TECHNICAL REPORT

ISO/TR 3151-1

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Visualization elements of PLM-MES interface —

Part 1: Overview

Éléments de visualisation pour l'échange de données entre systèmes d'information de gestion du cycle de vie de produits (PLM) et de pilotage de la production (MES) – vue d'ensemble —

Partie 1: Vue d'ensemble

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO document should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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This document was prepared by Technical Committee ISO/TC 184, *Automation systems and integration*, Subcommittee SC 4, *Industrial data*.

A list of all parts in the ISO 3151 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

This document is an overview of the ISO 3151 series of standards. It explains the main scope of the ISO 3151 series as well as why the Product Lifecycle Management and Manufacturing Execution System (PLM-MES) interface is needed. It also describes the elements constituting the PLM-MES interface and the visualization elements of the PLM-MES interface.

Product Lifecycle Management (PLM) is a technical item often covered within ISO/TC 184/SC 4 and in IEC/TC 65 where there is a standard for different lifecycles of various product parts. Conversely, Manufacturing Execution System (MES) is a technical item covered within ISO/TC 184/SC5, IEC/TC 65 and ISA (International Society of Automation). ISO/TC 184/SC 4 and SC 1 also cover the standard technology for the automatic machining of the product. Cooperation between these standards organizations is needed for standards in a PLM-MES interface.

Although literature is referenced to introduce the elements that make up the PLM-MES interface, more items are also referenced in [1-5] for the basis of this document.

Figure 1 shows the overall PLM-MES interface defined by this document and ISO 3151-2[1)]. The left side in Figure 1 shows the contents of this document, and the right side shows the contents of ISO 3151-2.

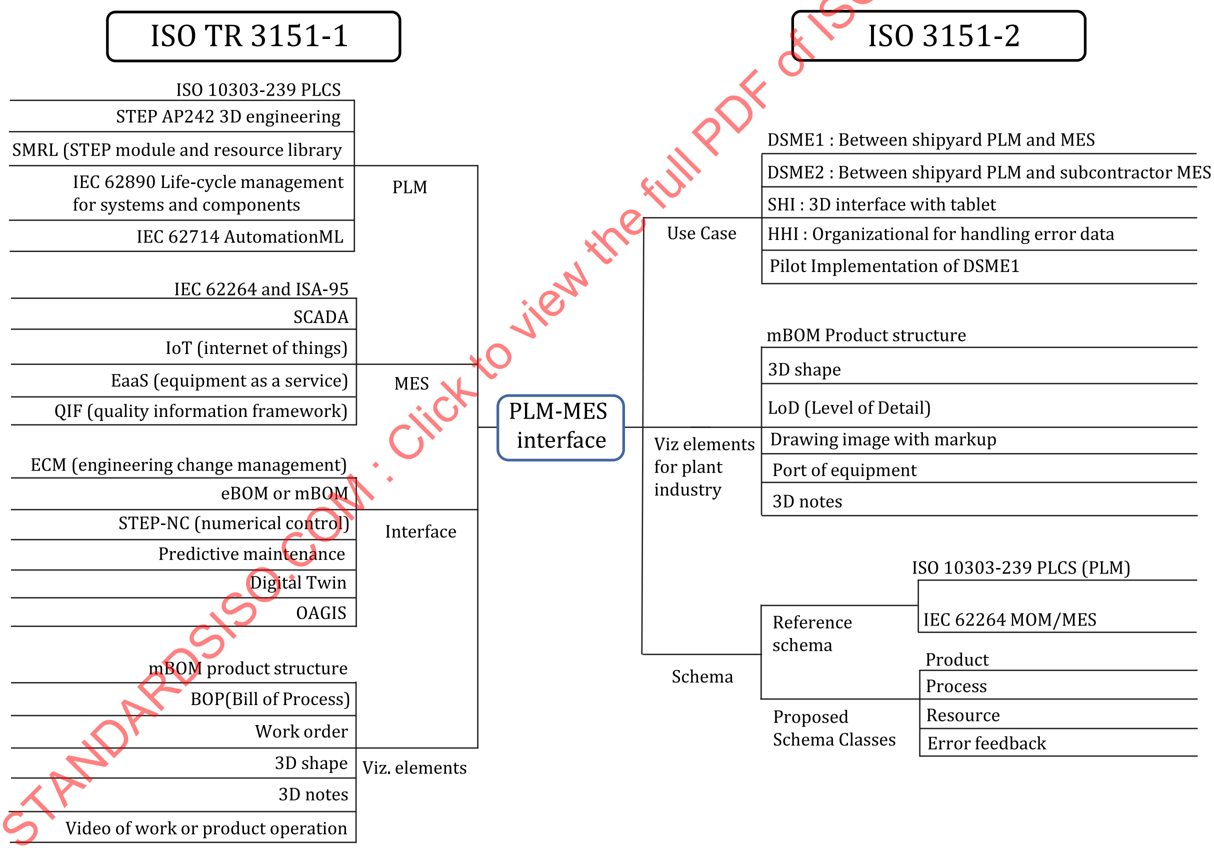


Figure 1 — Concept diagram of PLM-MES interface

The AP242 contains Product and Manufacturing Information (PMI), but its primary concern is to communicate design information to the manufacturing department. It is understood that the feedback loop from the manufacturing department to the design department is not well-supported. ISO 3151-2 focuses on a 3D interface that feeds back errors found by the production department to the design department.

1) Under development. Stage at the time of publication: ISO/CD 3151-2.

Visualization elements of PLM-MES interface —

Part 1:
Overview

1 Scope

This document outlines the visualization elements for data exchange between the Product Lifecycle Management and Manufacturing Execution System (PLM-MES) or Manufacturing Operations Management (MOM).

The following are within the scope of this document:

— the need for a PLM-MES interface;

— the technical elements that make up the PLM-MES interface;

— the visualization elements of the PLM-MES interface.

The following is outside the scope of this document:

— application of the PLM-MES interface and its visualization elements.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO/IEC 20924, *Information technology — Internet of Things (IoT) — Vocabulary*

3 Terms, definitions and abbreviated terms

For the purposes of this document, the terms and definitions given in ISO/IEC 20924 and the following apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1 Terms and definitions

3.1.1
3D note
3D text information attached to graphical information of a digital shape model of a product

3.1.2
batch size
number of jointly processed (semi-finished) products

[SOURCE: ISO 22468:2020, 3.1]

3.1.3
bill of material
BOM
listing of all the subassemblies, parts, and/or materials that are used in the production of a product, including the quantity of each material required to make a product

[SOURCE: IEC 62264-1:2013]

3.1.4
engineering bill of material
eBOM
list of part numbers and assemblies that make up the design engineering configuration that contains the raw stock size and the material specification.

[SOURCE: ISO 10303-240:2005, 3.4.3]

3.1.5
lot size
quantity of an item ordered for delivery on a specific date or manufactured in a single production run

Note 1 to entry: See [33].

3.1.6
manufacturing bill of material
mBOM
list of all the parts, labels, packaging, and assemblies required to build and ship a finished product to customers

Note 1 to entry: mBOM is different from an engineering bill of material (eBOM) which provides the as-designed BOM.

Note 2 to entry: See Annex A.

3.1.7
manufacturing execution system
MES
system for producing the desired products or services, including quality control, document management, plant floor dispatching, work-in-process tracking, detailed product routing and tracking, labour reporting, resource and rework management, production measurement and data collection

[SOURCE: ISO 16100-1:2009, 3.14]

3.1.8
manufacturing operations management
MOM
activities within Level 3 of a manufacturing facility that coordinate the personnel, equipment and material in manufacturing

[SOURCE: IEC 62264-1:2013, 3.1.22]

3.2 Abbreviated terms

3D	Three Dimensional
AAM	Application Activity Model
AIC	Application Interpreted Construct
AIM	Application Interpreted Model
ANSI	American National Standards Institute
AP	Application Protocol
ARM	Application Reference Model
ATO	Assemble-To-Order
BOD	Business Object Document
BOM	Bill of Material
BOP	Bill of Process
CAI	Computer-Aided Inspection
CAPP	Computer-Aided Process Planning
CC	Conformance Class
CMM	Coordinate Measuring Machine
DTO	Design-To-Order
EaaS	Equipment as a Service
eBOM	Engineering BOM
ECM	Engineering Change Management
ECN	Engineering Change Notification
ECO	Engineering Change Order
ECR	Engineering Change Request
ERP	Enterprise Resource Planning
ETO	Engineer-To-Order
GD&T	Geometric Dimensioning & Tolerancing
HVAC	Heating Ventilation Air Conditioning
IEC	International Electrotechnical Commission
IIoT	Industrial Internet of Things
IoT	Internet of Things
IR	Integrated Resource

ISA	International Society of Automation
ISO	International Organization for Standardization
mBOM	Manufacturing BOM
M2M	Machine-to-Machine
MES	Manufacturing Execution System
MOM	Manufacturing Operations Management
MS	Mapping specification
MTO	Make-To-Order
MTS	Make-To-Stock
NC	Numerical Control
OAGIS	Open Applications Group Interface Specification
OPC-UA	Open Platform Communications Unified Architecture
PDA	Personal Digital Assistant
PLC	Programmable Logic Controller
PLCS	Product Lifecycle Support
PLM	Product Lifecycle Management
PMI	Product Manufacturing Information
QIF	Quality Information Framework
SCADA	Supervisory Control and Data Acquisition
SMRL	STEP Module and Resource Library
STEP	Standard for the Exchange of Product model data
SW	Software
WSN	Wireless Sensor Network

3.3 Difference between MES and MOM

The terms MES (manufacturing execution system) and MOM (manufacturing operations management) system are often used interchangeably, so that by defining different functional spaces for manufacturing professionals it can be confusing.

