Interoperability for virtual manufacturing systems

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Abstract: As manufacturing systems are often costly to develop and operate, simulation technology has been demonstrated to be an effective tool for improving manufacturing system design and the efficiency of manufacturing operations and maintenance. However, effectively and efficiently using simulation remains an important issue in the manufacturing industry. One of the principal reasons is the difficulty in processing, organising, and making use of the production-related information about the manufacturing system to be simulated. The difficulty stemmed from no standard representation for such data, making the effort to input data such as product attributes, processing times, and material quantity requirements into simulations complex, time consuming, and error prone. The core manufacturing simulation data (CMSD) standards, SISO-STD-008-2010 and SISO-STD-008-01-2012, specifically address this data representation issue. CMSD enables the import/export of many different types of factory data into computer simulations and other manufacturing systems. This paper describes the motivation for creating CMSD, standardisation efforts for CMSD, and related research efforts. This paper also describes how CMSD could be used as an integration mechanism in a sustainable manufacturing test-bed being developed at the National Institute of Standards and Technology. The test-bed will be a virtual manufacturing environment to support the testing and validation of sustainability metrics, assessment methods, and tools for use in manufacturing.

Keywords: core manufacturing simulation data; CMSD; interoperability; manufacturing test-bed; simulation; standard; sustainable manufacturing; systems integration; virtual manufacturing.

Reference to this paper should be made as follows: Lee, Y-T.T., Lee, J.Y., Riddick, F., Libes, D. and Kibira, D. (2013) 'Interoperability for virtual manufacturing systems', *Int. J. Internet Manufacturing and Services*, Vol. 3, No. 2, pp.99–120.

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1 Introduction

Manufacturing systems tend to be complex and expensive to construct and operate. Simulation has been found to be a useful and powerful tool for designing and analysing manufacturing systems (Law and Kelton, 2000). Computer simulation models can be developed to predict the likely performance of complex systems, including manufacturing systems. Manufacturing simulation models using discrete-event simulation (DES) have been built to support aspects of manufacturing such as manufacturing system design, manufacturing system operation, production capability evaluation, and new technology investment.

A significant impediment to the more widespread use of simulation for the analysis of manufacturing systems is the effort necessary to develop simulations. Another impediment is the ability to perform simulation analysis using data gathered from real systems. The costs of developing and using simulation applications are high, and the costs of integrating simulation systems with other manufacturing applications are even higher (Johansson et al., 2007).

The ability to transfer and share data between simulations and other manufacturing applications is crucial for enabling the broader use of simulation analysis. Simulation technology has evolved over time to a point where standardisation efforts to support it are feasible (Banks et al., 2005). Standard data interfaces, among simulation modules or between simulation and other software applications, could make information sharing effective and efficient, and hence promote their wider use.

Based on earlier research (Lee et al., 2003) to define neutral structures to improve the interoperability of simulation systems and other manufacturing systems, an effort was started to standardise data in this arena. In 2004, the Simulation Interoperability Standards Organization (SISO)[1] established a product development group (PDG) to develop standard representations for manufacturing simulation data to support the efficient exchange of manufacturing life cycle data in a simulation environment (SISO, 2012). The primary goal was to develop a core manufacturing simulation data (CMSD) information model that defines neutral representations for common manufacturing entities and enables the integration of manufacturing software applications and simulation systems. The word 'core' in CMSD means that CMSD is intended to cover data related to the most common manufacturing entities associated with shop floor production and not all of the manufacturing domains. Using CMSD can reduce the effort necessary to create integrated simulation applications, thus reducing the time and cost to create such applications (Skoogh et al., 2012).

This paper describes CMSD, its supporting tools, and its applications. The organisation of this paper is as follows. In Section 2, a CMSD overview is presented. Topics include the motivation for developing CMSD, the CMSD concept, and a unique feature of CMSD. In Section 3, the standardisation of CMSD is discussed. Section 4 discusses several CMSD-related research efforts described in the literature. Section 5 describes several tools developed to support CMSD. A test-bed for sustainable manufacturing (SM) initiated by National Institute of Standards and Technology (NIST) and CMSD's role in the test-bed are described in Section 6. Section 7 presents a summary of the information about CMSD described in this paper.

2 CMSD overview

CMSD was designed to address integration issues associated with DES applications and manufacturing applications. Applications generally associated with manufacturing operations include process planning, scheduling, inventory management, and production management. It defines a neutral structure for the efficient exchange of manufacturing data in a simulation environment. The neutral structure can be used to support the integration of simulation software with other manufacturing applications.

2.1 Motivation for developing CMSD

The CMSD specification addresses issues related to information management, data exchange, and manufacturing simulation application development. CMSD provides a neutral framework that facilitates creating collections of related manufacturing data that may be used to create or enhance manufacturing simulations and other manufacturing applications. Some of the motivations for developing CMSD include:

- Improving the accessibility of simulation technology in the manufacturing industry by enabling the sharing and re-use of model data.
- Improving interoperability between manufacturing applications and simulations. Currently, integration opportunities in this arena are extremely limited.
- Providing a standard data exchange representation for manufacturing simulators and other manufacturing applications. Individual companies, simulation vendors, equipment and resource manufacturers, consultants, and service providers could use this neutral representation to develop sharable models.
- Facilitating better manufacturing software testing and evaluation.

