*Proceedings of the 2014 Winter Simulation Conference*
*A. Tolk, S. Y. Diallo, I. O. Ryzhov, L. Yilmaz, S. Buckley, and J. A. Miller, eds.*

# VIRTUAL FACTORY REVISITED FOR MANUFACTURING DATA ANALYTICS

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## ABSTRACT

Development of an effective data analytics application for manufacturing requires testing with large sets of data. It is usually difficult for application developers to find access to real manufacturing data streams for testing new data analytics applications. Virtual factories can be developed to generate the data for selected measures in formats matching those of real factories. The vision of a virtual factory has been around for more than a couple decades. Advances in technologies for computation, communication, and integration and in associated standards have made the vision of a virtual factory within reach now. This paper discusses requirements for a virtual factory to meet the needs of manufacturing data analytics applications. A framework for the virtual factory is proposed that leverages current technology and standards to help identify the developments needed for the realization of virtual factories.

## 1 INTRODUCTION

Advances in technology have led to an explosive growth in the amount of data being created and collected across a wide range of domains. Big data has been defined as “high-volume, high-velocity and high-variety information assets that demand cost-effective, innovative forms of information processing for enhanced insight and decision making” (Gartner 2014). The manufacturing domain is one of the areas where data analytics applications are being explored to help improve the performance.

The manufacturing industry and researchers continually make efforts to improve the industry’s competitiveness with a recent focus on smart manufacturing. Smart Manufacturing has been defined as integrating “network-based data and information that comprises the real-time understanding, reasoning, design, planning and management of all aspects of the manufacturing and supply chain enterprise, i.e., manufacturing intelligence. This is achieved through pervasive, comprehensive and orchestrated use of advanced sensor-based data analytics, modeling and simulation, and integrated performance metrics constructed for real-time action” (SMLC 2012). The work reported in this paper is aimed at facilitating the realization of smart manufacturing with the use of modeling and simulation to support manufacturing data analytics.

Manufacturing data analytics can significantly benefit from the use of modeling and simulation. Simulation models of manufacturing systems can be used to support data analytics in multiple ways. They can be used to support diagnostic analytics through the use of sensitivity analysis of factors influencing the performance, predictive analytics by estimating future performance based on planned inputs, and prescriptive analytics when used in combined simulation optimization schemes to identify the input settings that lead to the goal performance. In addition, manufacturing simulation models can be used to generate data streams to support development and testing of manufacturing data applications. A virtual factory, as a high fidelity simulation of a real factory, can thus provide substantial support for development and use of manufacturing data analytics.

978-1-4799-7486-3/14/$31.00 ©2014 IEEE

The concept of virtual factory as a high-fidelity representation of a real factory has existed for at least a couple of decades and perhaps longer (Jain 1995). Its implementation is envisioned as a multi-resolution model that allows the flexibility to utilize representations of its components at varying levels of detail appropriate to the analysis of interest. The capability to build such a virtual factory should be data-driven, that is the simulation model should be automatically generated based on data describing the real factory. A couple of decades ago it would have been highly challenging to create such a data-driven multi-resolution virtual factory capability, but with the technical advancements since then, the implementation of the virtual factory vision is now within reach. The implementation of the virtual factory concept requires a well-defined framework to support the needed integration of data sources and models at different levels of resolution. Jain (1995) defined a conceptual virtual factory framework that needs to be revisited. The requirements for such a framework have changed since then and so have the relevant technologies including simulation, distributed execution and integration. The contribution of this paper is to communicate high level requirements of a virtual factory via an updated description of the concept in the context of manufacturing data analytics. Further, the paper motivates development of a virtual factory through an updated framework that identifies current analytics interfaces, technologies for simulation software and distributed simulation, and *relevant* standards.

The next section discusses *relevant* efforts reported in the literature. Section 3 discusses the virtual factory concept based on the current envisaged requirements in the context of manufacturing data analytics. The associated framework is discussed in section 4 in the context of current technologies and standards. Section 5 concludes the paper with discussion of future work to implement the virtual factory concept.

## 2 RELATED WORK

The term "virtual factory" has been used in different contexts in the literature over the past few decades. Several definitions of the virtual factory exist in the manufacturing research and application domains. Jain et al. (2001) discussed four different definitions of "virtual factory" in the literature. Interestingly, the current literature indicates that the same four definitions of the term have continued to be in use as discussed below.