The term MES is commonly used in commercial products, whereas the term MOM is often used to summarize the technical features. While MOM covers the set of functions defined in this document, MES is the commercial product that implements the set of functions as a SW system, so there are variations in MES depending on the commercial product.

Because the term MES is used in many different senses, it is difficult to give an unambiguous, agreed-upon definition. However, many manufacturers mention MES in their daily work, and software vendors also use MES as their product name, so it is difficult to exclude the use of MES from a general discussion. Therefore, this document uses the term MES in high-level abstractions where there is no confusion.

MOM is used to represent a standard management process, while MES is used to represent a software system for MOM. Therefore, MES has a different scope or level depending on the implementation of the system. In this document, MES is mainly used, and if there is confusion and a clear definition is needed, the problem is solved by using the term of MOM defined by IEC and ISA.

As shown in Figure 2, ISA-95 defines the term MOM to cover Level 3 architecture and its functions. As smart manufacturing is integrated into the Industrial Internet of Things (IIoT) in the future, changes to the Figure 2 model are expected.

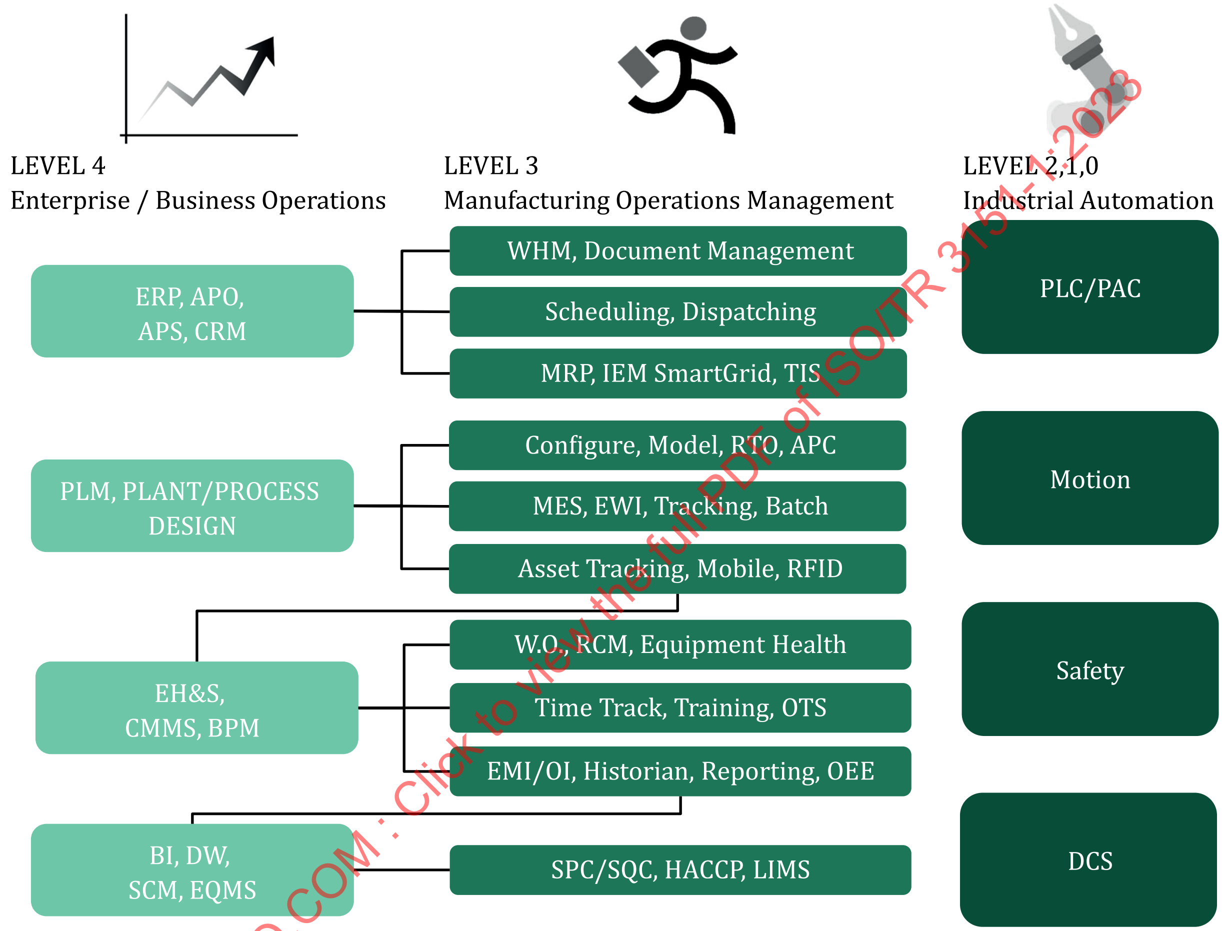


Figure 2 — 3 level architecture of MOM[6]

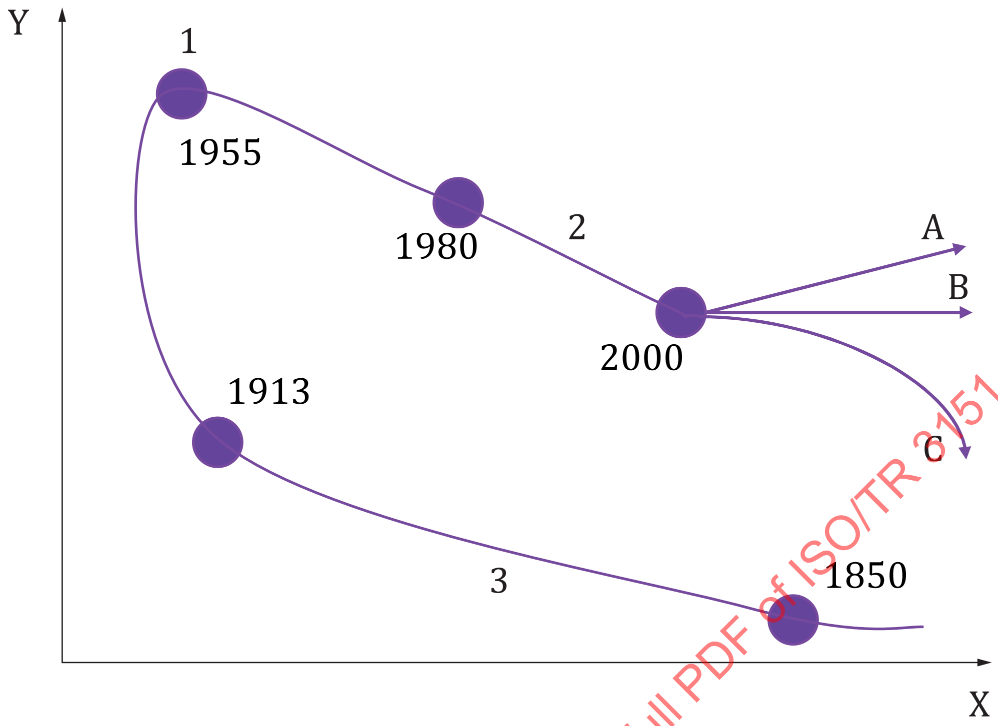
4 Needs for a PLM-MES interface

4.1 General

The modern commercial market has more suppliers than demand, so customers have more power than suppliers. Because of this imbalance, suppliers promote 'mass customization' to satisfy customers, and that force drives the concept of 'personalized production'.

The problem with customization is that it can increase manufacturing costs and time. The PLM-MES interface technology can help to provide personalized products with mass-production-level prices.

Figure 3 shows the technological development history of growing customer demand moving from manual production in the mid-19th century to mass production methods symbolized by the conveyor belt of Ford Motor Company in the early 20th century emerge and mature until the mid-20th century, with technological advancements as customer demand expands. Mass customization has been introduced since the late 20th century due to oversupply caused by the development and automation of production. It also shows the development process of personalized production, which has been introduced in line with the globalization trend of the 21st century.



Key

X product variety
Y product volume per variant
1 massive production
2 mass customization
3 craft production
A globalization
B regionalization
C personalized production

Figure 3 — Personalized production[7]

Another issue other than the cost issue of personalized production is the maturity level of the design. In the case of mass production environment, a small design error causes a big problem (high cost and time delay) in automated production lines. Therefore, a higher level of maturity of the design is needed. Through a series of test production cycles, the level of design maturity is further increased. This requires a high design cost through multiple stages of design cycles and verification. Since the design cost is relatively low compared to the mass production and production cost, it is possible to increase the design maturity level.

In the case of personalized production, it is difficult to increase the maturity level of the design due to cost or time constraints. Since only one is produced using the design, the design cost cannot be large, and the design time must be short for economic reasons. In many cases, production begins before the design is finished, so there is more possibility of production problems due to the immature design. In order to correct errors found after the design is completed, the design is sometimes modified during the production process. Modification of the errors found during production increases the total time of production, and the cost increases accordingly.

Figure 4 shows the current (As-Is) interface between PLM, ERP and MES systems optimized for mass production environments. Typically, ERP does not deal with 3D engineering information such as 3D

CAD models, a separate direct 3D link between PLM and MES is sometimes required. A typical mass production situation is that a production system is optimized for mass production through a series of test productions, and a direct link between PLM (design) and MES (production) does not exist in many cases.