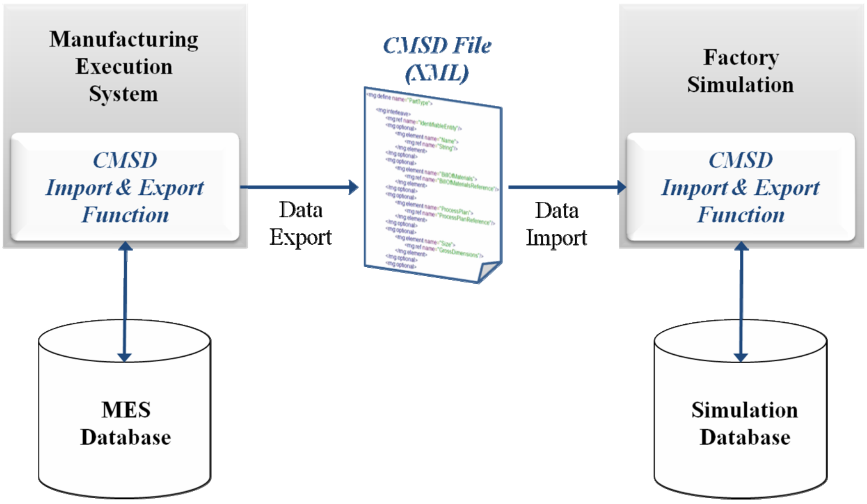
Before CMSD, there were no neutral data formats for storing manufacturing data for simulation models. CMSD's neutral structure represents the concepts, relationships, constraints, and rules that define the data semantics for the core or common information entities in the manufacturing simulation domain. The advantage of using a neutral structure is that it can enable the creation of organised, self-consistent collections of information that can be reused by different applications without regard to proprietary license or intellectual property issues. CMSD facilitates the integration and exchange of information for different manufacturing data sources. Without such integration mechanisms, simulation technology will remain too costly, particularly for small manufacturers.

2.2 The CMSD concept

Figure 1 illustrates the CMSD concept through a scenario of data transfer between a manufacturing application and a simulation. In the scenario, a manufacturing execution system (MES) has information about a factory's machine resources, products, and process plans. It also contains orders for the creation of specific quantities of products. To evaluate the efficiency of a factory's operations, a simulation of the factory could be built to analyse the best way to produce the correct mix and quantities of products requested by the provided orders.

Usually, once a simulation such as this is built it is very difficult to modify it to analyse ongoing operations using different collections of orders that call for the production of different kinds of parts in different quantities. Using CMSD, a simulation can be constructed in such a way that it can be used, without altering the simulation code, to evaluate different sets of orders calling for different collections of products to be produced. If the MES is modified to export data according to CMSD and the simulation is constructed or modified to take CMSD data as input, an integrated application is created that now can be used to evaluate ongoing operations. And this can be accomplished without knowledge of or modification to either application's proprietary internal format for storing data.

Figure 1 The CMSD concept (see online version for colours)



2.3 A unique feature of CMSD

Currently, several standards exist that cover manufacturing data related to production operations such as ISA-95 (2012) and Open Applications Group Integration Specification (OAGi) (2012). CMSD and these standards all offer some interoperability solutions for data exchange between manufacturing tools. Lee et al. (2011) examined and compared these three standards. Some of the results of this comparison are:

- CMSD is designed to support job shop manufacturing, but does not directly support flow shop manufacturing. ISA-95 and OAGIS focus on flow shop or continuous process manufacturing, but they claim to also support flow shop manufacturing.
- ISA-95 defines a framework, including a common terminology, abstract models and transactions, for enterprise-control system integration. The emphasis is on good practices for integrating manufacturing systems with other enterprise systems. The data models provided are in unified modelling language (UML) (OMG, 2012).
- OAGIS defines business messages and identifies business process scenarios that allow business applications to communicate. The OAGIS framework includes enterprise, commerce, and manufacturing functionality with emphasis on business process interoperability.
- OAGIS and ISA-95 often allow users to define attributes of the objects or entities as needed. This flexible approach makes it hard to develop software tools to interpret the data.
- CMSD provides the ability to define characteristics of manufacturing entities that are governed by stochastic processes. This ability allows statistical distribution

information to be defined and associated with different properties of manufacturing entities.

- CMSD is free to the general public. The ISA-95 specification is free to ISA members, but it requires a royalty payment from non-members. OAGIS offers free specification downloads after registration, which is also free.

Since CMSD provides a means to specify information about the stochastic characteristics of manufacturing processes using probability distributions, this feature sets CMSD apart from other existing manufacturing data standards. The unique feature enables distribution information to be used in and exchanged between discrete event and other types of simulations of manufacturing operations. This feature has been critical in enabling the development of applications that involve integration using several different DES technologies.

3 CMSD standardisation efforts

CMSD has been standardised under the auspices of SISO according to their guidelines documented in 'Balloted products development and support process' (SISO, 2011). CMSD defines an information model that is presented using two different methods:

1 UML

2 schema languages for eXtensible Markup Language (XML) (W3C, 2012a) representation.

UML and the XML approaches provide representations of the same information model; in fact, the CMSD-XML is mapped from the CMSD-UML.

In 2010, SISO published the CMSD-UML model standard as SISO-STD-008-2010 or CMSD Part 1 (SISO, 2010). In January 2013, the information model defined using XML, named SISO-STD-008-01-2012 or CMSD Part 2 (SISO, 2013), was also approved by SISO.

3.1 CMSD-UML model

Many manufacturing concepts are represented in CMSD such as the concepts of a part, resource, process, order, and job. In CMSD, these concepts are referred to as CMSD entities. UML classes are used to realise the meaning of the concepts represented by a CMSD entity and the characteristics associated with the CMSD entity are modelled as UML class attributes. Thus the CMSD-UML model (SISO-STD-008-2010) contains a suite of interrelated collections of information modelled as UML classes. The entities defined in the CMSD information model represent a core set of the data entities related to manufacturing simulation and their interrelationships.