### 2.1 Virtual factory - a simulation of a real factory

The virtual factory has been defined as a high fidelity simulation of a manufacturing factory. Jain et al. (2001) defined virtual factory as “an integrated simulation model of major subsystems in a factory that considers the factory as a whole and provides an advanced decision support capability.” A similar definition of virtual production is defined in VDI (2011) as "the simulated networked planning and control of production processes with the aid of digital models. It serves to optimize production systems and allows a flexible adaptation of the process design prior to prototype realization."

Many manufacturing companies have adopted the virtual factory concept and implemented it for their operations. Ford Motor Company has implemented its virtual factory systems of European facilities to improve assembly-line efficiency by previewing and optimizing systems using simulations and virtual environments (IMT 2013). Volvo Group Global (2014) has developed tools to create virtual factories to validate changes before they are introduced into an actual plant. They envision that “by 2020 all major Volvo Group plants will be virtually tested before any major changes are done in the real world. Complete production systems will be simulated with all aspects and constraints taken into account. Decision makers can run several thousands of simulations of different concepts to evaluate process flows, robots movement, and people’s risks and stress before the plant is built.” Major vendors such as Dassault Systèmes, Siemens PLM, PTC, and IBM provide commercial software solutions for product, process and system design, simulation, and visualization, as well as Product Lifecycle Management (PLM) to enable virtual factory implementation (Tolio et al. 2013).

### 2.2 Virtual factory - a virtual organization

In this usage, virtual factory is defined as linking multiple real factories at different locations in a network for manufacturing a product. This kind of virtual factory considers processes that are being executed at different locations belonging to different organizations as being carried out in a single logical factory (Schulte et al. 2013).

ADVENTURE (2011) defined virtual factory as a temporary alliance of factories from multiple organizations, managed by a distributed, integrated, computer-based system that interfaces with all systems (of the partnering organizations) necessary for the design, production, and delivery of a product.

Shamsuzzoha et al. (2014) state that the virtual factory concept has been increasingly accepted by industrial communities, especially the small and medium enterprises (SMEs). They developed a collaborative dashboard application that serves as a visualization interface for process monitoring, problem identification and solving, and performance metrics communication and sharing among participating companies of a virtual factory.

### 2.3 Virtual factory – a virtual reality representation

A virtual factory may be considered an Industrial Collaboration Environment that focuses on virtual reality representation of a factory. Back et al (2010) describes a 3D environment that is designed for simulation, visualization, communication, and collaboration using networked, real-time 3D and 2D information for the factory and its processes. Users can view real-time sensors' data on the factory floor and display it in the virtual world to perform process monitoring, virtual inspections, inventory tracking, customer tours, education, and training.

Menck et al. (2013) identify the application areas and steps for the expedient use of virtual reality as a collaboration tool to exchange and integrate information and data for factory planning. They overview the phases of factory planning that can be supported by virtual reality applications. A 3-D representation of a real factory can provide not only a 3D visualization, but also a means to allow users to access information such as design drawings, process plans, process and equipment statistics, and other manufacturing knowledge.

### 2.4 Virtual factory - an emulation facility

Emulation merges the virtual with the real world by taking advantage of advanced networked sensors and simulation modeling of the production activity in a factory. Real factory image and status data, collected using cameras and sensors, can be transmitted to and used to update the virtual representation. This helps achieve virtual-physical equivalency. Fraunhofer-Gesellschaft (2013) has introduced Industry 4.0 as a framework to enable machine, system, work piece, or tool with artificial intelligence so that they can mutually exchange information, make decisions, and interact with operators.

The purpose of emulation is to substitute part of the real system. It is also called Hardware-in-Loop simulation. The virtual factory can be controlled by real control systems and communicate with real sensors. Chalmers researchers have used an Allen Bradley PLC to control the virtual model of a machine from TetraPak. Experior Xcelgo software was used for communication between the real PLC and the virtual simulation model (Erlandsson and Rahaman 2013). Bengtsson et al. (2010) tested MTConnect, a machine tool data acquisition standard, using simulation modeling of selected Boeing machining operations for sustainability analysis. The actual production data was collected through MTConnect and modeled using discrete event simulation (DES). These research projects have contributed to the progress towards the goal of integration of the virtual and real factory.

