



BSI Standards Publication

Unified reference model for smart manufacturing

National foreword

This British Standard is the UK implementation of EN IEC 63339:2024. It is identical to IEC 63339:2024.

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(IEC 63339:2024)

Einheitliches Referenzmodell für Smart Manufacturing
(IEC 63339:2024)

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European foreword

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

UNIFIED REFERENCE MODEL FOR SMART MANUFACTURING

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This document was drafted in accordance with ISO/IEC Directives, Part 2, and developed in accordance with ISO/IEC Directives, Part 1 and ISO/IEC Directives, IEC Supplement, available at www.iec.ch/members_experts/refdocs. The main document types developed by IEC are described in greater detail at www.iec.ch/publications.

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INTRODUCTION

“Manufacturing” refers to a range of human activities, from handicraft to high tech, and is commonly applied to industrial production, where raw materials and parts are transformed into finished goods on small to large scale by a series of interconnected processes. Smart manufacturing (SM) is an emergent characteristic of manufacturing achieved by digital technologies, gradually built up through digital transformation, combining diversity and uniformity, demonstrating continuous value delivery by a highly complicated collection of processes interacting on different time scales. In today’s manufacturing landscape, manufacturing is no longer characterized as a set of serial processes, but instead as a highly interconnected set of distributed processes that are able to cooperate on different time scales. A set of supervisory processes achieve coordination of these distributed processes using links that enable dynamic response to changing conditions in demands, supply, environment, energy and, other human or naturally caused probabilistic events. Since these probabilistic events are not known before occurrence, they often are disruptive and result in changing conditions.

The purpose of smart manufacturing is to accommodate those disruptive events, while supporting the introduction of new technologies and methods in a coordinated manner across the variety of customers, suppliers and stakeholders at various stages in the value chain.

Building upon the common knowledge and results found in IEC TR 63319 [9]¹ – A meta-modelling analysis approach to smart manufacturing reference models, as depicted in Figure 1 – this document specifies the unified reference model for smart manufacturing (URMSM) to create purpose-specific domain and application reference models for smart manufacturing initiatives by specifying the necessary structure and terminology for expressing such models. The URMSM is applicable across the many domains and applications found within a manufacturing enterprise.

Smart manufacturing reference models (SMRM), which conform to the requirements of this document, provide SM standards developers and SM practitioners with better opportunities for implementing models of production systems and products that take full advantage of technological innovations. These innovations occur during:

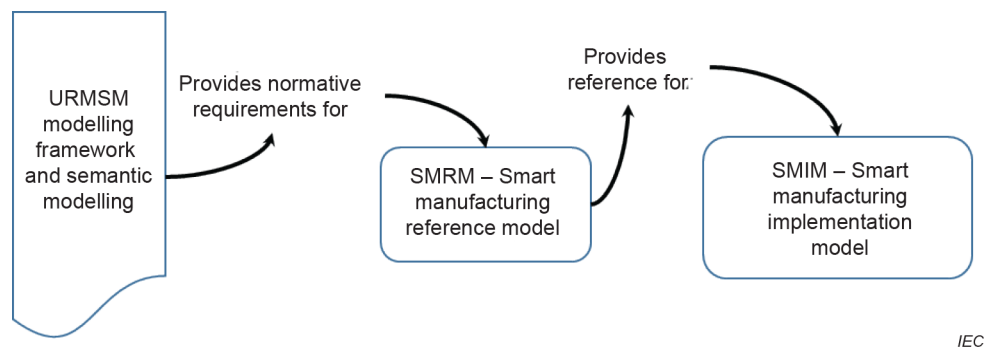
- analysis and synthesis using models of manufacturing,
- application of new materials, processes and facilities for manufacturing,
- understanding the emergence of digital twin concepts and other smart manufacturing technologies.

The URMSM is not one model or one model visualization. The URMSM is the specification for a family of reference models that share structural and behavioural properties intended to promote interoperability.

NOTE Subclause 8.2 provides more information regarding relationships among models and derivation relations.

The URMSM brings together concepts from existing works, both standards and practice, to support the variety of existing reference models, the adaptation of existing reference models for new uses, and the emergence of new reference models, all of which take advantage of the evolution in manufacturing technologies.

¹ Numbers in square brackets refer to the Bibliography.