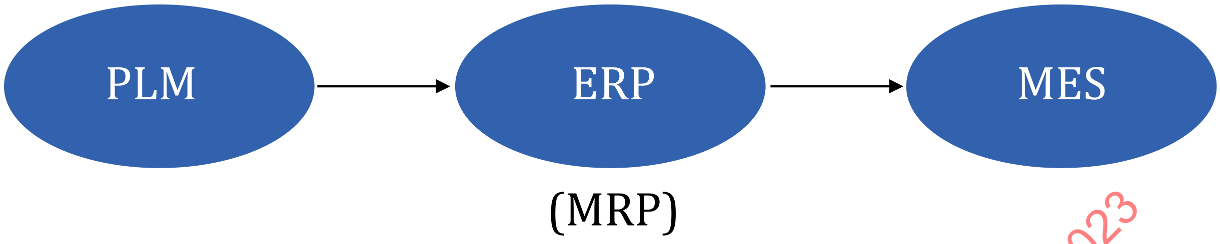


Figure 4 — As-Is configuration of PLM-MES data exchange[8]

Plant industries such as the shipbuilding industry and the construction industry are make-to-order (personalized production) since the start of the industry hundreds of years ago. Every product has an individual design, the production cycle begins even though the design is not yet complete, and there is pressure to design the product quickly. In the short time allowed for design, each product must be individually designed. Due to the design costs, it is difficult to afford multiple iterative design cycles. Also, design verification using the real product is impossible in most cases. Experiments using scaled-down models are being partially conducted.

Because design and production overlap (this concept is already widely used in “concurrent engineering”), the two departments of design and manufacturing must work closely together and exchange data. As the design department and the production department operate in a 3D world, 3D information needs to be shared between the two departments.

Figure 5 shows the proposed (To-Be) configuration among the three systems to support the personalized production environment. This configuration adds a direct link between the PLM and the MES. Since the two systems' PLM and MES are developed without mutual consideration, there is a discrepancy in terminologies and concepts. In order to support personalized manufacturing which is being discussed in the fourth industrial revolution or smart manufacturing, a standardized interface definition and interface implementation between PLM and MES is needed.

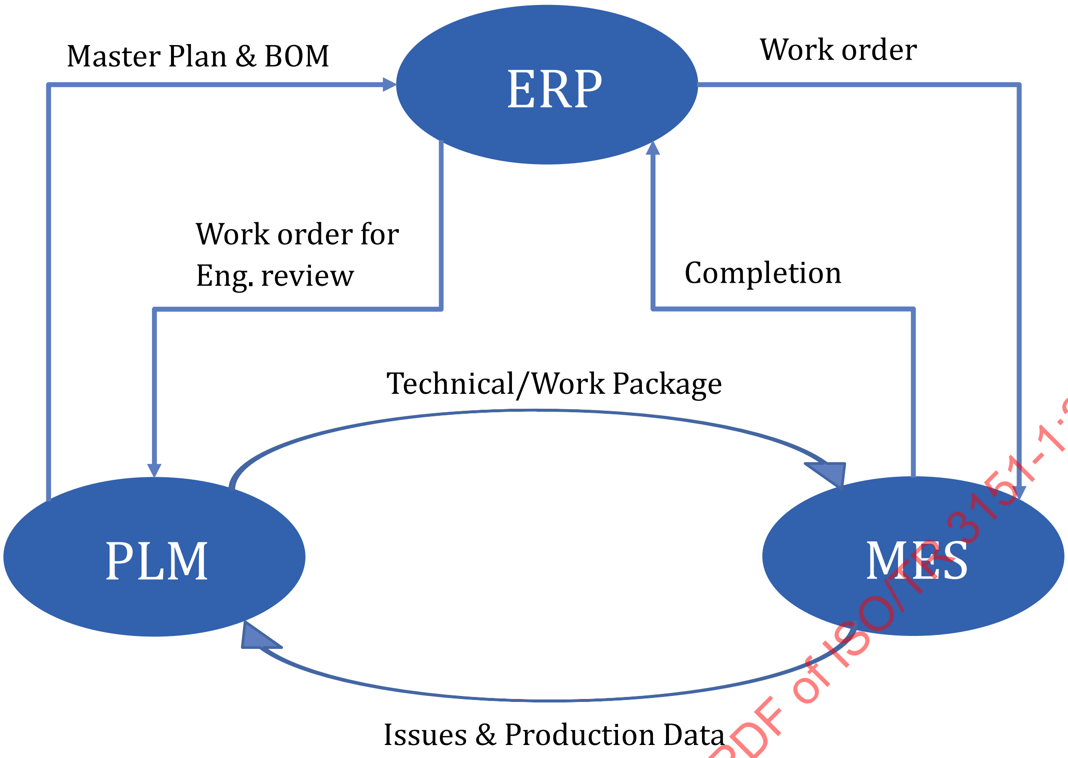


Figure 5 — To-Be configuration of PLM-MES data exchange[8]

PLM and MES have been independently developed and have been used independently for a considerable period of time. Since the data model for each field is well established, the data model that needs to be exchanged can be found and mapped in the PLM-MES interface.

The standard interface between PLM and MES can grow large. However, this document only deals with the visualization elements, to show the full scope of the work as a starting point. In this document, an overview of the entire PLM-MES interface is described, and the visualization elements are focused among them.

There is a commercial product for the PLM-MES interface,[9] but there is no international standard for the PLM-MES interface. Although there are separate international standards for PLM and MES respectively, there is no international standard for an interface for exchanging 3D product information and manufacturing information between PLM and MES. Therefore, this document proposes a part of the PLM-MES interface. Figure 6 shows an example of the PLM-MES interface developed by Siemens.

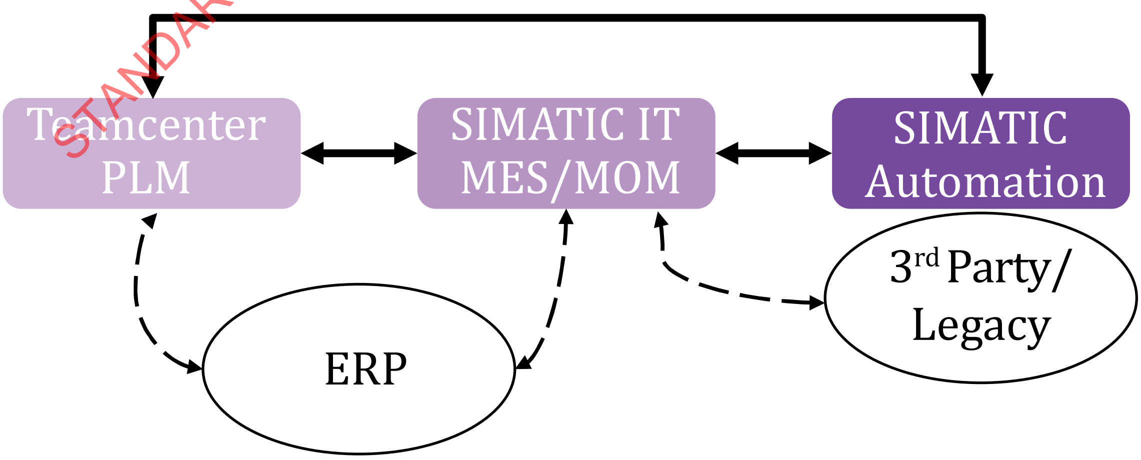


Figure 6 — Siemens integration between PLM, ERP, MES/MOM[9]

In order to establish the PLM-MES interface standard, a common data model between the existing PLM standards and MES standards can be used as a starting point of the interface. Because the full scope of the PLM-MES interface is diverse and complex, the scope of this document only focuses on the visualization elements of the PLM-MES interface.

When the interface is visualized, the detailed information of the interface is hidden so that the displayed image can intuitively show the overall outline. The text-format feedback sent from the production department to the design department can also be used as the interface by borrowing the schema from the existing PLM or MES standards. Since one of the main obstacles is 3D shape information, it is difficult to use the existing schema as it is. The visualization elements can therefore be the first priority to develop the overall PLM-MES interface standard.

4.2 Manufacturing automation pyramid

The manufacturing automation pyramid shown in Figure 7 is a diagram showing the various levels of automation in a discrete manufacturing factory.

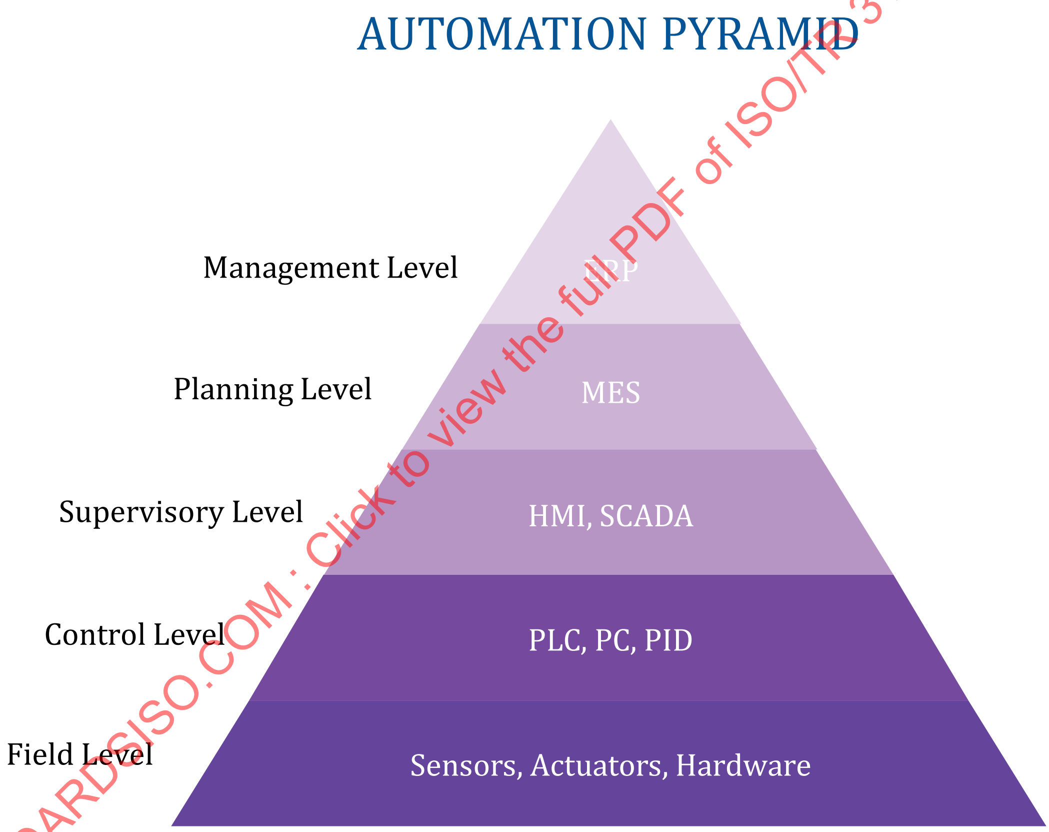


Figure 7 — Manufacturing automation pyramid[10]

At the field level in Figure 7, there are devices, actuators, and sensors that are visible in the field or on the production floor. The control level controls and operates field-level devices that actually perform physical tasks. PLC is used at the control level and SCADA is used at the supervisor level. SCADA can monitor and control multiple systems from a single location.