Schilberg et al. (2013) state that simulation, gaming, and other technologies and tools allow users to create and interact with virtual models of factories. However, currently, it is still not possible to have complete, real-time control of a physical plant via virtual representation. One of the major challenges is that the running times of individual simulations do not completely meet the real-time requirements. The run times are rapidly going down with advances in computing technologies and real-time control through virtual representation may soon become a reality.

## 3 VIRTUAL FACTORY CONCEPT

While this paper defines the concept of a virtual factory as a high-fidelity digital representation of a real or proposed factory, we focus only on the context of representing a real factory's operations as required to support manufacturing data analytics. Our virtual factory can thus serve in place of a real factory to support development of manufacturing data analytics applications. Even when access is available to real factory data, the corresponding virtual factory affords the ability to run experiments with results used for analytics. This section presents the virtual factory concept in more detail. The concept has been updated from the vision presented in Jain et al. (2001).

The scope of the effort reported in this paper is focused specifically on the discrete manufacturing industry. Depending on the objective of the analysis, a virtual factory should allow modeling phenomena typically analyzed in discrete manufacturing including production throughput at the factory level and operations of equipment at the work cell level. It should also be able to represent auxiliary processes that impact manufacturing performance such as maintenance processes, product engineering and manufacturing processes, and relevant business processes including order fulfilment, supply chain management, and change order management.

The virtual factory should be capable of generating data at various levels of resolution that in turn can be used to test and assess various manufacturing data analytics applications. In general, high resolution models, that is, models that include fine-grained detail will generate large volumes of data with high velocity and variety. A multi-resolution modeling capability may be implemented by including a set of component models that allow modeling at the various desired levels of resolution. In addition, it should accommodate component models that use different modeling paradigms; for example, continuous simulation for the physical-sciences-based representation of machining processes, and discrete event simulation for representing the factory throughput. The model outputs will, of course, need to be validated against the real factory outputs to ensure that the models correctly represent the real factory.

The flexibility to model at different levels of resolution may be exercised in two ways depending on the objectives of the analysis. A model may be composed using component models at a homogenous level of resolution or at multiple resolution levels. In addition, the entire factory or a subset may be modeled similar to the ability offered by a real factory to study a part of a system or the entire system. The analysis of failures in a work cell may require selecting the corresponding cell model composed of equipment models, all at a homogeneous high level of resolution. The analysis of production output variations on a line may require multi-resolution modeling that includes the particular line modeled at a high resolution with all its individual stations represented, while the other parts of the factory that have interactions with the particular line may be modeled at lower levels of resolution. This may be implemented using an overall low resolution factory level model and replacing the low resolution model of the line of interest with a set of connected high resolution station level models. The low resolution models for the rest of the plant will determine the rate at which parts arrive at different stations of the line of interest and the availability of common resources such as material handling. The detailed station level models in the line of interest can then generate the performance data over long periods of time based on the production scenario. Such a model provides higher accuracy in representing the line operations compared to standalone line level models that make assumptions about aspects such as part arrival rates and resource availability.

Our virtual factory would generate the performance metrics and output data streams at various levels of resolution in the same formats as real factories. This capability will be challenging to implement since the metrics used and output data stream format will vary among factories and even among equipment within a factory. The virtual factory should allow for capturing metrics called for in standards and current initiatives being implemented by the user organization. For example, it should allow generating metrics focusing on asset utilization, agility, and sustainability advocated by the smart manufacturing initiative (SMLC 2012) if that is being implemented in the real factory being modeled. It should also allow easy customization of metrics and data generation formats to meet the needs of different users.

The virtual factory capability should be data-driven to the extent possible to allow a large number of users to benefit. Similar to the output data generation discussed above, standard formats for configuration and input data should be used where possible. For example, the Core Manufacturing Simulation Data (CMSD) (SISO 2012) may be used for reading the configuration data for a factory.

Figure 1 enhances the concept of the virtual factory from Jain et al. (2001) with the envisaged interfaces and the flexibilities in resolution and scope. The original concept in the center of the figure shows the ability to model sub-systems of manufacturing in an integrated manner at different resolution levels. The hierarchy shown in the figure is in general agreement with the physical hierarchy presented in IEC 62264-3 standard (IEC 2007) though factory specific terms are used here. It is apparent that developing the virtual factory as conceptualized is a non-trivial task and may take a large amount of effort of highly skilled simulation experts. The effort to develop the virtual factory capability can be more efficient if they can be composed from existing or independently developed component models. The next section discusses the concept of a framework that facilitates the development and use of the virtual factory.