IEC

Figure 1 – Using URMSM

The model-based approach of the URMSM has two major structural components. The first is a modelling framework to support various arrangements of manufacturing elements into conceptual configurations deemed pertinent to domains of manufacturing enterprises. The second is the conceptualization of semantic models that reside within the modelling framework. A concise URMSM terminology supports both the modelling framework and the conceptual semantic models.

Since smart manufacturing is essentially a human conception of improved manufacturing technologies and practices, differences in interpretation of that concept can lead some practitioners to over-simplify the complicated nature of perspective and property interactions in today's manufacturing systems. Objectifying the notion of 'smart' for manufacturing is a challenge since developers and practitioners have been getting smarter about manufacturing for over 200 years already.

For IEC work in a domain of similar complexity, the author of [48] summarizes "smartness" in the domain of Smart Cities as follows:

Smartness is an emergent characteristic of a system

- achieved by digital technologies,
- explicitly architected and engineered to reduce complexity,
- gradually built up through digital transformation,
- permanently demonstrating value delivery,
- combining diversity and uniformity,
- coordinating and cooperating between all the stakeholders.

Considering this characterization, the URMSM provides the means for creating reference models for smart manufacturing that enable emergence of more digitally oriented, engineered solutions for delivering additional value from manufacturing operations. The result is improved performance aspects with integrated and intelligent use of processes and resources in cyber, physical and human spheres to create and deliver products and services, which also collaborate with other domains within enterprises' value chains [16].

This document identifies a collection of criteria for arranging aspects of the smart manufacturing domain as reference models. The important relationships among manufacturing elements enable useful examination and derivation of practical designs in order to fulfil a defined purpose, and to maintain and improve the resulting system through methods for analysis and synthesis.

The URMSM provides insight into the modelling of aspects of manufacturing elements to consider when developing new elements. Smart support methods for conducting that development or modification can require an evolution from existing practice to a more unified model-based approach.

This document can be used to support the development processes of smart manufacturing, and to assure coherence and compatibility during the development of standards.

This document identifies ways to apply those aspects of manufacturing and the acumen essential to developing a smart manufacturing model for a particular industrial enterprise.

The URMSM goes beyond the representational features of manufacturing elements to enable examination of interactions among those elements through the use of models to address issues arising in the course of smart manufacturing initiatives.

Expectations regarding the outcome of a satisfactory URMSM are:

- enabling the examination of value within a value creation network;
- enabling a range of appropriate libraries such as use cases, interface definitions, models for semantics, information and data, and international standards as modelled views relative to modelling purposes for particular smart manufacturing situations;
- enabling representation as a multi-dimensional space composed from various collections of aspects to accommodate particular modelling purposes, such as aspects of production, aspects of product, aspects of smart technology, and their relationships over their respective life cycles;
- enabling assurance that information is consistently structured using standards for information, data and modelling languages, without ambiguous meaning, by applying semantic models and techniques;
- enabling efficient usability for the creation of tailored smart manufacturing models that address a stakeholder's particular concerns.

The URMSM supports all three modalities of interoperation (unified, integrated, and federated) that can co-exist within a modelling framework, albeit with varying extents of effectiveness and efficiency (see ISO 11354 [17]). Having a formal understanding of modelling frameworks enables more effective and efficient utilization of frameworks.

Clause 4 specifies extents of conformance to URMSM based upon meeting the requirements and recommendations in their entirety, as full conformance, or for particular subclauses, as partial conformance.

Clause 5 presents aspects of manufacturing commonly associated with 'smart manufacturing'.

Clause 6 presents modelling concepts essential for constructing suitable reference models in the domain of smart manufacturing.

Clause 7 establishes examination and derivation criteria for interoperation of aspects in manufacturing.

Clause 8 presents ways to use the URMSM to create purpose-specific reference models.

Clause 9 presents use cases for the URMSM and a progression of capability markers that indicate maturity in the application of the URMSM.

Clause 10 discusses ways to manipulate and use reference frameworks for extended analysis and synthesis for systems used in smart manufacturing.

Annex A presents concept areas of smart manufacturing.

Annex B provides a formal foundation for the URMSM approach including a modelling framework for URMSM.

Annex C provides an example figure of cascading reference models.

Annex D provides a summary of the meta-model for reference model analysis from IEC TR 63319 [9].

Annex E provides an introduction to the principles underlying semantic modelling.

Annex F provides a practitioner's modelling activity in a systematic usage of URMSM.

Annex G provides an extended example of the URMSM applied to a multi-dimensional manufacturing scenario.