The planning level utilizes a computer management system known as the MES. MES monitors the entire manufacturing process of a plant, from raw materials to finished products of the plant. The management level uses an integrated management system known as Enterprise Resources Management (ERP).

4.3 Types of manufacturing

According to the nature of product orders, manufacturing industry types are generally classified as follows[11]:

a) Engineer-to-order (ETO), Design-to-order (DTO)

A customized product that does not make any parts in advance, and when an order comes in, the entire process from design to production is made according to the order specifications: Shipyard, facility manufacturing, aircraft/aerospace industry, engineering.

b) Make-to-order (MTO)

Part of the product is made in advance, and the rest of the parts are made according to the order specifications when an order is received and the finished product is made: Luxury goods, yachts.

c) Assemble-to-order (ATO)

All parts that go into the finished product are made in advance, and when an order comes in, it is assembled from that point on to make the finished product: Automobile industry, furniture industry, machinery industry, rolling stock industry.

d) Make-to-stock (MTS)

Products that are made in large quantities in advance and piled up in stock for sale. Most standardized products: Electronics industry, machinery industry, steel industry.

e) Continuous

A flow production method used to manufacture, produce, or process materials without interruption: Chemicals, medicines, cosmetics.

Depending on the arrangement of manufacturing facilities, they can be classified as shown in Table 1[11].

Table 1 — Classification of processes according to the layout of the manufacturing facility[11]

Category	Sub-Category	Description
Process layout	Unit job shop	Placing processing equipment with similar functions in the same space and processing an individual part.
	Batch job shop	Placing processing equipment with similar functions in the same space and processing bundled parts.
Product layout	Discrete flow shop	Gathering facilities with different functions to form an independent production line. Processing parts of assembling products that follow the same order.
	Continuous flow shop	The batch process in which processing or assembly is performed in exactly the same order along the flow line.

5 Elements of the PLM-MES interface

5.1 General

The related technologies that enable the interface of PLM-MES are briefly introduced. They are grouped into subgroups as PLM, MES and the interface.

5.2 PLM

5.2.1 ISO 10303-239

The ISO 10303 series covers computer-interpretable representation and exchange of product manufacturing information (PMI). It is designed to exchange product data between different CAD systems using a neutral file format and data structure.[3] Its official title is: Industrial automation systems and integration - Product data representation and exchange. It is known informally as "STEP" (Standard for the Exchange of Product model data)[36]. The ISO 10303 series is made of hundreds of modular parts.

ISO 10303-239 is a standard for PLM that defines an information model for product design, production processes and resources during the entire product lifecycle of a product, as shown in Figure 8.

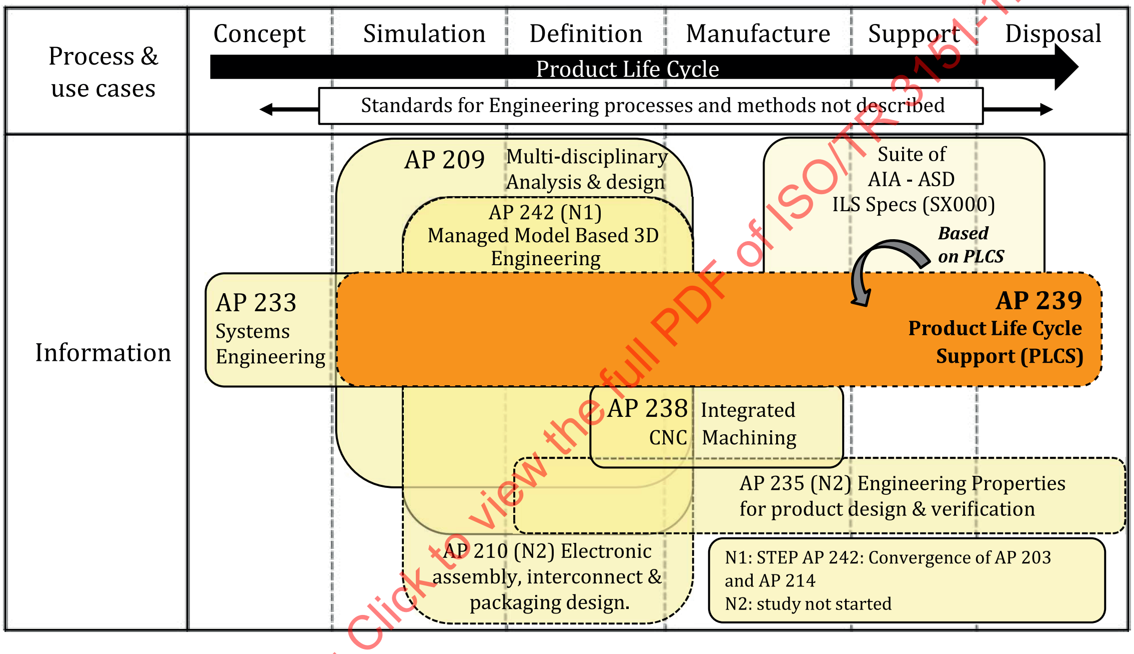


Figure 8 — Scope of ISO 10303-239 and related standards for PLM[12,13]

In Figure 8, AP239 is an application protocol (AP) that manages the lifecycle of a product, so it shows the relationship with other APs of the ISO 10303 series along the time axis of product development. The core of AP239 is to manage the whole product data for a long period of time, while other APs are in charge of more detailed areas in a certain part of the time axis.

AP233 is responsible for the initial requirements' management of the product. AP209 is responsible for the performance analysis simulation of the product model. AP242 is responsible for the 3D engineering design of the product. AP210 is in charge of designing electrical and electronic circuits together with AP242. AP238 is used to NC machine the model of the designed product, and AP235 is responsible for material engineering used to manufacture the product.

PLM covers the entire lifecycle of a product, including the production cycle. However, this TR defines the narrow scope of PLM as a design management tool because, in many manufacturing sites, PLM is viewed as a tool for design departments.

5.2.2 ISO 10303-AP242

The STEP community has completed the development of STEP AP242 (see Figure 8 and Figure 9) for "Managed Model-Based 3D Engineering", with a focus on representing 3D model data, geometric tolerances and PMI for global design and manufacturing collaboration. In addition, STEP AP242 enables streamlined product design, process planning and manufacturing.

Geometric Dimensioning & Tolerancing (GD&T) data via the AP242 is automatically made available to downstream applications such as: Computer-Aided Process Planning (CAPP), Computer-Aided Inspection (CAI), Computer-Aided Tolerance Systems (CATS), Coordinate Measuring Machine (CMM).

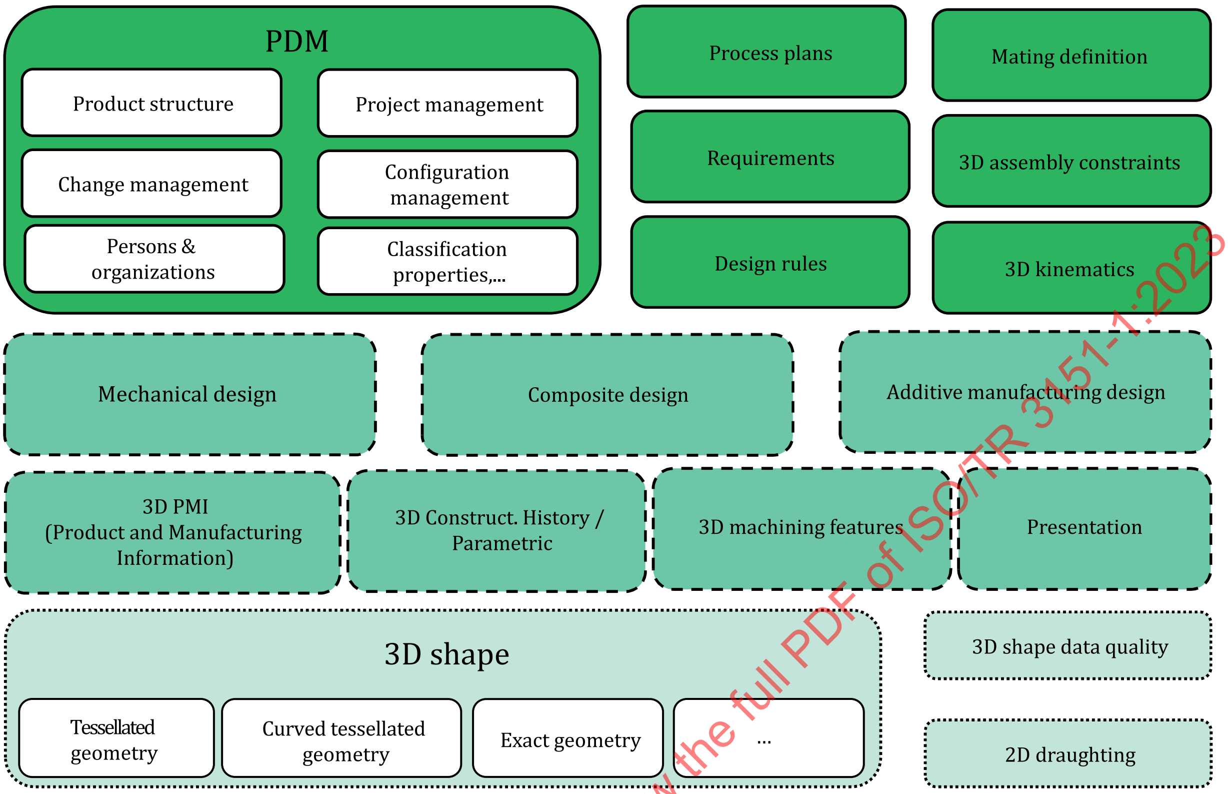


Figure 9 — High-level scope of ISO 10303 AP242[3]

The AP242 contains PMI, but its primary concern is to communicate design information to the manufacturing department. It is understood that the feedback loop from the manufacturing department to the design department is not well-supported. ISO 3151-2 focuses on a 3D interface that feeds back errors found by the production department to the design department.

