addressed by process and system improvements. Supply chains are getting more complex as well, and it is critical to improve the fractional value added time while making parts. Figure 1 traces historical developments in the organization of manufacturing processes and systems. Figure 2 shows that as the paradigms "shifted", costs that were hitherto considered externalities were included into the scope of the system. These costs now need to be controlled as well.

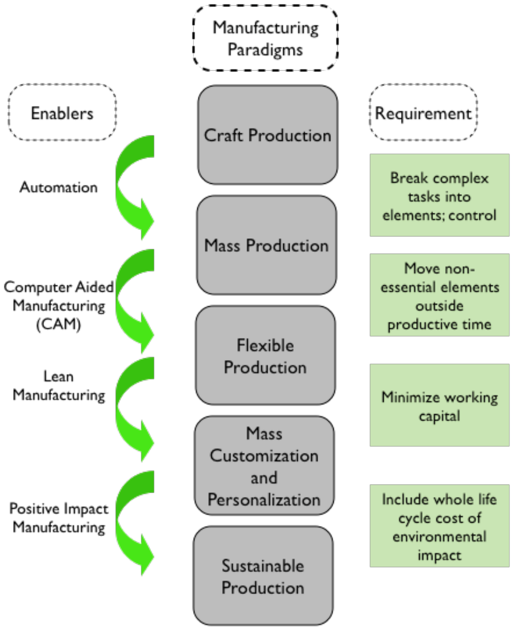

FIGURE 1: CHANGING MANUFACTURING PARADIGMS (DORNFELD, 2008, AFTER JOVANNE, 2003).

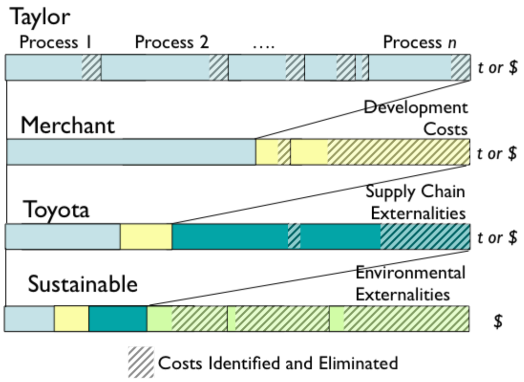

FIGURE 2: IDENTIFYING AND ELIMINATING EXTERNALITIES (ZHANG, 2006).

A useful metaphor to employ while visualizing the complexity of manufacturing systems is the popular mapping application, Google Earth. Google Earth and similar packages offer a seamless way of visually processing and presenting information at different levels of detail made possible because information at different levels of detail is stored in way that allows these applications to interoperate with information at the other levels. We can apply this metaphor to a manufacturing system similarly organized from the enterprise as a whole to the process physics at the tool-chip interface (see Figure 3).

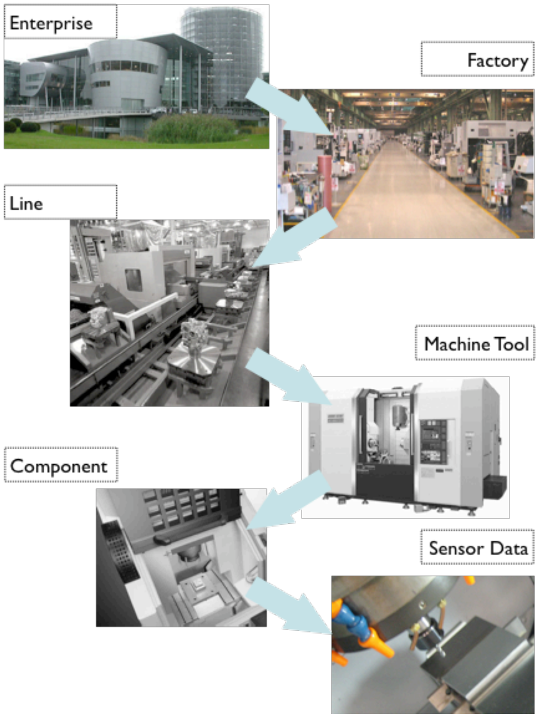

FIGURE 3: LEVELS IN MANUFACTURING SYSTEM.