UNIFIED REFERENCE MODEL FOR SMART MANUFACTURING

1 Scope

This international standard specifies the unified reference model for smart manufacturing (URMSM) using a terminology and structure, and establishes criteria for creating reference models, as specializations, that support smart manufacturing. The terminology and structure comprise a set of common modelling elements, their associations, and conformance criteria. These common modelling elements address aspects and perspectives of products and production and their lifecycle considerations.

The URMSM enables an approach for creating multiple models based upon a reference model that is sufficient for understanding significant relationships among entities involved in smart manufacturing (SM) and for the development of standards and other specifications.

The URMSM specifications in this document accommodate consistent, coherent, compatible specializations for relevant aspects of manufacturing systems consisting of equipment, products, and services within the domain of manufacturing. Provisions of this document are applicable for a new smart manufacturing reference model (SMRM) or elaboration of existing SMRM capabilities, for example, improving capabilities for analysis of opportunities and synthesis of technological advances, and improving interoperability of new and existing systems.

This document is not intended to prescribe interoperability considerations or data schemas of models. Standardization of content relative to models will be the subject of other standards and texts specific to those model domains.

2 Normative references

There are no normative references in this document.

3 Terms, definitions, abbreviated terms, acronyms and conventions

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

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

- IEC Electropedia: available at <https://www.electropedia.org/>
- ISO Online browsing platform: available at <https://www.iso.org/obp/ui>

3.1.1 aspect

labelled designation for a collection of concepts in a particular context

EXAMPLE functional, structural, information, security, availability, customer.

Note 1 to entry: An aspect is often expressed as a view across one or more model for a manufacturing system.

Note 2 to entry: Elements of an aspect can have functional, non-functional or other kinds of descriptors.

Note 3 to entry: The identification of an aspect is often the result of prior knowledge, experience and practice in the domain to which the aspect applies.

3.1.2**aspect interaction**

relationship between two or more *aspects* (3.1.1) where one aspect influences or is influenced by the presence of another aspect

Note 1 to entry: Influence includes but is not limited to dependence and control.

3.1.3**business**

series of processes, each having a clearly understood purpose, involving one or more person, realised through the exchange of information and directed towards some mutually agreed upon goal, extending over a period of time

[SOURCE: ISO/IEC 15944-20:2015, 2.2]

3.1.4**complex****<context>**

decision situation characterised by unordered decision variables, and ill-defined categories, criteria and dependencies

3.1.5**complicated****<context>**

decision situation characterised by enumerated decision variables, and well-defined categories, criteria and dependencies

3.1.6**concern**

matter of relevance or importance to a *stakeholder* (3.1.20) regarding a manufacturing system or element thereof

Note 1 to entry: Stated concerns are useful when relevant to the purpose of the modelling effort and refer to specific rather than categorical difficulties, problems, or requirements.

Note 2 to entry: Concern expression takes many forms, including among others: as questions about features or characteristics, as a keyword label for many related matters, and as expected quality attributes of the manufacturing system or its products and services.

[SOURCE: ISO/IEC/IEEE 42010:2022, 3.10, modified – added "regarding a manufacturing system or element thereof"]

3.1.7**dimension**

coherent collection of *aspects* (3.1.1) relevant to a *manufacturing domain* (3.1.12)

Note 1 to entry: The coherence requirement of the dimension can result in a collection of aspects that are unordered, partially ordered, fully ordered, or related in some other manner, or not ordered in any way (see 6.4 on dimensional coherence for further information).

3.1.8**element**

tangible or intangible constituent of a manufacturing system or of a product

Note 1 to entry: A constituent can range from atoms of raw material or logical constructs or items of information through manufacturing models or equipment and entire factories, plants or supply chains and added value networks to finished goods, and software and services.

Note 2 to entry: While the term as defined has broad meaning, designation of a specific meaning for an element of manufacturing or manufactured product includes an adjective to constrain the meaning appropriate to that particular manufacturing element.

3.1.9

facet

framework composed of one or more dimension(s) (3.1.7)

Note 1 to entry: Composition rules for coherent dimensions distinguish facets from other modelling frameworks.

Note 2 to entry: The location at which dimension aspects intersect are containers for models representing each of the intersecting aspects.

3.1.10

granularity

extent of detail or specificity

Note 1 to entry: The possible extent ranges from coarse to fine.