5.2.3 STEP module and resource library (SMRL)

AP of ISO 10303, which is an industry-specific data schema, consists of

— application activity model (AAM);

— application reference model (ARM);

— application interpreted model (AIM);

— the mapping table mapping specification (MS);

— conformance classes (CCs).

The boxes in the upper left in Figure 10 show the relationship between the five components of an AP[14].

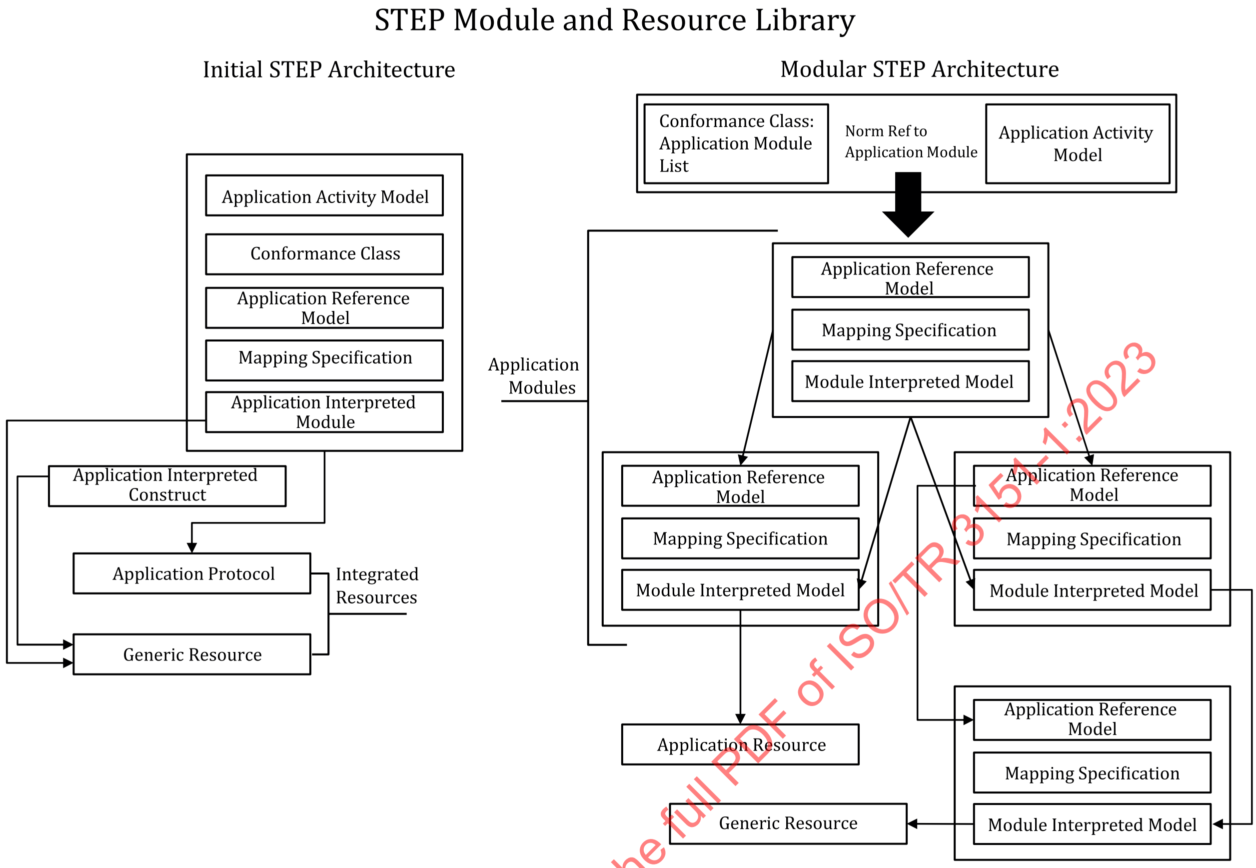


Figure 10 — Evolution of the STEP architecture and current SMRL[14]

The problems of the existing monolithic AP which is composed of AAM, ARM and AIM are that they are too large, overlap each other, and are not fully harmonized to each other. These deficiencies led to the development of the STEP modular architecture (400 and 1000 series) around the year 2000. It is for the adoption of ISO 10303 modular AP for product data representation and exchange, based on application modules and resource modules.[3]

A common resource or SMRL is a common concept and basis that supports the entire ISO 10303 series. For consistency and interoperability throughout ISO 10303, it is necessary to implement APs based on the schemas defined in SMRL. [15]

The schemas of AAM and ARM are usually defined using concepts and terms unique to the industry domain. They are different from the schemas defined in SMRL, which are resources commonly used in various industries. The development of AIM is to express the schema defined in ARM developed for a specific industry by schemas of the corresponding SMRL of common resources. A mapping table (MS: mapping specification) of schemas is created in the development process of AIM.

STEP ISO 10303 application module defines common building blocks for creating modular AP within ISO 10303. The lowest level modules are wrappers of concepts defined in Integration Resources (IR) or Application Integrated Constructs (AIC). SMRL contains all STEP resource parts (IR) and application modules (AIC).

5.2.4 IEC 62890 Life-cycle management for systems and components

In automation applications, the lifecycle of components, devices, and systems is becoming increasingly diverse compared to the lifetime of the entire engineering plant. Due to the increasing capabilities of automation components, advances in electronics, and innovations inherent in hardware and software, the lifecycle of individual automation components continues to shorten. For example, certain semiconductor components are manufactured only for a short period of time and then discarded.

The lifetime of an automated system is quite long, but it also varies considerably from industry to industry. In the automotive industry, the lifetime of a production line is usually equal to the period in which a new car model is manufactured, which is about seven to eight years. In comparison, the operating lifetime of process plants in the chemical industry is typically around 15 years, whereas in the oil and energy industry, and power plants can operate up to 50 years.

IEC 62890 establishes the basic principles for the lifecycle management of systems and components used in the measurement, control and automation of industrial processes. These principles apply to a wide range of industries. This standard provides the lifecycle of a product type and the lifetime of a product instance, and associated definitions and reference models. It also defines a coherent set of general reference models and terms. This standard is used for design, planning, development and maintenance of automation systems and components, and technical aspects related to plant operation[16].

In contrast to ISO 10303-239 PLCs, IEC 62890 is a standard focused on automation systems and their components. Since the lifespan of an automation system or its parts is usually shorter than that of the entire plant, the focus is on harmonizing and managing different lifecycles in terms of plant operation and maintenance. On the other hand, ISO 10303-239 PLCs is a standard for generalized PLM that manages the entire lifecycle from design to production, maintenance and disposal of products which is subject to manufacturing.

An additional difference of IEC 62890 is that since the importance of embedded software for automation is relatively large, the lifecycle is divided based on the managed type and instance along the software lifespan. On the other hand, ISO 10303-239 divides the lifecycle of a product from conception, design, purchase of parts, manufacturing, operation, maintenance, and disposal.

5.2.5 IEC 62714 AutomationML

IEC 62714 AutomationML can model connected production systems and transfer the engineering data of these systems between domains and companies in a heterogeneous engineering tool environment[17].

Looking at the goals and components of AutomationML, it is similar to the ISO 10303 STEP standard. Introduced in 2006, it is being developed based on the XML language. On the other hand, ISO 10303 STEP uses its own language called EXPRESS, and recently, more new languages such as XML are also used in line with the trends of information technology.

3D visualization format of AutomationML is standardized as ISO 17506 COLLADA[40].

5.3 MES

5.3.1 General

This document analyses the interface between PLM and MES. The technologies corresponding to the MES and the substructure of the MES in the automation pyramid are briefly described in this subclause.

5.3.2 IEC 62264 and ANSI/ISA-95

IEC 62264 is developed based on ANSI/ISA-95.[18,19] The IEC 62264 series consists of the following parts:

Part 1 (2013): Object models and attributes of manufacturing operations (First edition 2003-03)

Part 2 (2013): Object model attributes (First edition 2004-07)

Part 3 (2016): Activity models of manufacturing operations management (First edition 2007-06)

Part 4 (2015): Objects models attributes for manufacturing operations management integration

Part 5 (2016): Business to manufacturing transactions

Part 6 (2016): Messaging service model

The interface between ERP and MES is standardized in IEC 62264-1, IEC 62264-2 and IEC 62264-5. The interface defines an information model and methods for exchanging data between ERP and MES (see Figure 11). IEC 62264-3, IEC 62264-4, and IEC 62264-6 define the functions and properties of MES.