The major CMSD entities and their definitions are presented as below:

- *Bill of materials*: A description of the hierarchical relationships between a part and its subcomponents.

- *Calendar*: A long term focused collection of shift and holiday information that, taken together, specify the time periods during which production is and is not expected to take place.
- *Distribution*: The name and parameter values that define a statistical distribution. A statistical distribution is a mathematical function where:
  1. the range of possible values of the function is known
  2. the probability that a random input to the domain of the function will produce an output value in a subset of the range is also known.
- *Inventory*: A part or (non-employee) resource for which information about its availability for production activities is tracked.
- *Job*: A request for production-related activities to take place, originating from a person or organisation internal to the manufacturing enterprise.
- *Layout*: A representation of the spatially-relevant characteristics of, and relationships between, the manufacturing resources that are a part of a manufacturing facility.
- *Order*: A request for products or services originating from a person or organisation external to the manufacturing enterprise.
- *Part*: A raw material or sub-component used in or produced by some stage of production, or an end product that is the final objective of production. (Note that CMSD does not cover product design or geometric information.)
- *Process plan*: A collection of processes that provide the necessary instructions for producing a part.
- *Resource*: A piece of equipment or an employee that is performing or is to perform a manufacturing activity.
- *Schedule*: A plan containing a time-ordered collection of production activities, and/or the results obtained by carrying out such a plan.

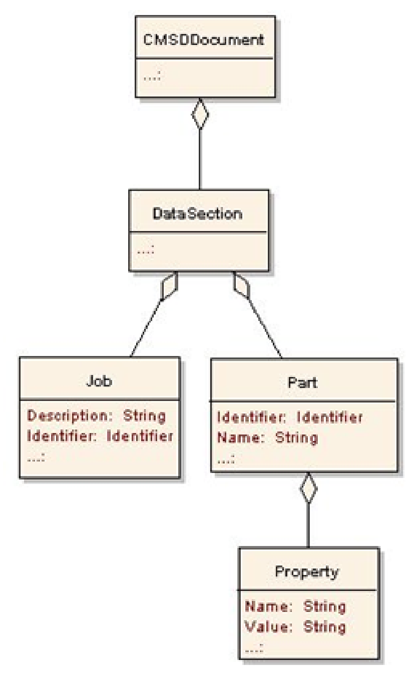
3.2 CMSD-XML representation

The CMSD-XML representation (SISO-STD-008-01-2012) is derived from the CMSD-UML model (SISO-STD-008-2010). Although UML, a graphical model language, was used to define and provide visualisation for the CMSD information model, UML was not suitable for creating instances of information that adhered to the CMSD information model that could be easily manipulated by or exchanged between many software applications. The objective of the CMSD-XML representation is to define the structure and content for XML documents that adhere to the rules and constraints defined in the CMSD-UML model. With the CMSD-XML representation, an XML instance document can be validated, thereby showing that it adheres to the structure, content, and constraints defined by the CMSD-UML model.

To ensure that the XML adheres to all of the rules and constraints defined in the CMSD-UML model, multiple schema languages are used to define the CMSD-XML representation. The two languages are REgular LAnguage for XML Next Generation (RELAX NG) (RELAXNG, 2012) and Schematron (2012). This two-language approach was taken because no existing schema language for XML could support all of the complex interrelationships between the entities defined by the CMSD-UML model. RELAX NG is a grammar-based XML schema language; it is the primary schema language for defining the XML representation of CMSD. Schematron is a rule-based XML schema language designed to allow multiple, well-focused XML validation languages to work together. This ability allows Schematron to be used in concert with RELAX NG to define the content or structural constraints specified in the CMSD-UML model in a way that could not be accomplished by using Relax NG alone.

Figure 2 provides an example of a CMSD document (SISO, 2013). It shows how a CMSD document is defined in UML and how that information should be realised in XML. On the left side of the figure, simplified versions of several classes that make up the CMSD-UML model are presented in a UML class diagram. Some of the attributes for and the aggregation relationships between those classes are presented. The right side of the figure shows how the same CMSD document information would be represented in XML.

Figure 2 (a) Example CMSD-UML (b) XML mapping (see online version for colours)




```
<CMSDDocument>

    <DataSection>

      <Job>
          <Identifier>111_abc</Identifier>
          <Description>
              A job to make the part widget1
          </Description>
          ...
      </Job>

      <Part>
          <Identifier>widget1_abc123</Identifier>
          <Name>Widget1 Computer part</Name>
          <Property>
              <Name>ModelName</Name>
              <Value>Widget1_abc123</Value>
              ...
          </Property>
          ...
      </Part>
      ...
    </DataSection>
    ...
</CMSDDocument>
```

(a) (b)

Source: SISO (2013)

3.3 CMSD model validation

The content of CMSD and its feasibility for use as a data exchange and application integration mechanism was validated through CMSD's use in prototype applications. These applications were developed through collaborations with several industrial and academic users (Bengtsson, et al., 2009; Lee et al., 2011). The prototypes were used to provide evidence that CMSD was mature enough to warrant standardisation. Prototype development based on CMSD was undertaken to ensure that the information model is sufficiently detailed to fully describe the data needs of simulation applications. For example, a pilot implementation was performed under the Swedish research project, '*Factory analyses in conceptual phases using simulation*'. Its purpose was to represent a detailed virtual model, including reusable objects and generic solutions, of a paint shop at a Volvo Car Corporation plant in Sweden (Johansson et al., 2007). The model was created using the enterprise dynamics (Incontrol Simulation Solutions, 2012) DES tool. In this study, CMSD was used to enable data collection of resources and work processes in the conceptual stages of production development programmes. As a result, some discrepancies between CMSD data and enterprise dynamics input data were identified. One discrepancy was that the draft version of CMSD, upon which this prototype is based, did not directly support material handling equipment, such as conveyors and elevators. Also, that version of CMSD included mean-time-between-failure and mean-time-to-repair as attributes for *resource* definition, but not mean-time-to-failure and mean-down-time. The SISO CMSD PDG resolved the issue in the final version of CMSD by introducing a class called *property* to represent user-defined attributes in many CMSD classes, such as those for *resource* definition.