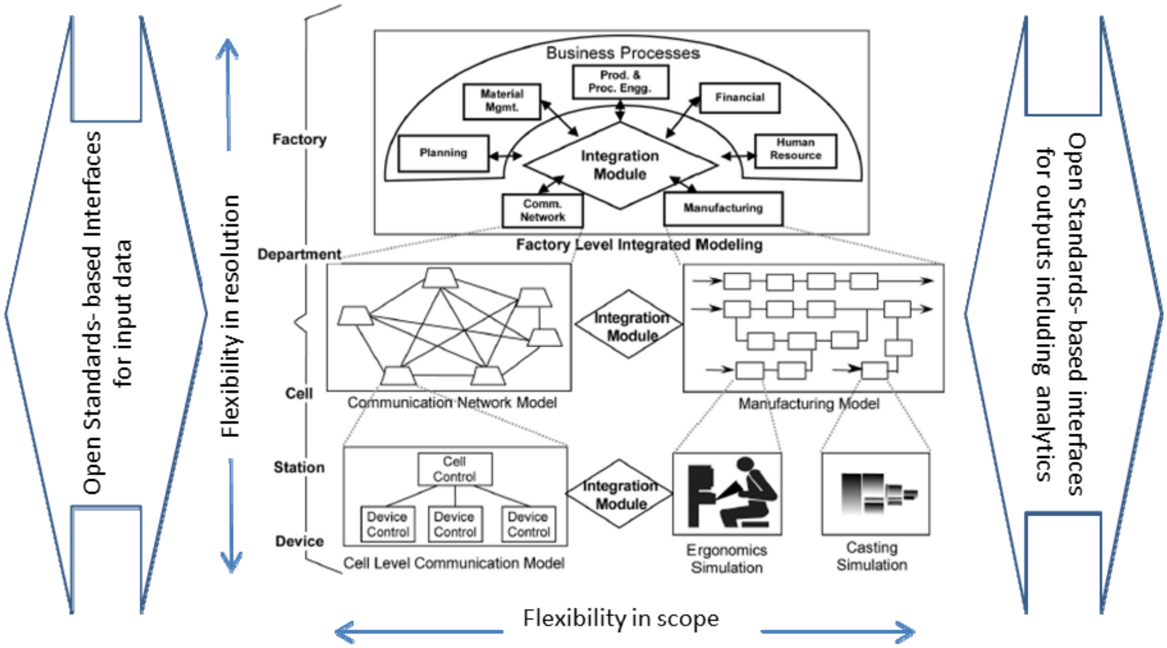

Figure 1: Virtual Factory concept (adapted from Jain et al. 2001).

## 4 VIRTUAL FACTORY FRAMEWORK

Implementing the virtual factory concept to its fullest potential requires a structured approach that allows integration of contributions from multiple researchers and developers. A high level concept for the virtual factory framework (ViFF) was defined almost two decades ago by Jain (1995). The computing technologies have improved tremendously since then and have made execution of large and complex simulations possible within reasonable timeframes. This section presents an updated concept for ViFF and discusses current developments, beyond hardware technologies, that have made the implementation feasible.

### 4.1 Framework conceptual description

The ViFF is proposed as a simple structure that guides scoping of component models and interfaces needed to integrate them into a virtual factory. The focus is on utilizing as many available and under development technologies and standards that facilitate such integration. The component models should be plug and play compatible, capable of being "plugged together," that is, easily integrated to obtain more complex models. The principles for smart manufacturing architecture (SMLC 2012) include the use of open standards that leverage existing capabilities and encourage participation for development of new capabilities. These same principles have guided the enhancement of the ViFF concept and the implementation will utilize interfaces and technologies identified in the SMLC architecture as far as possible.

The ViFF can be realized through the development of component models that have plug and play compatibility to other component models, allowing easy integration to represent parts or all of a real factory. Figure 2 presents the concept of a component model of the framework. The component model should be able to support any of the simulations shown in Figure 1, including simulation of a specific manufacturing process (e.g., casting) at high resolution to an entire factory at low resolution. The component model in Figure 2 is represented as the level n model in the middle. The model itself may be comprised of multiple objects with defined interactions. The objects may be connected to represent a process flow typical of discrete event simulation paradigm, or they may interact to represent a physical phenomenon. The flows between the objects hence may be single or multi-directional as shown in Figure 2.