3.1.11

life cycle

lifecycle

life-cycle

set of distinguishable phases and steps within phases that an entity goes through from its creation until it ceases to exist

Note 1 to entry: The phases of a nested enterprise can be steps within the life cycle of the containing enterprise.

Note 2 to entry: The use of the terms 'phase' and 'step' does not imply any prescribed temporal ordering of activity types. The term 'life history' chronicles instance occurrence of activities.

[SOURCE: ISO 15704:2019, 3.12, modified – addition of lifecycle and life-cycle alternatives, and Note 2 to entry]

3.1.12

manufacture

any or all of the activities in the design, procurement, construction, commissioning, deployment, screening, testing, production, storage, labelling, packaging or distribution of products and production systems

3.1.13

manufacturing domain

portion of a *business* (3.1.3) dealing with the *manufacture* (3.1.11) of products

3.1.14

meta-model

description of modelling elements for use in constructing *models* (3.1.15) pertaining to a domain

Note 1 to entry: A meta-model is always relative to the model in which its modelling elements appear.

[SOURCE: ISO 19440:2020, 3.47]

3.1.15

model

simplified, purposeful representation of certain entities and their characteristics and relationships either (a) using a formalism, or (b) using an established or ad hoc modelling paradigm, approach, or technique

Note 1 to entry: An ad hoc model is more difficult to implement using an established design technique.

Note 2 to entry: A model can be a subset of a broader model.

[SOURCE: ISO 15704:2019, 3.15, modified – addition of "simplified, purposeful" and "and relationships"]

3.1.16**model kind**

category of *model* (3.1.15) distinguished by its key characteristics and modelling conventions

EXAMPLE Functional models, activity models, structural models, use case models, geopolitical models, analytic models and economic models.

[SOURCE: ISO/IEC/IEEE 42010:2022, 3.15]

3.1.17**perspective**

way of thinking about an entity of interest, especially as it relates to concerns

Note 1 to entry: The way one thinks about an entity can be influenced by one's beliefs, training, experience, etc.

[SOURCE: ISO/IEC/IEEE 42010:2022, 3.18, modified – removal of "stakeholder" and EXAMPLE]

3.1.18**reference architecture**

set of common architectural elements for a particular domain and their general relationships usable to derive a specific architecture from it in order to fulfil a defined purpose within that domain

3.1.19**reference model**

abstract description or domain-specific ontology consisting of an interlinked set of clearly defined concepts produced by an expert or body of experts in order to encourage clear communication

Note 1 to entry: A reference model can represent the component parts of any consistent idea, from business functions to system components, as long as it represents a complete set. This frame of reference can then be used to communicate ideas clearly among members of the same community.

[SOURCE: ISO 22549-1:2020, 3.11, modified – replacement of "framework" with "description"]

3.1.20**semantic model**

model kind (3.1.16) which conveys meaning with respect to the elements of the *model* (3.1.15) or to the model as a whole

3.1.21**stakeholder**

role, position, individual, organization or classes thereof, having an interest, right, share, or claim, in an entity

EXAMPLE End users, operators, acquirers, owners, suppliers, architects, developers, builders, maintainers, regulators, taxpayers, certifying agencies, and markets.

Note 1 to entry: A modeller, that is someone who conceives, constructs and utilizes models of various kinds as part of their customary program of work, is often considered a stakeholder in the project or product with which they are engaging.

[SOURCE: ISO/IEC/IEEE 42010:2022, 3.17, modified – replacement of "entity of interest (3.12)" with "entity" and addition of Note 1 to entry.]

3.1.22

supply chain

set of organizations with linked set of resources and processes, each of which acts as an acquirer, supplier, or both to form successive supplier relationships established upon placement of a purchase order, agreement, or other formal sourcing agreement

[SOURCE: ISO/IEC 27036-1:2021, 3.10]

3.1.23

system

combination of interacting elements organized to achieve one or more stated purposes

[SOURCE: ISO/IEC/IEEE 15939:2017, 3.38]

3.1.24

use case

technique for capturing potential functional requirements

Note 1 to entry: This technique employs the use of one or more scenarios to convey how the system interacts with the end user or another system to achieve one or more specific objective.

Note 2 to entry: Typically use cases treat the system as a black box, and the interactions with the system, including system responses, are as perceived from the outside of the system. Use cases are popular because they simplify the description of requirements, and avoid the problem of making assumptions about how the functionality will be accomplished.