4 Applications using CMSD

Section 3 described several prototype applications using CMSD integration and information exchange that were developed in collaboration with industrial and academic partners to support the CMSD standardisation effort. A literature review showed that in recent years many organisations have applied CMSD, both in draft and in final form, in various application domains where simulation has been involved. The application domains where CMSD has been applied include:

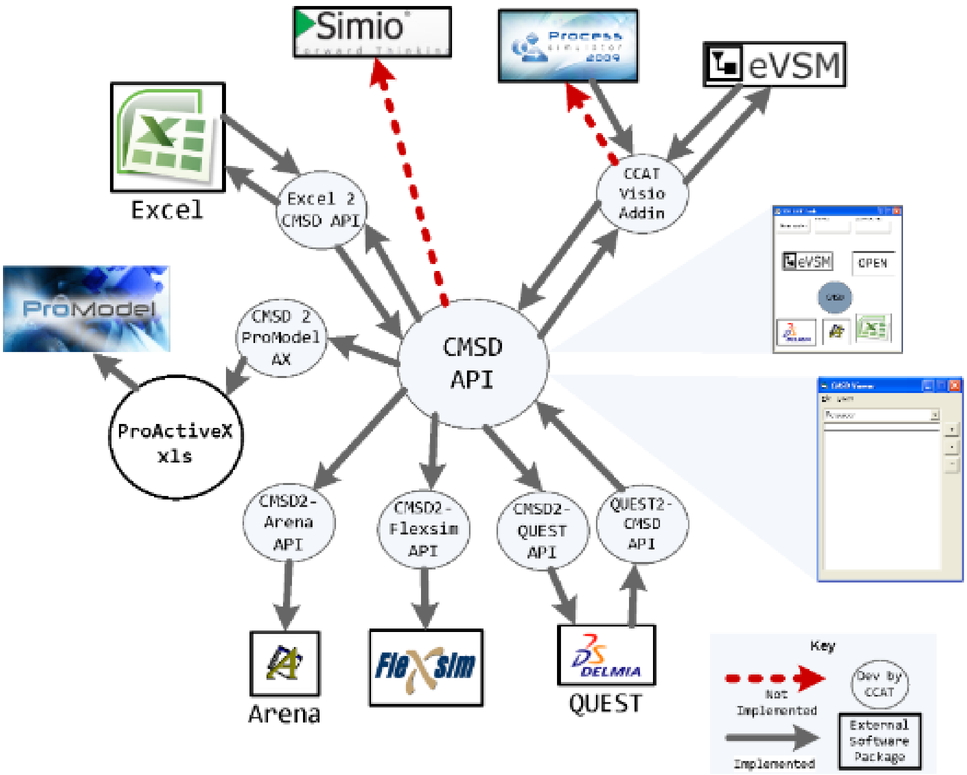
- design and planning (Bloomfield et al., 2012; Harari, 2012; Johansson et al., 2009)
- production engineering (Bloomfield et al., 2012; Lu et al., 2008)
- supply chain (Jain et al., 2007)
- SM (Andersson et al., 2012; Heilala et al., 2008; Johansson et al., 2009; Johansson, 2010; Lind et al., 2008a; Lindskog et al., 2011; Michaloski et al., 2012;)
- construction (Mohamed and Yousef, 2012).

Many different commercial simulation systems were involved in these efforts, including ExtendSim V8 (Harari, 2012; Imagine That Inc., 2012), 3DCreate (Lind et al., 2008b; Visual Components, 2012), Plant Simulation (Bergmann et al., 2010; Siemens, 2012), Enterprise Dynamics (Skoogh et al., 2012), Arena (Boulonne et al., 2010; Rockwell

Automation, 2012) and QUeuing Event Simulation Tool (QUEST) (Dassault Systemes Simulation Software, 2012; Jain et al., 2007) to improve interoperability in terms of the representation of manufacturing simulation data.

Some research efforts have focused on the development of CMSD support methodologies or tools (Bergmann et al., 2011; Boulonne et al., 2010; Fournier, 2011; Johansson et al., 2009; Lind et al., 2009; Skoogh et al., 2012). The following subsections highlight three of these projects.

Figure 3 Interoperability between CMSD and heterogeneous simulation tools (see online version for colours)



Source: CCAT (2012)

4.1 Special-purpose CMSD programming toolkit

The Connecticut Center for Advanced Technology (CCAT) has developed a set of tools for authoring CMSD data files and converting them to forms that can be input into applications created using different DES packages. Their main tool is called the CMSD application programming interface (API). It is used to hold information organised according to the CMSD standard in memory and provide callable functions to effect the exchange of that information between applications (Fournier, 2011). This CMSD API development effort has been focused on supporting value stream map (VSM) related applications. A VSM normally consists of a series of process boxes, connected together in some sequence and holding various process attributes. CCAT created tools to extract simulation data from a VSM created in eVSM, a software used to visualise, analyse, and capture the value stream (GumshoeKI Inc., 2012), and then used the CMSD API to transfer the data to different simulation applications for further analysis. In several cases, translators to convert data held in the CMSD API to an application's native input format were also created.