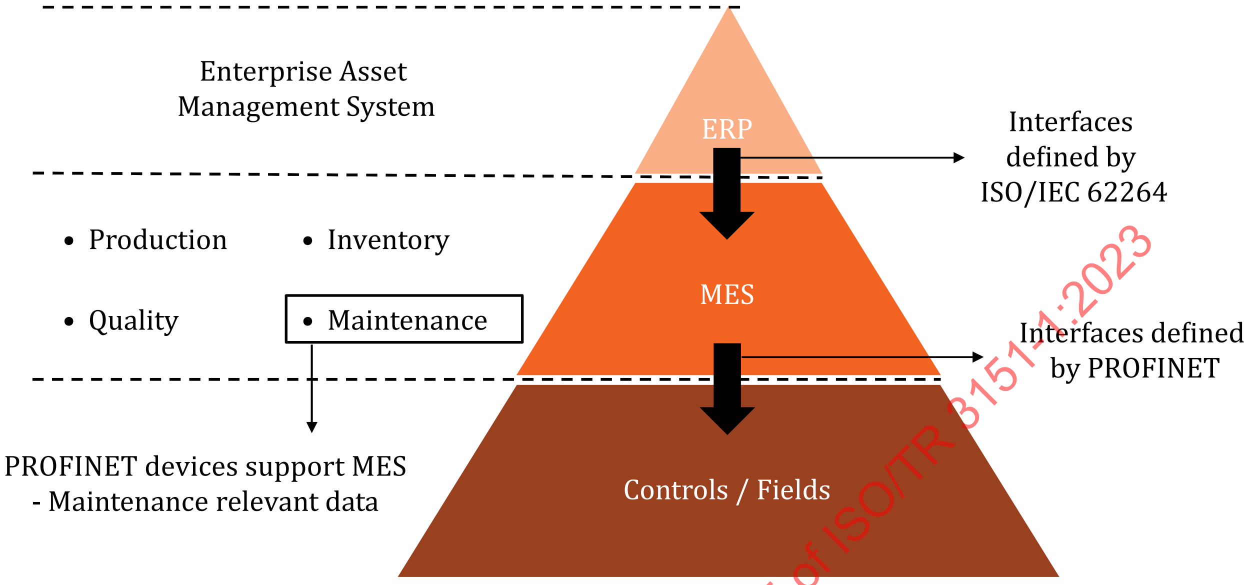


Figure 11 — Scope of IEC 62264 for MES[20]

This standard is based on the reference model of Purdue University for computer integrated manufacturing, as shown in Figure 12. It defines the interface between control functions and other enterprise functions, and focuses on data exchange between levels 3 and 4 of the Purdue model[21]

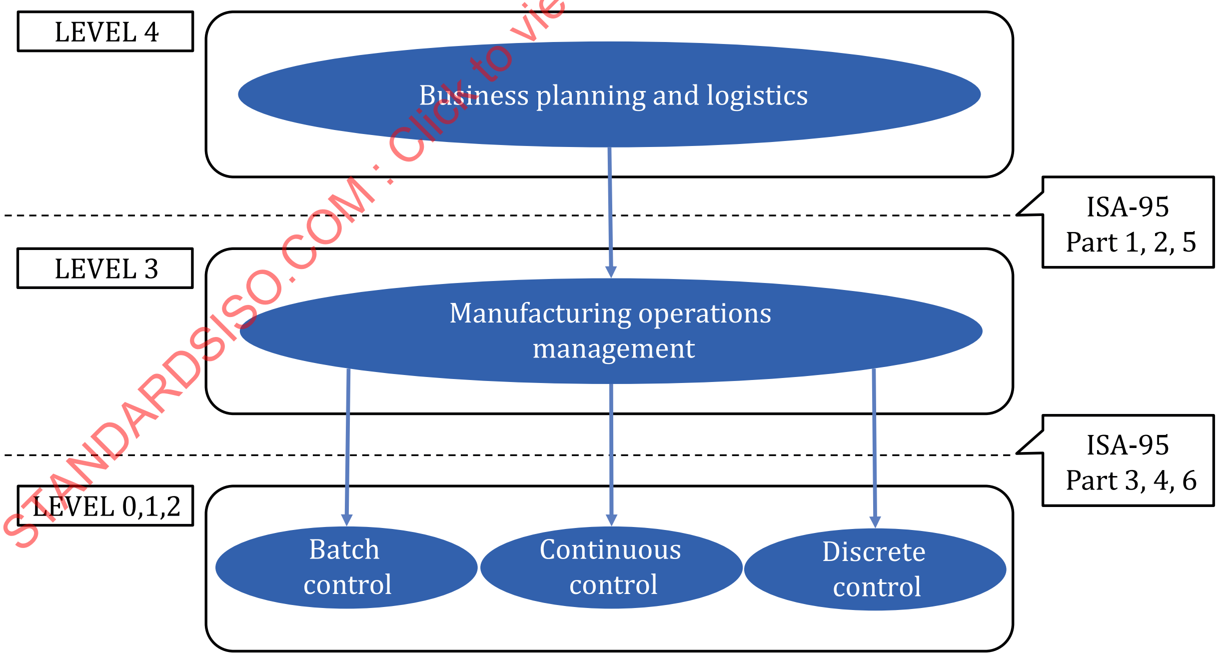


Figure 12 — ISA domain hierarchy[21]

5.3.3 Supervisory control and data acquisition (SCADA)

ISA 88 is the batch processing industry standard and defines a reference model and data model for batch control. BatchML is the XML implementation of ISA 88. PackML models standardized machines and SCADA for batch control in the packaging industry. Figure 13 shows the relationship of related standards around the SCADA level using the manufacturing pyramid.[22] OAGIS and AutomationML are introduced in this document.

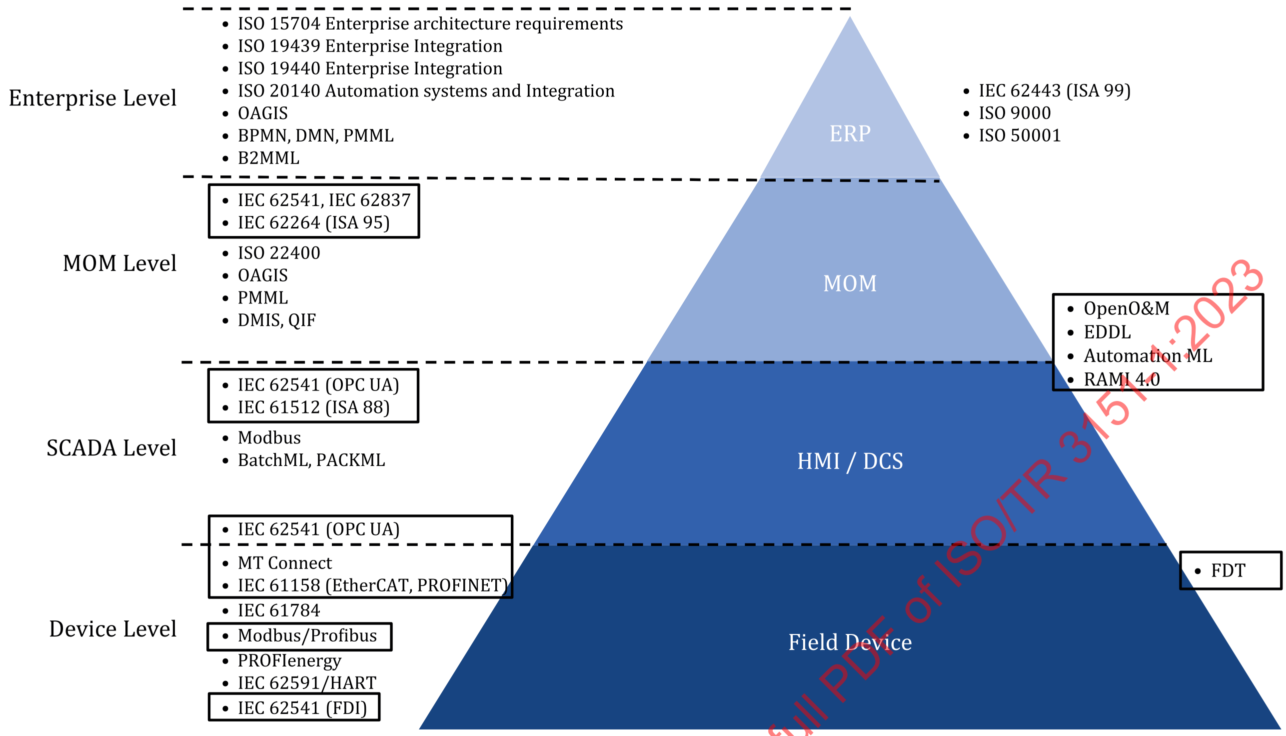


Figure 13 — Manufacturing pyramid based on ISA 95 and NIST[22]

At the SCADA level, IEC 62541 OPC Unified Architecture (OPC-UA) can be used to connect the components of a production system. It also defines a platform-independent communication mechanism for online data exchange. It provides generic, extensible, and object-oriented modelling capabilities for the information that production systems want to expose.

MTConnect, like OPC-UA, is used to access real-time data from shop floor manufacturing equipment, such as machine tools. The MTConnect standard enables manufacturing equipment to capture execution monitoring data and transmit it to external sources in structured XML format. From its inception, MTConnect has been widely used to monitor machine tool health, with limited efforts to contextualize the collected machine data.

5.3.4 Internet of things (IoT)

As Internet technology matures, Ethernet-based networks, such as EtherNet and EtherCAT, have become popular to facilitate higher levels of communication. Influenced by IoT and Wireless Sensor Network (WSN) application needs since 2000, some modern approaches have adopted new standards such as IEEE 802.11, IEEE 802.15.1 and IEEE 802.15.4. Industrial communication goes beyond the transfer of physical data packets between manufacturing entities[3].