[SOURCE: IEC TS 62443-1-1:2009, 3.2.132, modified – part of definition moved to Note 1 to entry]

3.1.25

value chain

entire sequence of activities or parties that provide or receive value in the form of products or services

[SOURCE: ISO 27917:2017, 3.1.4]

3.1.26

view

work product expressing a selective perception or representation of a *model* (3.1.15), which emphasizes some specific feature or characteristic and disregards others

[SOURCE: ISO 19439:2006, 3.25, modified – addition of 'work product expressing a' before 'selective', replacement of 'an enterprise model that' with 'a model (3.1.15), which', replacement of 'aspect' with 'specific feature or characteristic'.]

3.1.27

viewpoint

identification of one or more kind of *model* (3.1.15) useful for addressing a collection of related *stakeholder* (3.1.21) *concerns* (3.1.6)

Note 1 to entry: When the term viewpoint is used without any qualifier it refers to the general case. When the term viewpoint is used with a qualifier, the viewpoint applies to a specific collection of concerns, e.g. operational viewpoint, capability viewpoint, services viewpoint.

Note 2 to entry: A viewpoint identifies one or more models necessary and sufficient for expressing one or more enterprise model views that address the specific collection of related stakeholder concerns.

[SOURCE: ISO 15704:2019, 3.24]

3.2 Abbreviated terms and acronyms

ADT	Abstract data type
ALEI	Authoritative Legal Entity Identifier
AM	Additive Manufacturing
CAD	Computer Aided Design
EBNF	Extended Bachus-Naur Form
EDI	Electronic Data Interchange
IDEF0	Integration DEFinition for Function modelling
IIC	The Industry IoT Consortium
IoT	Internet of Things
GERA	Generalized Enterprise Reference Architecture
GUI	Graphical User Interface
IT	Information Technology
IVRA	Industrial Value chain Reference Architecture
KGI	Key Goal Indicator
KPI	Key Performance Indicator
MES	Manufacturing Execution System
ML	Machine Learning
MOM	Manufacturing Operation Management
NC	Numerical Control
NIST	National Institute of Standards and Technology
NLP	Natural Language Processing
OMG	Object Management Group
OT	Operation Technology
OWL	Web Ontology Language
QC	Quality Control
QCD	Quality, Cost, Delivery
RA	Resource Authority
RAMI4.0	Reference Architecture Model Industrie 4.0
RDFS	Resource Description Framework Schema
SM	Smart Manufacturing
SM2	Smart Manufacturing Standards Map
SME	Small and medium enterprise
SMIM	Smart Manufacturing Implementation Model
SMRM	Smart Manufacturing Reference Model
SMU	Smart Manufacturing Units (IVRA)
SSIF	Scandinavian Smart Industry Framework
SysML	System Modelling Language
UML	Universal Modelling Language
URI	Universal Resource Identifier
URL	Uniform Resource Locator
URMSM	Unified Reference Model for Smart Manufacturing
UUID	Universally Unique Identifier
XML	eXtensible Markup Language

3.3 Conventions

The phrase 'one or more' is interpreted as 'one or more than one', and therefore needs a singular verb form.

An abbreviation given in 3.2 stands for singular as well as plural form.

Annex A and Annex E use coloration in figures to signify distinct corners of the semiotic triangle. Blue indicates the concept corner, green indicates the symbol corner, and grey indicates the phenomenon corner in Figure A.2, Figure E.1, Figure E.2, Figure E.4, Figure E.5, Figure E.6, Figure E.7 and Figure E.8.

Annex B includes a set of symbols that use an alphabet in **AR HERMANN script bold** lower case with subscripts and superscripts, and *French Script MS* for uppercase bold as elements of logical expressions to characterize the modelling framework foundation for URMSM.

Annex D includes a set of symbols comprised of a "*" followed by a word or word phrase in italics, for example "**aspect*", that signify a concept within the meta-model extracted from IEC TR 63319 [9].

4 Conformance

4.1 Intended usage

The requirements specified in this document as URMSM are always with respect to an SMRM (or SMIM). The user of this document is someone who applies the stated requirements of URMSM to produce an SMRM or perhaps an SMIM. Conformance to this document only occurs by applying URMSM requirements to an SMRM or SMIM. There is only one URMSM – as specified in this document. No other URMSM can exist.

Requirements of this document are marked by the use of the verb "shall." Recommendations are marked by the use of the verb "should." Permissions are marked by the use of the verb "may".