The API and translators initially supported the creation and exchange of CMSD information for parts, resources, jobs, and process plans. The CMSD API was demonstrated at the 2011 Winter Simulation Conference with a case study that compared the results of using CMSD to transfer data into QUEST, arena, and FlexSim for analysis. In this study, the CMSD file contained value streaming mapping data, parts (containing two subassemblies and one main assembly), job steps, and machine and labour resources (Fournier, 2011).

Figure 3 shows how simulation data can be translated to the CMSD format using CMSD API and loaded into DES tools (CCAT, 2012). CCAT also has created or intends to create the following translators: CMSD to/from QUEST, CMSD to/from arena, CMSD to/from ProModel (2012), CMSD to/from FlexSim (2012), CMSD to/from QUEST, and CMSD to/from Excel. CCAT also created a CMSD viewer that provides an interface for interacting with data in a CMSD file and provides access to installed CMSD translators.

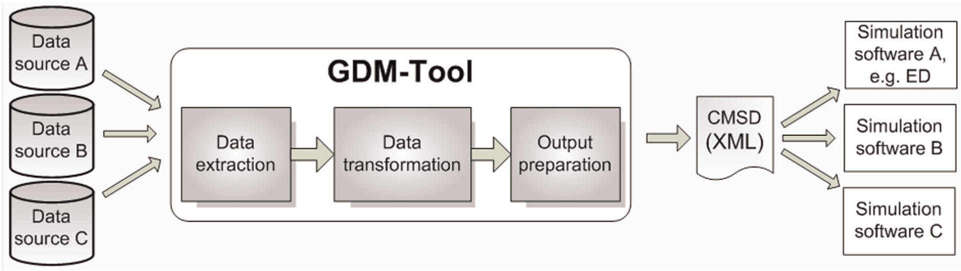
4.2 SIMTER – a joint simulation tool for production development

The SIMTER project was undertaken as collaboration between Finnish and Swedish researchers (Lind et al., 2009). In Finland, the project participants included VTT Technical Research Centre of Finland and two companies, Visual Components and Hollming Works. In Sweden, the SIMTER project involved Chalmers University of Technology, Volvo Technology, and EKA Chemicals. The project is a pioneering effort to introduce simultaneous, multi-parameter analysis for optimised design of manufacturing systems. The parameters being studied include ergonomics, levels of automation, and environmental impacts, in addition to conventional production simulation parameters. The project's core result is the SIMTER simulation tool, which enables production simulation to be created that jointly take into account levels of automation, ergonomics, and environmental impacts. The tool was developed using the CMSD standard as the mechanism for describing the manufacturing system to be simulated. In the case study, CMSD's data structures are used to represent resource data for all resources in the simulation model, which is then created using the 3DCreate simulation tool.

4.3 Generic data management tool (GDM-tool)

Researchers at the Chalmers University of Technology in Sweden developed a software application, the GDM-tool, that automatically extracts raw data from several sources (e.g., database or output from some manufacturing simulation), synthesises and transforms the data to other forms, and presents the data in a format accessible for a range of DES software (Skoogh et al., 2012). In a case study of an assembly department in the automotive industry, CMSD is used as the common representation for data that was input into different simulation applications. Figure 4 illustrates the GDM-tool concept of automated input data management, including three major functions: data extraction, data transformation, and output preparation. The results of the study show that the time needed for input data management was reduced by 78% relative to a traditional approach preparing data specific to each source and simulation software.

Figure 4 Schematic of data management process using GDM-tool



Source: Skoogh et al. (2012)

5 CMSD support tools

Developing custom-built proprietary interfaces is costly. It would be preferable for manufacturing application vendors to provide translators and APIs to import and export manufacturing data to and from CMSD documents. NIST and its collaborators developed support tools for validating and manipulating CMSD XML instance documents. Until vendor translators become available, these tools will make integrating simulation and other manufacturing applications using CMSD effective, efficient, and less costly. The objective of the project was to include an implementation of the CMSD information model in commonly used languages, a set of converters to convert from the objects/classes in the those languages to CMSD documents, and an API to validate CMSD documents.

CMSD uses UML to define an information model that describes manufacturing information. This approach was undertaken to preserve independence from both usage and implementation. Implementation independence allows users to select their implementation methods (Lee, 1999). For this reason, source code in different programming languages is provided to create CMSD-supporting applications. The project is organised into directories of related information as shown below:

- CMSDDotNet: C# classes to create a .Net library that enables CMSD documents to be created, manipulated, and validated using objects defined based on the classes defined in the CMSD-UML specification
- CMSDJava: Java classes to create a Java library that enables CMSD documents to be created, manipulated, and validated using objects defined based on the classes defined in the CMSD-UML specification
- Resources:
  1. RELAX NG and Schematron schemas to validate CMSD documents
  2. examples of valid and invalid CMSD documents

- Tools: scripts to extract Schematron information from RELAX NG schemas and to be converted into XSL (W3C, 2012b).

6 The role of CMSD in the test-bed for SM

Traditionally, manufacturing industries are concerned with quality, cost, and time. All manner of products and processes have been evaluated along these dimensions. Recently, sustainability has emerged as an important factor to consider in evaluating products and manufacturing processes. The US Department of Commerce defines SM as "the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound" (US DOC ITA, 2012).

To effectively engage in SM, industry needs a trusted system of metrics pertaining to sustainability and the underlying measurement science to compute those metrics. To address these needs, the SM programme has been established at NIST (2012). This programme is developing methodologies to enable assessment and decision making in resource (energy, material) efficiency and waste reduction across manufacturing processes and product assembly. To verify and validate these methodologies, the programme will also develop a test-bed based on real-world manufacturing scenarios. This section provides an overview of the test-bed for sustainable manufacturing (or SM test-bed) and identifies how CMSD could be used in the test-bed.