Clearly, to harness and process information across these levels we need robust methods for communication and interoperability in and between the levels (Vijayaraghavan, 2008). Interoperability is defined as "the ability of two or more systems or components to exchange information and to use the information that has been exchanged" (IEEE, 1990). The Association for Manufacturing Technology recently launched MTConnect, a data standard for communication between manufacturing equipment (MTConnect, 2008). Currently, MTConnect has been adopted primarily by machine tool manufacturers and their end-users who see immense value in being able to interoperate with other equipment. Details of MTConnect, and example applications using MTConnect are presented in another paper in this volume (Vijayaraghavan, 2009).

In this paper, we argue for greater interoperability in manufacturing research. A key benefit of interoperability is that it reduces the number of custom interfaces needed to integrate

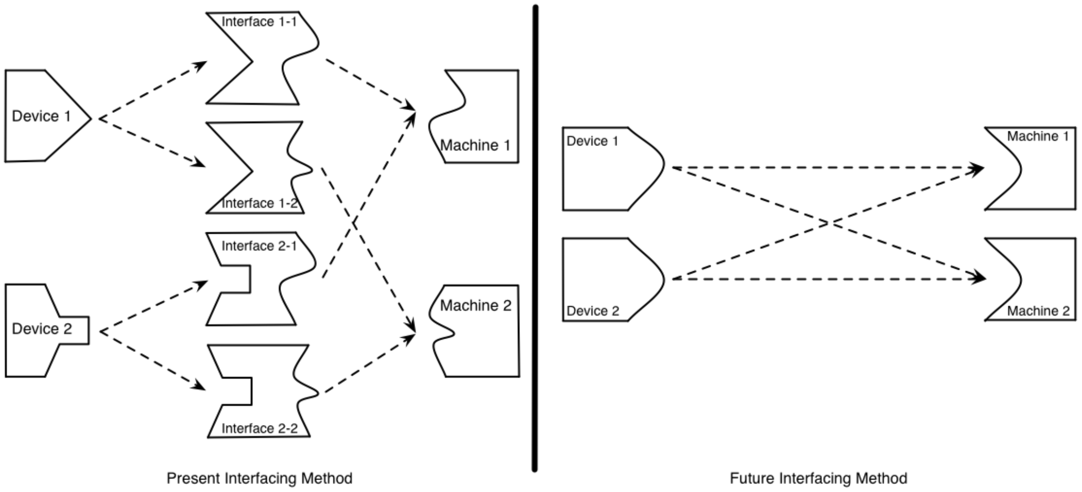

FIGURE 4: STANDARD INTERFACES DRASTICALLY DECREASE THE NUMBER OF CUSTOM INTERFACES NEEDED.

equipment on the factory floor. Consider the example in Figure 4 where we are trying to interface external devices (such as monitoring equipment) with machine tools. Without interoperability standards, we will require custom interfaces between each device and machine tool. Here, the number of custom interfaces needed (software or hardware) scales rapidly. However, standardized interfaces allow devices and machines to communicate with each other “out-of-the-box” greatly reducing the developmental time and effort needed to get the system working. The ultimate goal of interoperability standards is to allow researchers to focus on the development of tools to solve specific manufacturing problems rather than the methods to allow devices and machines to work together in a real-world system.

In this paper we will show the benefits of interoperability when studying manufacturing systems at the different levels outlined in Figure 3. Specifically, we begin by discussing the state-of-the-art in, and the value of interoperability to process monitoring (tool-chip level), CAD/CAM/CAPP (process-design level) and flexible and reconfigurable systems (factory level). We also discuss the advantages of interoperable systems in fulfilling growing sustainability and environmental requirements in manufacturing.