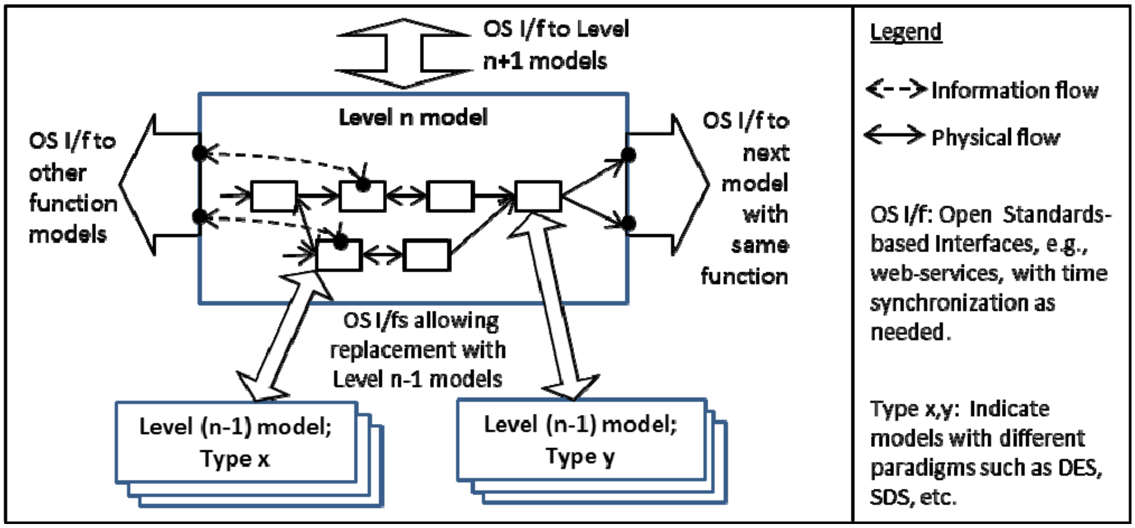

Figure 2: A generic model for a component of the Virtual Factory Framework.

A component of the framework should have interfaces that allow its integration in both horizontal and vertical dimensions of levels of resolution. Building these interfaces is non-trivial but anticipated to become easier with development and acceptance of standards for the purpose. An integration across different levels of resolution is identified in the vertical dimension. A model should allow replacing any object within itself with another component model with a higher resolution representation. For example, the manufacturing model shown in the middle layer in Figure 1 should be capable of replacing the object representing the casting process with the high resolution model of the casting process shown in the lower layer. This idea is presented in Figure 2 via the interfaces shown between the level n model and component models at level (n-1). The component models at the higher resolution level may be of different types, that is, they may use different paradigms such as DES, System Dynamics Simulation (SDS), or Agent Based Simulation (ABS). A model should be able to become a component of a lower resolution model as represented in Figure 2 via the interface block arrow on the top from level n model to level (n+1) model. Such integration would involve summarization of detailed characteristics, such as operation times on individual machines, to representative abstractions such as processing rates per month for the line.

Any model should also be able to integrate with other models in the horizontal dimension, that is, with a model of another function at the same level of resolution. For example, a model of manufacturing line may be integrated with a logistics model that represents arrival of shipments of parts and subassemblies brought directly to specific stations on the line. This may require integration between specific objects of one model to those of another model. Such an integration is represented in Figure 2 via the interface on the left side of the level n model. Another type of horizontal integration is when outputs of one model are passed on as inputs to the next model, such as, representation of manufactured parts from one line being sent to the next line for further processing. This kind of integration of output of one model as input of next model is represented in Figure 2 via the interface on the right side of the level n model.

It is recognized that the component models should be composable, that is, they should have a consistent representation of the real system. The understanding of the composability requirements has also increased rapidly in recent years. Tolk (2013) discusses the implications of composability for distributed simulations.

Development of generic components following the above framework will facilitate implementing virtual factories. The entire virtual factory model should itself have open standards-based interfaces as shown in Figure 2. The candidate standards for such interfaces are discussed in Section 4.5. While the current focus in on representing factories, the plug and play compatibility of the factory models can be used to develop virtual representations of entire supply chains.