6.1 NIST sustainable manufacturing test-bed

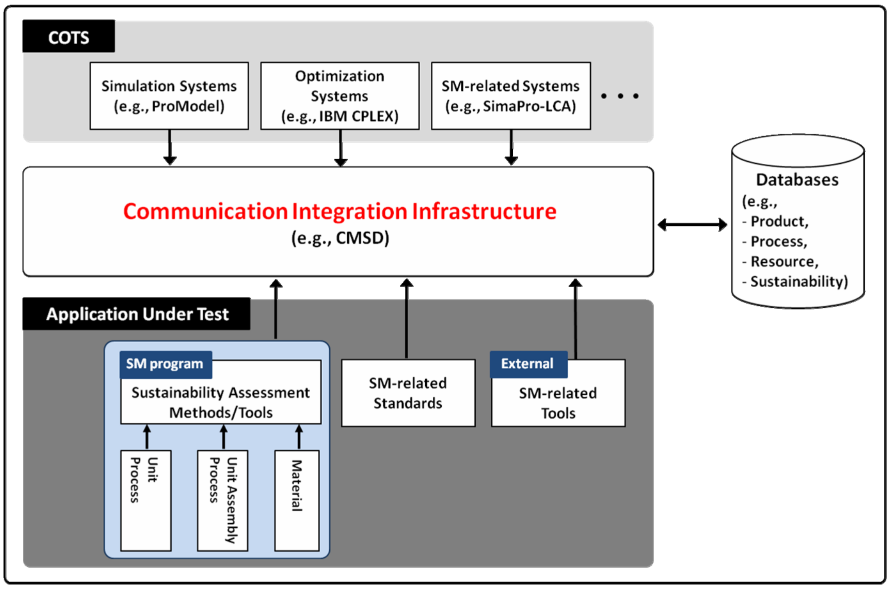
The SM test-bed is a networked facility that consists of hardware, software, and other system components. The test-bed will establish a virtual manufacturing facility using simulation-based manufacturing systems. Simulation technology will enable the development of large, realistic virtual worlds in software. To ensure that they reflect the operation of real manufacturing facilities to the fullest extent possible, the virtual manufacturing facilities will be created based on data collected from real manufacturing facilities and will be verified to be able to operate similarly to those facilities' production scenarios. Data gathering for and the development of the production scenarios about the real manufacturing facilities will be done in collaboration with industrial partners from those facilities.

The SM test-bed aims to provide:

1. the ability to demonstrate, test, and validate sustainability assessment methods and tools
2. the ability to test implementations of sustainability assessment related standards
3. a facility for the industry partners to perform sustainability assessments
4. a neutral arena for maintaining real manufacturing data relating to products, resources, processes, and sustainability data from test cases describing manufacturing scenarios.

Figure 5 provides a conceptual depiction of the software configuration of the test-bed with the focus on the relationship and communication among the components. The elements of the system include commercial-off-the-shelf (COTS) software applications, databases, a communication integration infrastructure, and an application-under-test (AUT) module. COTS software will be used to model the behaviour of real manufacturing systems, generate and select a best solution from some set of available alternatives, and assess environmental impacts associated with manufacturing sustainability. An AUT module can be a sustainability assessment application or a SM standard. The communication integration infrastructure will allow software applications including simulators to share data. Databases act as a central repository. This repository may include manufacturing and sustainability datasets that are associated with real manufacturing use scenarios. The integration will be based on existing standards (e.g., CMSD) and information models developed under the SM programme. Given the number of applications included in the test-bed, management functions will be needed to control its operation. A test-bed management system is now under design, but a discussion of it is out of scope for this paper.

Figure 5 Example software configuration of the test-bed (see online version for colours)



6.2 CMSD role in the test-bed

The communication integration infrastructure plays an essential role in the test-bed. The infrastructure will bring together test-bed components in an interactive environment that will then allow the testing of applications, the evaluation of sustainability assessments, and the testing of implementations of sustainability-related standards. Since a number of software applications including simulators will need to share data, they require a common understanding of its meaning and structure. Interoperability standards or common information models will be needed to facilitate integration. Candidate standards include CMSD, ISA-95, and OAGIS. The SM programme is developing methods for representing manufacturing sustainability information including the sustainable process description methodology (SPDM). SPDM enables the representation of SM processes, their use of materials and resources, and process execution precedence (Shao et al., 2012). CMSD, however, focuses on facilitating the exchange of information between manufacturing-oriented simulations and other applications in manufacturing domains such as process planning, scheduling, inventory management, production management, and plant layout. The virtual manufacturing environment of the test-bed enables CMSD to play a unique role in the integration infrastructure.

The CMSD specification is not intended to be an all-inclusive definition of either the entire manufacturing domain or simulation domain (SISO, 2010). However, *property*, a CMSD class, provides a means to extend the information that can be associated with a CMSD entity by allowing name and value information for any noteworthy characteristic of the entity to be associated with that entity. Many CMSD classes support their extension with *property* data, and consequently user-defined attributes can be added to many CMSD classes. While the SM application domain is not directly supported by CMSD, the *property* class' flexibility and extensibility allows CMSD to be used to model information from this domain. Johansson states that "Sustainability measures and metrics can be included in this standard – CMSD – with ease, since the user can specify [their] own parameters and measures within the structure, e.g., on a product and or a resource level" [Johansson, (2010), p.113]. Examples of such implementations were presented in Section 4.