MANUFACTURING RESEARCH

Machining Process Monitoring

Historically, machining process monitoring implemented stand-alone sensors as diagnostic devices for the process (Byrne et al., 1995). Throughout the late 20th Century, stand-alone sensors were transformed into sensor systems used primarily for tool condition monitoring, surface/workpiece monitoring, and process monitoring in general (Byrne et al., 1995, Liang et al., 2004). In the future, it is widely accepted that manufacturing process monitoring and control will trend towards intelligent, multi-sensor systems capable of monitoring many aspects of the process to minimize breakage and downtime and optimize the process itself (Byrne et al., 1995, Liang et al., 2004).

Significant research has been completed on many different sensor types and the suitability of each sensor type for various applications. Some of the types of sensors still prevalent in manufacturing include: vision, force, acoustic emission (AE), power, torque, vibration, direct gauges, and temperature (Byrne et al., 1995, Liang et al., 2004). Of these sensor types, the sensor technology with the greatest recent research activity is AE (Byrne et al., 1995). Typically, AE is paired with a more conventional sensor (usually force) in order to reduce the dependence of the AE signal on process parameters (Byrne et al., 1995). This coupling highlights the shift in process monitoring towards sensor fusion (or using a multi-sensor approach where each sensor type compliments the other sensor types).

Sensor fusion and multi-sensor approaches have been the new focus of much of the research activity in sensors (Byrne et al., 1995, Liang et al., 2004). The main emphasis of this work has been to determine how best to reduce the large information flow from the sensors in the system to those signals of greatest importance for process control. While there have been many examples in the literature of successfully integrated sensor types for tool condition monitoring and machining process monitoring in general, multi-sensor approaches have not been generally accepted in industry due to the substantial training and setup time required for sensor systems to function properly (Byrne et al., 1995). Furthermore, the lack of commonly adopted sensor codes and protocols only serves to increase the learning curve required to properly implement many of the strategies devised in the research community (Liang et al., 2004).

Standardization is the key enabler for industrial adoption of the intelligent, multi-sensor approach that the research community agrees is the next logical step for machining process monitoring and control. Without standardization, industry will always be expected to learn many competing protocols and thus will lack the incentive to adopt any novel monitoring strategies developed via research. To achieve standardization, an interoperability approach like MTConnect is ideal since it provides plug-and-play ability such that systems engineers need only learn one standard. They can then use that standard with any monitoring algorithms over a wide range of sensor technologies. In fact, it is this ability that has helped MTConnect gain wide acceptance among industry practicioners.

Computer-Aided Design, Manufacturing and Process Planning

Computer-Aided Process Planning (CAPP) methods are critical in automating the manufacturing of complex parts. In a comprehensive review discussing the state-of-the-art in process planning, Marri et al (1998) described CAPP as a decision making process which identifies the set of instructions and parameters required to manufacture a part. They discuss various generative process planning methods that develop the process plan based on an analysis of part geometry, material properties and other factors. Figure 5 shows a schematic of CAPP methods. Here, information from the CAD system is combined with physical rules, knowledge from prior experiments, and other inputs, to generate the process plan. Clearly the data that is transmitted through the different "boxes" in the system needs to be in a consistent format for the system to operate smoothly. For this system to be modular (where individual entities in the flowchart can be replaced at will), consistent and standardized data formats need to be used. The authors argue that CAPP systems need to integrate more closely with real-time factory monitoring systems so that dynamic effects and system uncertainties can be captured. To enable this integration, the CAPP system needs to use data standards that integrate well with machine-level data standards, such as MTConnect.