## 4.2 Analytics interfaces

The ViFF should provide for interfaces that can be integrated with manufacturing data analytics applications. The interfaces described in Figure 2 above are anticipated to meet the needs of such applications. The proposed interfaces should allow collection of data from individual objects or the overall component model. This is similar to the ability to collect data from individual machines or the entire line in a real factory. For example, a physical-sciences based machine simulation should allow generation of data streams for temperatures and vibration from simulated sensors on different machine components that may be represented as individual objects. Similarly, data streams for production events should be generated from the machine model. The horizontal interfaces identified in Figure 2 are defined to meet the needs of a data analytics application in addition to the horizontal integration discussed in Section 4.1.

The analytics interfaces should generate data in formats and at frequencies used in the industry. This will allow the virtual factory to mimic the generation of input data streams from a real factory. Such data streams can be used for evaluation of manufacturing data analytics applications. Data formats used in industry will be largely dependent on the resolution level and the corresponding commercial application software used. For example, plant floor execution data formats are generally set up based on the Manufacturing Execution System (MES) software used. The virtual factory capability should allow generating data using formal standards; for example, ISA95 standard (ANSI 2010) across multiple manufacturing levels and MTConnect (AMT 2013) for machine level data.

## 4.3 Simulation software technology

The concept of a plug and play compatible generic component model utilizes object-oriented programming. Few object-oriented simulation software applications were available a couple of decades ago when Jain (1995) proposed the ViFF concept. Simple++ was one of the first object-oriented simulation software that appeared just before the end of the millennium and was used by Jain et al. (2001) for implementing a prototype of the virtual factory concept. The software could have allowed implementation of virtual factories as long as all levels of resolution could be represented in the discrete event paradigm and custom interfaces were built to read the input data as there were no formal standards for such data. The effort to develop virtual factories therefore was quite demanding and hence, received limited interest.

Simulation software technology, both commercial and open source, has developed rapidly over the last decade. Some of the currently available commercial software offer object based development environments, the ability to integrate model components, and representation of multiple paradigms in the same model. Such software allow developing virtual factory models that include components using different modeling paradigms. Jain et al. (2013) used a commercial simulation software to develop a low resolution SDS model of a supply chain with the capability of replacing a node with a higher resolution DES model of a factory. While current simulation software allows integration of components within the same executable file, integration among separate models (in separate executable files) developed using the same software or with models developed in different software requires the use of distributed simulation technology discussed in the next subsection.

## 4.4 Distributed simulation technology

A decade or so ago integration of simulation models in different executable files required the use of the run-time infrastructure (RTI) of the High Level Architecture (HLA) (Kuhl et al. 1999) with significant expertise and effort. A few efforts have attempted to reduce the effort to set up distributed simulations. A distributed manufacturing adapter was developed to reduce the effort required for implementing distributed simulation for manufacturing scenarios (McLean et al. 2005). Jain et al. (2007) used the adapter to integrate a supply chain simulation model in one software with a manufacturing plant model developed using another software for a synchronized distributed execution. While the adapter was an improvement over the full scale HLA at the time, better options have become available since then.

In recent years, web services technology has been used to coordinate distributed simulation (Yoo et al. 2009). The HLA itself has evolved as defined in the updated IEEE HLA-1516 2010 standard and includes support for web services (IEEE 2010). Another standard has been developed to facilitate identification of interoperability problems between commercial-off-the-shelf simulation packages and assessing candidate solutions (SISO 2010). Wang et al. (2013) proposed a service-distributed run time infrastructure that deploys the RTI simulation services on the Internet and provided test results to show that it does not suffer from the deficiencies of HLA/RTI. Overall, recent developments have made the implementation of distributed simulation significantly easier than it used to be a decade ago. In the interest of open implementation, a web services based distributed simulation approach may be selected for ViFF implementation.

## 4.5 Data interface standards

The ViFF interfaces have to support the generation of data that real factories provide for production and business systems. A major challenge, of course, is that there are a wide range of formats used for such data streams in practice. The situation has improved over the past two decades with the development of standards for some of these interfaces. In this subsection, relevant data interface standards for data streams where available are identified. These standards will be candidates for the open-standards-based interfaces shown earlier in Figures 1 and 2.