6.3 An example of the role of CMSD in SM test-bed

This section demonstrates the role of CMSD in the SM test-bed with an example. The scenario used in this example was previously used for describing the concept of SPDM (Shao et al., 2012). In this scenario, a user of the QUEST simulation system (which is a component of the test-bed) wishes to use it to evaluate the sustainability of a particular manufacturing production line for a product. The sustainability indicators to be evaluated are the consumption of materials, energy, other substances, and the waste produced (steel scrap in this case).

The company in this example is a manufacturer whose product is a steel case box. The case consists of a top cover and bottom. This company's usual production calendar is four weeks per month, five days per week, two shifts per day, and eight hours per shift. The basic processes for the top cover and bottom are very similar, but each process has specific constraints and conditions for producing its target part. The top cover and bottom separately move through press, inspect, and clean processes. The bottom part has a print/dry process that takes place after the clean process. Production is concluded when both parts pass simultaneously through pack and ship processes.

An XML file was generated based on the CMSD-XML representation (SISO, 2013) to represent the scenario described above. The file was also validated using a tool included in the *resources* directory of the CMSD-tools project (Section 5). The file was prepared for creating a QUEST simulation that simulates the production line. To show the CMSD concept within the test-bed, only the press process for a top cover and required resources for the process are presented here. Table 1 summarises inputs, outputs, constraints, and additional information about the press process for a top cover. Figure 6 presents a portion of the XML file that represents the corresponding information in Table 1. In this case, sustainability data related to the press process is described using *property* attribute.

Table 1 Specification of the press process for a top cover

Process	*Resource*	*Inputs*			*Outputs*			*Constraints*	
		Item	*Type*	*Unit*	*Item*	*Type*	*Unit*	*Item*	*Unit*
Press	Press machine	Steel sheet	Material	kg	Top cover	Part	kg	Cycle time	Sec
		Electricity	Energy	kWh	Scrap	Substance	kg	Cost	$
		Lubricant	Substance	L					
Additional information									
Press machine • Type: 300 ton press machine • Energy consumption: 30 kWh Cycle time and cost per day • Cycle time: 30 sec • Cost: $1,000					Additional requirements • Steel sheet: 3 kg per part • Lubricant: 0.003 L per hour • Scrap rate: 11%				

Figure 6 Portions of CMSD-XML file (a) process-press (b) resource-press machine (see online version for colours)

(a)


```xml
- <ProcessPlan>
    <Identifier>ProcessPlan:TopCover:0001</Identifier>
  - <PartsProduced>
    - <PartType>
        <PartTypeIdentifier>Part:TopCover:0001</PartTypeIdentifier>
      </PartType>
      <PartQuantity>1</PartQuantity>
    </PartsProduced>
  - <Process>
      <Identifier>Process:Press:0001</Identifier>
    - <PartsProduced>
      - <PartType>
          <PartTypeIdentifier>Part:TopCover:0001</PartTypeIdentifier>
        </PartType>
        <PartQuantity>1</PartQuantity>
      </PartsProduced>
    - <PartsConsumed>
      - <PartType>
          <PartTypeIdentifier>Part:SteelSheet:0001</PartTypeIdentifier>
        </PartType>
        <PartQuantity>1</PartQuantity>
      </PartsConsumed>
    - <ResourcesRequired>
      - <Resource>
          <ResourceIdentifier>MC0001</ResourceIdentifier>
        </Resource>
      </ResourcesRequired>
    - <OperationTime>
        <Unit>second</Unit>
        <Value>30</Value>
      </OperationTime>
    - <CostAllocationData>
        <CostCategory>indirect</CostCategory>
        <CostType>fixed</CostType>
      - <TotalCost>
          <Unit>USD</Unit>
          <Value>1000</Value>
        </TotalCost>
      </CostAllocationData>
    - <Property>
        <Name>ScrapRate</Name>
        <Description>Steel_Scrap</Description>
        <Value>0.11</Value>
      </Property>
    </Process>
  </ProcessPlan>
```


(b)


```xml
- <Resource>
    <Identifier>MC0001</Identifier>
    <Name>300TPress</Name>
    <ResourceType>machine</ResourceType>
  - <Property>
      <Name>Press_Machine_Capacity</Name>
      <Unit>ton</Unit>
      <Value>300</Value>
    </Property>
  - <Property>
      <Name>Electricity_Consumption_Rate</Name>
      <Unit>kWh</Unit>
      <Value>30</Value>
    </Property>
  - <Property>
      <Name>Lubricant_Consumption_Rate</Name>
      <Unit>liter</Unit>
      <Value>0.003</Value>
    </Property>
  </Resource>
```


To execute the QUEST model of the manufacturer's production line, the information in the XML file must be converted to instructions interpretable by QUEST. The file was converted to the QUEST simulation model elements through a converter developed by NIST. The converter contains a set of mapping rules that allow CMSD data to be converted into QUEST batch control language (BCL) statements. BCL is a command language that can be used to create/modify QUEST models and to control QUEST simulation execution. For example, if the required resource is a 'machine', the BCL instruction needed is 'CREATE MACHINE CLASS.' Similarly, other BCL instructions can be generated to enable the creation of other simulation model elements such as parts or part attributes.

The simulation time of this example model was experimentally set for a month. The results of running for that simulation time show that 10,560 cases (10,560 top covers and 10,560 bottoms) were produced. The SM test-bed is designed to read the simulation results and execute the sustainability assessment function provided by the test-bed to calculate sustainability performance. The sustainability assessment function may consist of indicators, metrics, tools, or methods to assess sustainability. However, at the time of the writing of this paper the assessment function is still under development. Therefore, to illustrate how it will function once implementation of the automated assessment function is complete, the assessment function calculations were performed manually and the results are presented below. Table 2 summarises the sustainability results (in column 3) of the press process for a top cover that were calculated using the provided metrics (in column 2) with data from the simulation results.