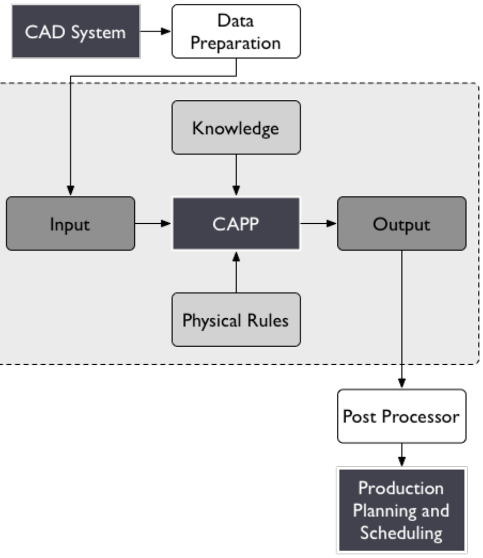

FIGURE 5: BASIC CAPP MODEL (ADAPTED FROM MARRI, 1998).

In a review of integrating process planning methods with shop scheduling algorithms, Tan and Tan (2000) argued that integrated process planning and scheduling methods needs integration at the factory level especially with legacy equipment. Again, standardization of data exchange is key in achieving this level of integration.

The effectiveness of integrated CAD-CAM-CAPP systems such as CyberCut is directly dependent on the ease with which data can be exchanged between the different entities in the system (Ahn et al, 2001). MTConnect is particularly useful for web-powered systems such as Cybercut as it is built using web standards such as XML for data representation and TCP/IP for communication. The automated macro-planning and micro-planning capabilities provided by Cybercut can be bolstered by providing efficient methods to gather data from the machining process to use to improve the process plan's effectiveness. Interoperability standards are the "next step" in the development of integrated manufacturing planning and execution methods. We have applied MTConnect in integrating process monitoring data with CAD/CAM analysis and validation. Having a standardized method to address and process data markedly improves the range of applicability of the tools we have developed (Vijayaraghavan 2008, Vijayaraghavan 2009).

Reconfigurable and Flexible Manufacturing Systems

From Merchant (1961) to more recent efforts characterizing flexible and reconfigurable manufacturing systems, researchers have extensively explored methods to characterize the complexity in manufacturing systems (Hon, 2005). Figure 6 shows the overall effect of flexible manufacturing systems, which spans from the level of the individual process to the business environment where the system functions. Clearly, this will benefit from standardized communication across the span of the system.

Reconfigurable manufacturing systems (RMS) are systems designed to be able to rapidly change structure, hardware, and/or software components to quickly adjust capacity and functionality within a given part family in response to sudden changes in market or regulatory requirements (Koren et al., 1999). RMSs differ from dedicated machining systems (DMSs), or systems with narrowly defined requirements designed for production of one part with fixed tooling and automation, by offering flexibility when required without compromising robust performance (Koren et al., 1999, Mehrabi et al., 2000, Landers et al., 2001).

Flexible manufacturing systems (FMSs) are systems with broadly defined requirements with fixed hardware and programmable software that accommodates for changing volume and product mix (Koren et al., 1999, Mehrabi et al., 2000, Landers et al., 2001). FMSs differ from DMSs and are similar to RMSs in that FMSs provided the flexibility and scalability to produce an almost infinite number of parts. However, the key distinction between FMS and RMS is that FMS provides significantly more flexibility and is thus more applicable for prototyping parts whereas RMS provides equal flexibility but only for a particular set of parts so that it is more applicable for batch production.

The key characteristics of RMSs include being modular, integrable, convertible, diagnosable, and customizable (Koren et al., 1999, Mehrabi et al., 2000). Perhaps the most important enabler of these characteristics is well-defined hardware and software interfaces (Koren et al., 1999). Koren et al. (1999) states that well-defined interfaces are necessary for RMSs to become open-ended enough to allow for the incorporation of improvements and upgrades necessary for efficient reconfiguration. Furthermore, reconfiguration becomes more difficult to achieve due to the difficulty in realizing proper interfaces due both to the inherent technical complexity (hardware interfaces) and the lack of standardization (software and control interfaces) (Koren et al.,