Enterprise Resource Planning (ERP) systems deal with business and customers, and MES systems deal with manufacturing and production. However, usually these systems are developed by different vendors using proprietary technologies. Users of these systems have to spend time or money to re-enter the same data multiple times or customize the interfaces between these systems. GE Intelligent Platforms (2014) discusses the benefits of enabling real-time bi-directional integration between the ERP and MES systems to optimize plant operations using ISA-95 and B2MML (Business to Manufacturing Markup Language) standards to communicate valuable information between the two systems. These and other relevant standards are briefly discussed below ranging from factory level to machine level applicability.

- The Open Applications Group Integration Specification (OAGIS) is an open standards based, cross industry canonical model for information integration that is applicable for factory-to-factory interfaces. OAGIS uses eXtensible Markup Language (XML) for defining business messages and identifying business processes (called scenarios) that allow application-to-application and business-to-business integration (Connelly and Hertlein 2010).
- Core Manufacturing Simulation Data (CMSD) is a standard to help achieve simulation applications interoperability (SISO 2012). CMSD was initiated by NIST researchers and standardized in collaboration with industrial partners through the Simulation Interoperability Standards Organization (SISO) to provide neutral data interfaces for manufacturing applications and simulation. CMSD allows information exchange in a shop floor simulation environment between various manufacturing applications, such as DES, ERP, Master Production Schedule, and MES. Therefore, the same data structures can be used for managing actual production operations and simulating the machine shop. The rationale was that if one structure can serve both purposes, the need for translation and abstraction of the real data would be minimized when simulations are constructed. The CMSD model has been tested in a few case studies. For example, the same set of model input data described using CMSD has been used by two different DES software applications to create models (Johansson et al. 2007).
- International Society for Automation (ISA) coordinated the development of ISA-95 as an international standard for the integration of enterprise and control systems. ISA-95 consists of models and terminology, which can be used to determine what information needs to be exchanged between manufacturing systems (ISA 2014). This information is structured in UML models, which are the basis for the development of standard interfaces between ERP and MES systems. Features of the international standard ISA-95 include (1) models and terminology that are technology and vendor independent, (2) definition of the information that must be exchanged between the ERP and MES layers, and (3) broad support of many companies.
- Business To Manufacturing Markup Language (B2MML) is a set of XML schemas that implement the data models in the ISA-95 standard. B2MML makes it easier for businesses to integrate with their MES solutions regardless of which vendor provided their ERP system modules. It ensures that the data can be processed and enables communication across the business.
- MTConnect (with “MT” apparently referring to Machine Tools) is a middleware standard that enables the data extraction from numerically controlled machine tools using the XML standard (AMT 2013). MTConnect provides a mechanism for system monitoring and process optimization with respect to energy and resources. The information is valuable for analyzing sustainability performance of processes and facilities (Vijayaraghavan et al. 2008). Bengtsson et al. (2010) developed a case study using MTConnect to acquire Boeing production data for modeling of sustainable machining.

Discrete product manufacturers who need to integrate their factory floor with ERP, supply chain, scheduling, quality, and other systems have several other standards to consider (Fraser and Gifford 2013). These standards will be explored in the future for inclusion in ViFF at the appropriate levels.

## 5 CONCLUSIONS AND FUTURE WORK

The need for virtual factory capabilities, as defined in this paper, has been reconfirmed with the push towards smart manufacturing and the associated need to gather intelligence using manufacturing data analytics applications. A virtual factory can serve as an analytics application itself, and it can also serve as a data generator for evaluation of other manufacturing data analytics applications.

The ability to develop a virtual factory has gained from developments on several fronts over the last two decades. This paper updates the vision of virtual factory and the associated framework from those developed multiple years ago in view of the relevant developments. A plug and play compatible component model concept is described as a building block for the virtual factory framework. Current available technologies and standards have been reviewed and will be further analyzed to select a subset for use in a concept demonstration prototype.

For the initial development of the virtual factory we will use a hypothetical dataset that combines knowledge from past factory modeling projects. The virtual factory concept will then be verified using data from one of our industrial partners. The virtual factory will continue to be useful for preparing for a wide range of scenarios.

## DISCLAIMER

No approval or endorsement of any commercial product by NIST is intended or implied. Certain commercial software systems are identified in this paper to facilitate understanding. Such identification does not imply that these software systems are necessarily the best available for the purpose.

## ACKNOWLEDGMENT

Sanjay Jain's work on this effort has been sponsored under the cooperative agreement 70NANB13H158 between NIST and George Washington University. The work described was funded by the United States Government and is not subject to copyright.

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