At the physical level, messages can be exchanged over physical communication channels, wired or wireless. The basis of M2M communication is stable information exchange. Since the 1980s, industrial communication networks have evolved through several stages. Industrial communications began with dedicated field bus networks, such as PROFIBUS and Modbus, to enable M2M communications.

5.3.5 Equipment as a service (EaaS)

As the industrial Internet and interoperable machine control interfaces mature, manufacturing equipment can become an on-demand manufacturing service through connectivity and control over the Internet[23].

Different from the traditional equipment sales, EaaS model provides equipment to the manufacturing user company for a fee. EaaS equipment manufacturers are responsible for maintenance, service, consumables and spare parts. Availability and output can also be guaranteed. The equipment user saves a high investment cost for the purchase of the equipment, and partially transfers the operational risk to the equipment manufacturing company.

Cloud-based EaaS can contribute to the automation of manufacturing processes and manufacturing systems. This is because the possible service-oriented architecture of cloud-based manufacturing equipment can be embedded directly into the manufacturing digital thread or self-configuring manufacturing network.

Manufacturing assets are connected to the Internet in the form of cyber-physical production systems, via machine communication standards such as MTConnect or OPC-UA. In this scenario, manufacturing assets become smart services thanks to intelligent technologies such as service-oriented architectures and machine communication standards.

More importantly, vendor-neutral data formats (e.g. STEP, STEP-NC and Function Blocks) play an important role in communicating manufacturing operations between companies and machines. Because the STEP-NC standard (see 5.4.3) can be used to describe common manufacturing operations, manufacturers can easily interpret received manufacturing requirements and create adaptive machine control strategies based on local machine conditions and settings.

5.3.6 Quality information framework (QIF)

Online in-process inspection, which is integrated into the product manufacturing process, is important. Online in-process inspection is essential to produce highly personalized products in small batches (lot sizes). This is because the production of personalized products cannot afford the costs of manual or semi-automated inspection.

QIF defines a unified set of XML information models for exchanging measurement data in manufacturing quality measurement processes (see ISO 23952). Figure 14 shows the execution procedure of QIF.

QIF covers product design, inspection planning, execution of inspection plan, analysis and reporting of inspection results. QIF provides complete and accurate 3D product definitions, along with semantic geometric and dimensional tolerances, definitions for measurement resources, templates for measurement rules, and statistical functions.

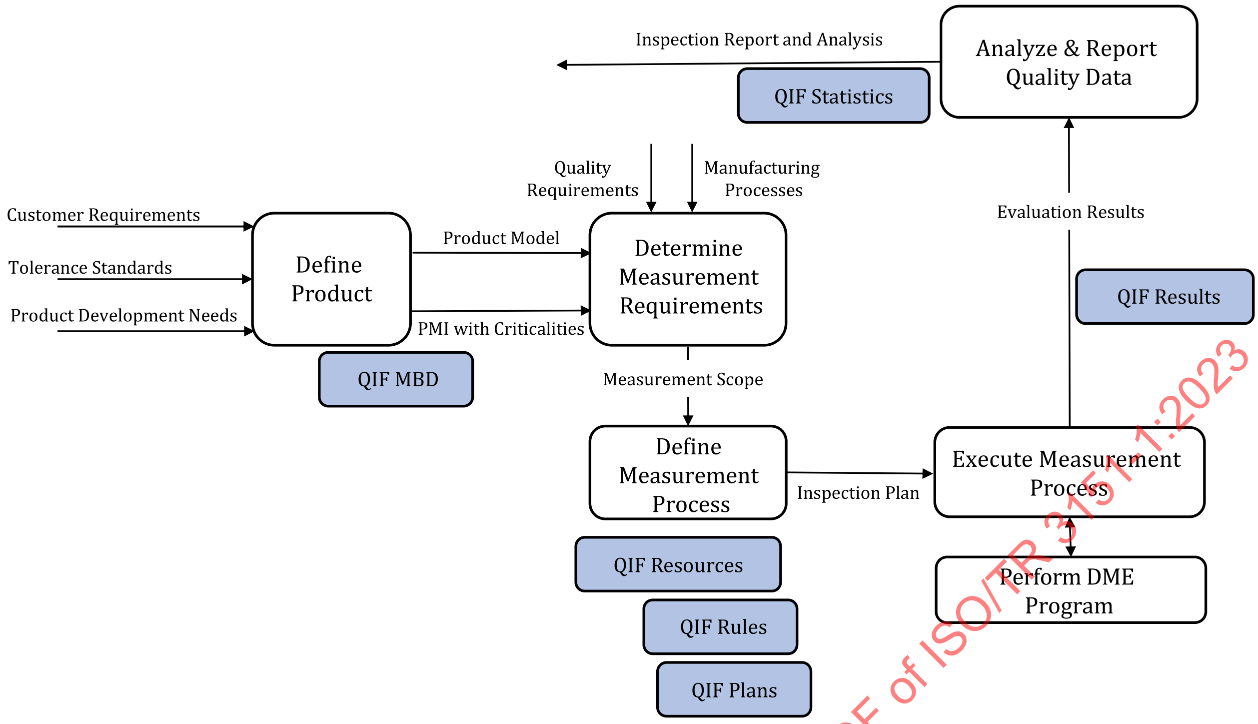


Figure 14 — Integrated metrology process with QIF standard[3]

5.4 PLM-MES Interface

5.4.1 General

Although a PLM-MES interface standard does not exist, there are technologies that play a similar role or are related. These technologies can help to define the PLM-MES interface.

5.4.2 Engineering change management (ECM)

One of the goals of managing work procedures in the engineering domain is to systematically manage design changes. One design change can be expressed as a single characteristic event, and the event can be used as a delimiter along the process of Engineering Change Request (ECR), Engineering Change Order (ECO) and Engineering Change Notification (ECN). [24]

When a product problem occurs or a new improvement occurs at the product development, manufacturing, or sales site, the person in charge at the site will explain their opinion in general sentences to the product development engineer, or, more specifically, pinpoint or request technical review and action. Such a request generates one task in the product development procedure. The ECR usually includes the requestor information, the content of the request, and the date on which the action is required. This is a path that delivers feedback of error data from the manufacturing site.

In personalized production, design change management is more important. This is because the scope and number of design changes are increased compared to the case of mass production. It is said that 15,000 design changes occur during the process of producing one ship. Depending on the scope or size of the design change, the reaction can be different. Small changes are handled within the manufacturing department and in many cases, they are not recorded, or counted. If the scope or importance of the design change is so big that the customer's approval is required, the scale or scope of the change task also increases. The scope of design change can be classified by levels of scope.

Errors found in the production site which are of great scope or importance are the main subjects of this standard interface between PLM and MES. ECR is notified to the design department, and design changes and additional procurement can be made. Visualization elements for 3D error feedback are the major concern in ISO 3151-2.

Change management is an important issue that is usually addressed in the PLM domain. In order to expand change management to a wider range scope, it is necessary to collect and check problems found in the production process through MES and communicate with PLM to solve the problems. An interface between PLM-MES is required for wider-scale change management. Participation and cooperation with the PLM domain helps to solve the problems found during the production process.

5.4.3 eBOM or mBOM

eBOM is used during the development phase or design phase of a product. Technical specifications of parts or modules, design information, drawing data and detailed information of parts are provided in eBOM.

mBOM is a list of parts required for assembly of a product. It displays parts and material information and factory facility information necessary for manufacturing (processing, assembly, outsourcing). It is also used for production schedules, production indicators, process management, and parts preparation (schedule to place orders with suppliers). Table 2 summarizes the differences between eBOM and mBOM[35].

Table 2 — Difference between eBOM and mBOM[35]

Items	eBOM	mBOM
Creation/usage department	Design	Procurement, production management, or manufacturing
Purpose	— Component configuration management — Cost estimation	— Production schedule — Production statistics — Process management — Parts preparation
Data	— Specification of components and modules — Design information — Technical information	— Parts and materials necessary for manufacturing — Process sequence
Grouping of components	— Position or function	— Procurement unit — Manufacturing management unit

However, the above description and comparison are suitable for the mass production industry and should be arranged differently for the engineering plant industry, where ETO production has been carried out from the beginning of the industry hundreds of years ago. The differences between eBOM and mBOM are summarized below, with examples of the shipbuilding and offshore industry.

Process design is in many cases carried out by the production management department. In shipyards, block division is an important part of process design. mBOM is made through production design, including process design in shipyards. In other product domains, block division can be described as module division, but in general, modules are often divided into functional units rather than into zonal units.

In automobiles, an air conditioner module is a module for a cooling function and is usually divided into an outdoor unit and an indoor unit. The air conditioner module is mostly outsourced as an integrated module. A similar function in a ship or engineering plant is called Heating, Ventilation, and Air Conditioning (HVAC). The automotive industry also uses the term HVAC. In particular, the term HVAC is commonly used in electric vehicles.

In the basic design stage, which is responsible for the functional design of the engineering plant, the HVAC function of the entire engineering plant is designed into one functional module, which determines the capacity and equipment for production. One HVAC system is designed for the entire engineering plant.

In the block-division stage of production, the engineering plant is split into 10 or more blocks, such as cutting pieces of a fish, so each block contains a part of the HVAC system. Many of the blocks contain ducts, piping, and equipment that correspond to the indoor unit of a car, and another block contains the main equipment of the HVAC system, which corresponds to the outdoor unit of the car.

If some blocks are outsourced abroad, the block division should be carried out at an early stage. Block division also plays an important role in the construction schedule management. In shipyards, schedule management is divided into large-schedule, medium-schedule, and small-schedule, and among them, the medium-schedule is dependents on block division.