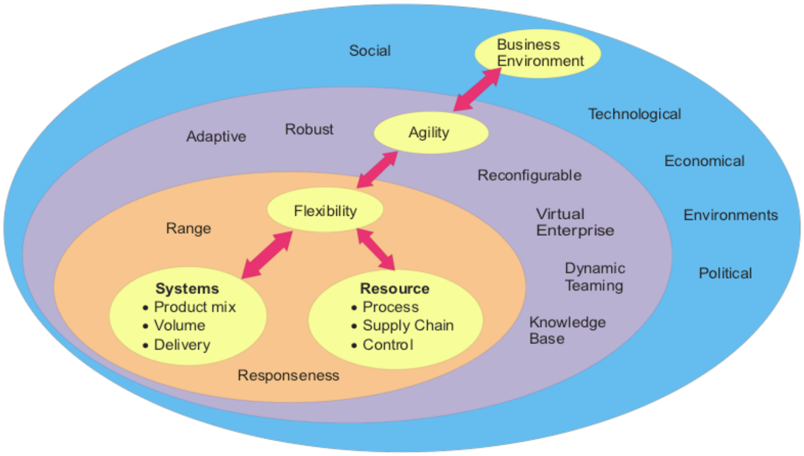

FIGURE 6: OVERALL EFFECT OF FLEXIBLE MANUFACTURING SYSTEMS (FROM HON, 2005).

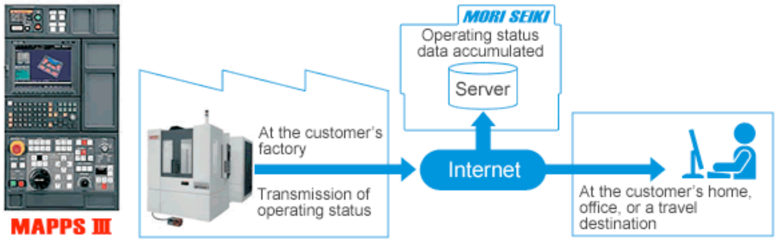

FIGURE 7: MORI-NET BY MORI SEIKI (2008).

1999). Landers et al. (2001) also concurs that integration of heterogeneous software and hardware components necessary for RMSs “will require standard software and electrical interfaces or the development of special components that interface custom devices to standard interfaces”.

Even more so than for a RMS, a FMS must be continually reconfigurable in order to meet its flexibility requirements. Furthermore, FMSs are limited by their inability to easily incorporate new hardware and software advances. While not a traditional requirement in the FMS community, integrability would offer FMSs the ability to continually expand and improve their flexibility and usefulness through the addition of new modules. So, FMS can also significantly benefit from well-defined hardware and software interfaces. To achieve these types of interfaces, standardization is required.

Because a RMS and FMS should be quickly adaptable and able to integrate new technologies efficiently, easily, and quickly, standardization is vitally important. However, there has been limited work in addressing this need. For example, RMS research has focused on systems and machine-level design or ramp-up time reduction. Initiatives for open-architecture controls also exist (OSACA and HÜMNOS in Europe, OSEC in Japan, and OMAC-TEAM in North America), but each has focused on reference architecture for vendor-neutral control systems without development of a general IT standard (Koren et al., 1999, Pritschow et al., 2001). Furthermore, RMS research has tended to view software and control interface issues to be more trivial than hardware interface issues because software and control interface issues are viewed as simply standardization problems (Koren et al., 1999). Thus, the RMS and FMS research communities have not given standardization much attention.

A significant development in interoperability is required to connect the various areas of research in the RMS and FMS communities by offering the standardized protocol necessary for components to easily interface with each other for efficient, easy, and quick reconfiguration. Interoperability would allow researchers to properly and fully integrate their work into a general RMS or FMS test bed to better be able to test their advances. Without a tool like a standardized protocol, the RMS and FMS communities may never be able to fully prove out concepts in the practical sense required for industry acceptance.