Table 2 Example calculation results for sustainability indicators from the test-bed

Indicator (press process)		*Metric*	*Result*
Material consumption	Steel	$\text{kg}/\text{part} \times \text{number of part } (3 \times 10{,}560)$	31,680 kg
Energy consumption	Electricity	$\text{kWh}/\text{hour} \times \text{total processing time (hour) } (30 \times 9{,}600)$	20,800 kWh
Substance consumption	Lubricant	$\text{L}/\text{hour} \times \text{number of part } (0.003 \times 9{,}600)$	28.8 L
Waste produced	Steel scrap	$\text{Steel consumption} \times \text{scrap rat } (31{,}380 \times 0.11)$	3,484.8 kg

Figure 7 Integration between example model and QUEST simulation model via CMSD-XML (see online version for colours)

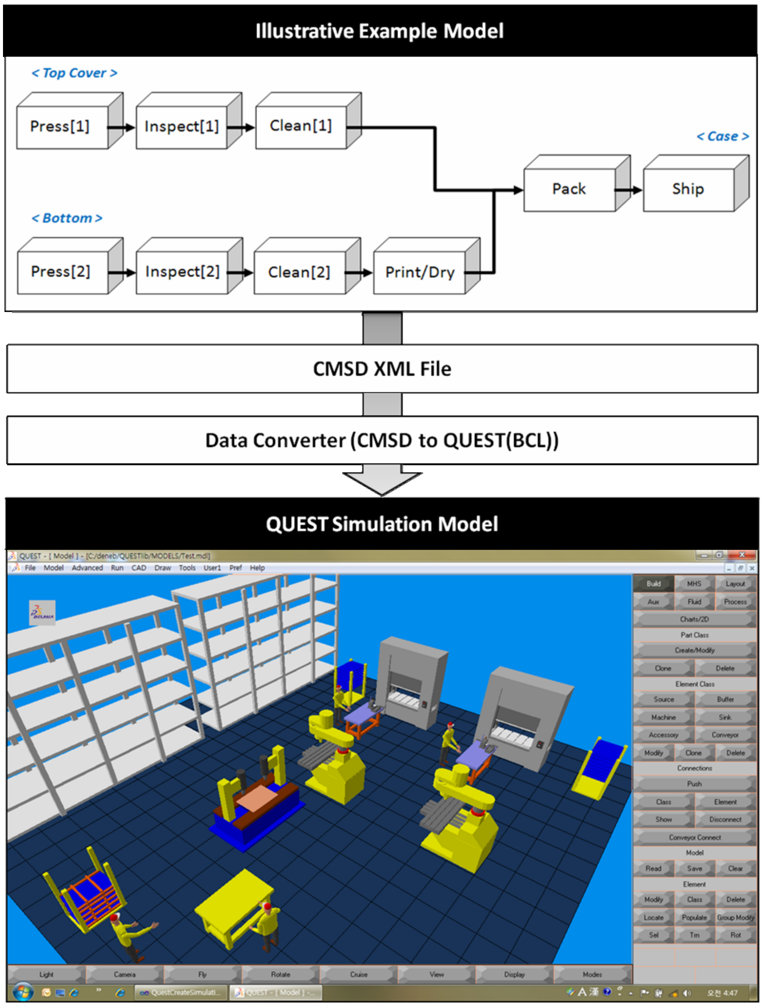


Figure 7 depicts the integration process through which manufacturing simulation data including sustainability data in XML is converted and imported into QUEST to execute the simulation model. It shows a conceptual flow between the example model and QUEST simulation via a CMSD-XML file. This test case demonstrates how the CMSD information model serves its interoperability role in the test-bed.

7 Summary and conclusions

In this paper, information about the CMSD standard, commonly referred to as CMSD, was presented. Some of the motivations for developing CMSD, the kinds of manufacturing entities that can be represented, how CMSD is organised, and how CMSD can be used to enable manufacturing systems and/or manufacturing-oriented simulations integration were discussed. That CMSD is being developed as a two-part complementary specification was discussed; one specification defines an information model in UML (providing for structural, content, and constraint definition along with model visualisation) and the other defines an XML representation (facilitating the creation and exchange of CMSD information using widely available open source and commercial XML tools). Descriptions of many research projects that were undertaken that used CMSD as a major mechanism for content definition, information exchange, and application integration were presented. These projects helped guide the development of the final CMSD standard and verify its usefulness as an integration mechanism.

CMSD is a candidate standard to be used for information exchange and application integration as part of the test-bed project in the SM programme at the National Institute of Standards and Technology. In this project, traditional manufacturing data is being collected from real manufacturing facilities, and that data is being incorporated with information about the sustainability of the products being produced and the processes that produce them. Simulation technology is used to create virtual representation of real production facilities for the test-bed. Using the collected data, the virtual production facilities are used to assess the sustainability of the processes of the real facility, to propose possible improvements to the manufacturing processes producing the product, and to test the feasibility of proposed improvements virtually before any changes are made to the real facility.

Disclaimer

A number of software products and services are identified in the context of this paper. This does not imply a recommendation or endorsement of the software products and services by the authors or NIST, nor does it imply that such software products are necessarily the best available for the purpose. The work described was funded by the United States Government and is not subject to copyright.

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Notes

1 SISO, an IEEE sponsor, is an international organization dedicated to the promotion of modelling and simulation interoperability.