If the size of a block increases, the same vessel can be divided into a smaller number of blocks, thereby the smaller number of blocks helps to improve productivity of the shipyard. In many cases, the capacity of the crane owned by the shipyard determines the size of the block. If the same ship is built at two shipyards, and the crane capacity of the two shipyards is 1,000 tons in one and 3,000 tons in the other, the theoretical productivity can differ by up to three times.

Since it is the same ship, the basic design uses the same design. The design and capacity of the HVAC system and the performance of the equipment used are the same. However, if the crane capacity of the shipyard is three times different, the size (weight) of the block can also be three times different, so the mBOM should have a different structure. Moreover, the block to be outsourced is often divided into smaller parts due to the limitations of the crane capacity or transportation capacity of the outsourcing factory.

Although the organization of each shipyard is different, block division experts work in the production engineering team within the production department, and the production engineering team divides the blocks in cooperation with the basic design department at the initial stage of ship design. Therefore, in the plant industry centred on ETO production, consideration of the construction method and process of block division is included in the basic design stage where functional design is carried out. As this trend is expected to increase in personalized production, the role of PLM-MES interface increases.

5.4.4 STEP-NC (numerical control)

In the era of smart manufacturing, manufacturing should focus on producing one-of-a-kind orders that could potentially include a collection of manufacturing methods such as automated NC machining, robotic machining, and additive manufacturing. The ultimate machine tool can link directly with CAD files and generate tool-path plans without going through the offline process planning phase[3].

ISO 14649-1[25] and ISO 10303-238[26] (also known as STEP-NC) aim to replace RS274D (ISO 6983-1) G and M codes.[27] STEP-NC connects CAD design data directly with downstream processes. Unlike G-code, STEP-NC describes "tasks" (information about what to do) to be performed instead of "methods" (information about how to do it) to perform a task on a machine tool.

ISO 14649-1 is an ARM-based implementation and ISO 10303-238 is an AIM-based implementation.

A STEP AP is composed of AAM, ARM, and AIM. AAM and ARM are developed by domain experts in the corresponding industry, and AIM is developed by IT experts or standards experts (see also Figure 10). AAM, ARM, and AIM are all expressed using a language dedicated to the development of the ISO 10303 STEP standard called EXPRESS, but the terminology is different for each industry domain and the modeling method of the product is also slightly different for each industry domain.

STEP-NC relies on the machine tool to interpret machine-dependent machining instructions according to local machining conditions. Local machining instructions are interpreted by individual CNC controllers, and this conversion maximizes interoperability between machine tools.

Smart manufacturing requires an adaptive CNC controller that can directly import STEP-NC files and pass the executed product model back to the CAD/CAM system. The adaptive CNC controller can understand the design intent and quality requirements of a product and devise an optimal manufacturing strategy according to the real-time local machining environment. Also, according to the online inspection results, the machining process and parameters can be adjusted. On the other hand, 3D printing responds to these demands by using simple parts and layering equipment.

5.4.5 Predictive maintenance

Predictive maintenance means predicting an abnormality of a device by monitoring its operating condition and performing maintenance in advance based on the operation data. The predictive maintenance solution integrates and analyses data collected by sensors to equip an intelligent system. The technology which manages and analyses big data is included in the platform.

It collects a large amount of operation data obtained from equipment or machines in operation using communication technology such as IoT. It predicts performance or abnormal symptoms with simulation technology installed in the digital twin (DTw) of the facility. Likewise, it is a technology that takes appropriate measures before a failure occurs in the facility. Artificial intelligence and big data processing are used in the technology.

5.4.6 Digital twin (DTw)

DTw technology enables various simulations by composing a digital replica of a physical product. It is similar to cyber physical system (CPS) and has many similarities to augmented reality (AR). The difference is that the DTw is supplemented with driving big data obtained through IoT, and this big data is analysed (including simulation) to optimally control or improve the physical twin (PTw), so that the two twins augment each other in near-real time[28].

The relationship between the DTw system and the PLM-MES interface can be a mutually beneficial relationship. For the implementation of the twinning function in the DTw system, the function of the PLM-MES interface can be utilized. In the DTw of a standalone production facility, the operation data of the facility can be directly transmitted to the facility DTw so there can be no role of the MES. However, since the MES manages the operation status of various facilities in a wider range of plant-level DTw, the MES can help the design department to provide feedback on errors found during manufacturing phases.

The twinning function is a feedback loop in which the operation data of the PTw is transmitted to the DTw, and the control or design change determined in the DTw is transmitted to the PTw to ensure optimal operation. The PLM-MES interface can be utilized as the connection path.

5.4.7 Open Applications Group Interface Specification (OAGIS)

The Open Applications Group Inc. (OAGi) is a non-profit consortium focused on best practices and process-based XML content for eBusiness and application integration. Members of OAGi are major suppliers of ERP software and some large users of such software[29].

The OAGIS is a standard within the supply chain domain that uses the XML format and specifies a standard way to pass data into and out of applications. According to the OAGIS standard, related information is grouped into a structure called Business Object Document (BOD) and over 120 BODs have been issued.

OAGi does not specify an implementation architecture (also known as an implementation framework). To date, three major B2B implementation architectures have been developed. They are RosettaNet's RNIF, Microsoft's BizTalk, and the vendor-neutral ebXML transport and routing specification. They provide the basis for interoperability between different vendors and in-house solutions. The OAGi policy is technology-sensitive, but not specific, and allows using existing open standards whenever possible.

Since OAGIS is a standard that interfaces ERP data with various business data, it has played a role as an indirect link establishing the PLM-MES connection and will play an auxiliary role when the PLM-MES interface is ready in the future (see Figure 3 and Figure 4).

OAGIS is standardizing data, mainly for ERP. In contrast to the content covered in this document, OAGIS is an upper-level data model that belongs to the business management area. However, most of the current PLM systems and MES systems are connected through ERP.

6 Visualization elements of the PLM-MES interface

6.1 General

There are many elements that can be visualized to interface PLM and MES. This document introduces only a few key elements for standardization. Many of the primitives used for visualization are already standardized in computer graphics or geometric modelling standards. What to visualize depends on the industry-specific use case, so more use cases can be added as needed. Figure 15 is a use case detailed in ISO 3151-2. 3D shapes and 3D notes are visualization elements of the interface between PLM and MES in the shipbuilding and offshore industry. Currently, WebTransCAD implemented based on X3D is used as a visualization tool.[30] WebTransCAD is a web-based CAD system for collaborative design. It is based on a macro-parametric approach and it supports collaboration among multiple designers over long distances[41].

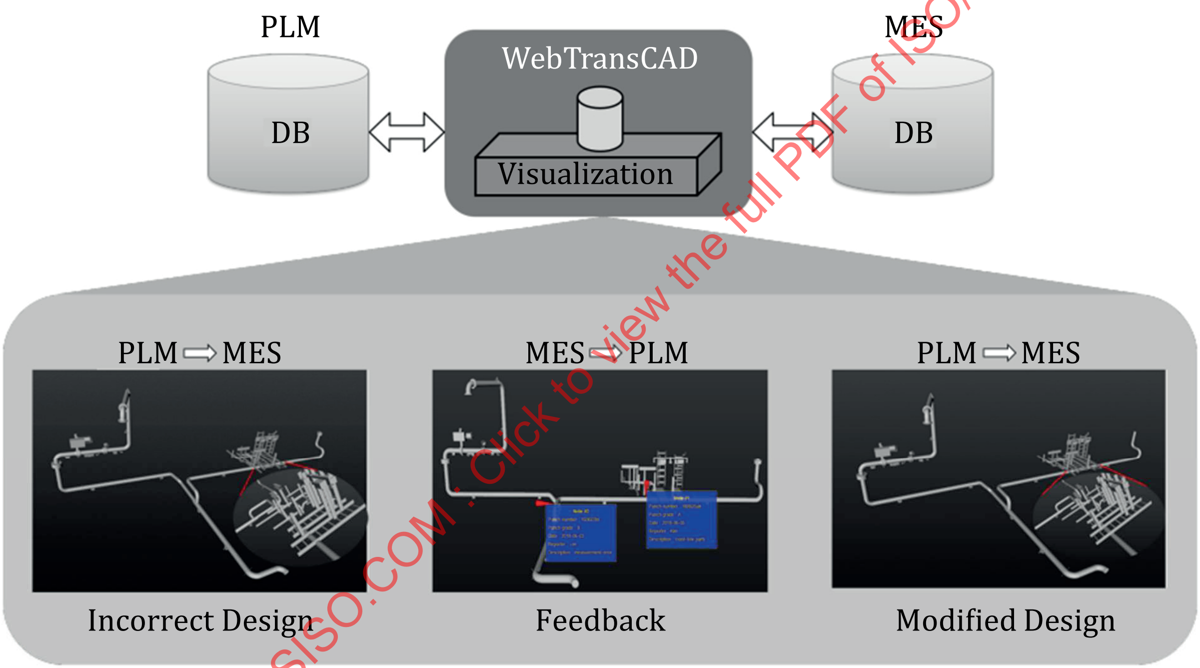


Figure 15 — 3D feedback notes with 3D shape of a PLM-MES interface[30]

6.2 Needs for 3D visualization in a PLM-MES interface

Because MES or ERP do not hold or handle 3D information, various problems arise in the manufacturing site. When problems are discovered in the manufacturing process, feedback to the design department is not smooth. Since both the design department and the production department work in a 3D environment, direct exchange of 3D data between the two departments is needed. It is helpful to visualize and share error information of the production in 3D between the design department and the production department.

Currently, these 3D functions are not provided by MES or ERP, so 2D images drawn by hand and pen on paper drawings are often delivered to the design department. The current detours of information exchange and the low level of information transfer create problems in improving efficiency (due to misunderstandings and delays).