INTEROPERABILITY IN THE FACTORY

Major machine tool builders have recognized the need for better integration of their hardware. For example, Mori Seiki has developed the MORI-NET system, which allows remote monitoring of the machine tool over the internet (Figure 6). This system works with later model control hardware in their machine tools and allows users to monitor the status of the machine tools while simultaneously logging data for post processing use. Mazak has similar systems (CYBER MONITOR and CYBER TOOL MANAGEMENT) that help remotely track the status of the machine tools in a factory. While these technologies are very robustly integrated into the respective machine tool systems, they are proprietary “walled” systems. Only specific machine tools can be used with these systems, which limits their applicability. Also, since these are not extensible systems they are limited by their inherent capabilities and cannot be modified by the user community.

MTConnect does not attempt to replace these methods of interfacing machine tools. Instead it provides the basic tools necessary to “talk” to a machine tool. Value added applications (like the ones we just looked at) can then be built on the MTConnect layer. So the benefits that advanced systems, such as MORI-NET, bring to newer machine tools can be applied in older systems as well. MTConnect interacts in a similar way with existing interoperability standards used in the industry. The most significant of these are ControlNet, DeviceNet, IPC-CAMX, OPC, and STEP/STEP-NC (Vijayaraghavan, 2008). These standards take a more comprehensive and specific view of enabling communication in and between machine tools. For example, DeviceNet and ControlNet are specialized protocols defining connectivity for controls and automation applications (ODVA, 2008). MTConnect serves two important roles relative to these existing standards: it facilitates basic communication between the entities by standarizing a simple communication protocol, and it provides a lightweight alternative for simple deployments. MTConnect can similarly work in conjunction with other standards such as the NIST IEEE 1451 standard for sensors and transducers (NIST, 2008).

INTEROPERABILITY AND SUSTAINABLE MANUFACTURING

In developing sustainable or environmentally benign manufacturing processes and systems, it is important to first characterize the behavior of the system by identifying critical flows of energy and material (Dahmus, 2004). To build robust, sustainable manufacturing measurement tools, the data from various manufacturing systems need to be represented using common standards. So, interoperability standards are very important as they provide a common base upon which environmental monitoring, reporting, and calculation tools can be built. A systemic view of manufacturing is also necessary as environmental impacts from the supply chain to the actual process physics have to be taken into account (Reich-Weiser, 2008a). Interoperable systems are especially useful in developing the metrics required to characterize the system because all the data is available in the same format. This is an important benefit since computing metrics using the same data types and methodologies is critical for effectively characterizing the sustainability of a manufacturing system (Reich-Weiser, 2008b). Figure 8 identifies the flows of material and energy which need to be characterized in life-cycle analysis of manufacturing systems. The complexity of this problem, especially when comparisons need to be made across diverse systems, is reduced when data standards are adhered to.

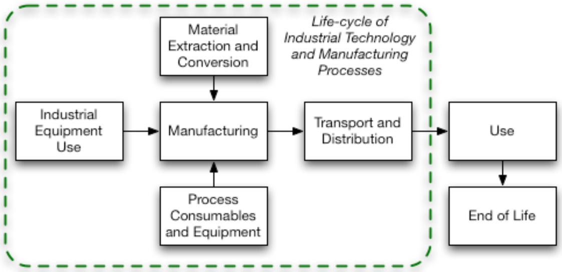

FIGURE 8: LIFE-CYCLE OF MANUFACTURING PROCESSES (FROM REICH-WEISER, 2008).

CONCLUSIONS

There is a tremendous body of research and technology in the manufacturing community that was developed over the years to address specific critical problems. These solutions often appear as islands of technology with limited impact due to the specific tool, machine, process, or system used for validating or implementing the solution. In the most basic terms, interoperability offers the possibility to fully integrate these solutions across many manufacturing platforms to finally realize computer integrated manufacturing. One such interoperability approach, MTConnect, has been discussed in this paper with respect to specific manufacturing challenges. It has shown great potential in several initial validations to bridge the gap in communications between machine tools and components.

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