This document is designed such that "tailoring" is neither required nor permitted for its use when making claims of conformance.

4.2 Full conformance

An SMRM can claim full conformance to URMSM when the SMRM demonstrates that the specification of the SMRM conforms to URMSM requirements of Clauses 6, 7, 8, 9 and 10.

This document also identifies four situations in which a claim of partial conformance with the provisions of URMSM are possible.

4.3 Partial conformance

4.3.1 Conformance to purpose and context requirements

When conformance is claimed for SMRM purpose and context, the claim shall demonstrate that the specification of the SMRM meets the requirements of 6.2, 6.9, 7.1, 8 and 9.1.1.

4.3.2 Conformance to dimensions and coherence

When conformance is claimed for SMRM dimensions and coherence, the claim shall demonstrate that the specification of the SMRM meets the requirements of 6.3, 6.4, 7.2, 7.5 and 10.1.

4.3.3 Conformance to semantic modelling of aspects

When conformance is claimed for SMRM semantic modelling of aspects, the claim shall demonstrate that the specification of the SMRM meets the requirements of 6.10, 6.12, 7.4 and 9.2.

4.3.4 Conformance to facets and frameworks

When conformance is claimed for facets and frameworks, the claim shall demonstrate that the specification of the SMRM meets the requirements of 7.6 and 10.3.

5 The URMSM in smart manufacturing concepts

Using a family of models approach where many purpose appropriate models can be derived from the same overarching paradigm, the URMSM qualifies methodologies for examining the impact of smart technologies in the context of SM initiatives and enables identification of many of the concerns practitioners need to address as they implement SM programs. Moreover, the URMSM becomes a set of principles and practices regarding:

- construction of representational frameworks for SM;
- guidelines for implementing SM reference models;
- suggestions or examples of existing or potential representations of SM reference models; and
- criteria for capturing the modelling elements necessary for decision-making in an SM context.

To enhance the representation and subsequent examination of SM initiatives, this document identifies three useful categories common to all manufacturing situations and that can cover the entire life cycle of manufacturing and its supply chain. These fundamental categories for understanding SM opportunities and achievement of positive outcomes are:

- the elements that comprise production and products from raw materials to finished goods in service;
- the relationships among those elements that capture the dynamic interactions of elements of production and of products; and
- production and product life cycles in a manufacturing environment.

These fundamental categories combine in a wide variety of ways to characterize SM initiatives. The focus of this document is a reference model that offers a unified way to represent the variety and uses of models to examine the interactions of manufacturing elements within the context of SM.

From the perspective of standards developers, a modelling framework, including the kind of framework envisioned for reference use in smart manufacturing domains (see Annex B), possesses two primary qualities related to the purposeful interoperation of manufacturing elements: 1) analytic, for identifying elements of manufacturing and their relationships that form a whole for the manufacturing enterprise with regard to a target operational system; and 2) synthetic, for identifying elements and relationships within the manufacturing enterprise that must interoperate to achieve a new whole or portion thereof as an operational system.

The analytic quality offers a decomposition approach while the synthetic quality offers a composition approach. For smart manufacturing, the analytic quality enables examination of the potentially disruptive impacts that come when new technology and new methodology are inserted into an established operational system. The synthetic quality enables the creation of new configurations of manufacturing elements and relationships that include smart manufacturing technologies and methodologies after any disruptive impacts are resolved and new interoperation opportunities are clear.

Exploitation of analytic and synthetic qualities provides the basis for the primary use cases for reference model use in smart manufacturing. For both analytic and synthetic qualities, an understanding of a firm foundation for modelling, the utility such a foundation provides, and the fitness of that foundation to achieve the modelling purpose are essential for efficient and effective use of the framework [57].

This document identifies four concept areas associated with SM (see Annex A):

- aspects of production and products that identify the manufacturing elements within a specific domain of SM,
- perspectives of production and products that identify the characteristics of importance to stakeholders within that domain,
- lifecycle considerations impacting these aspects and perspectives, and
- modelling of manufacturing elements using semantic models.

NOTE 1 Aspects are related to characteristics of the product or production system (the item to be modelled); perspectives are related to the stakeholder considerations (the user of the item).

This document identifies the semantic modelling concept as the means for expressing modelling content for the other three concept areas associated with SM. Various extents of semantic modelling allow sufficient elaboration of SM aspects that enable the analysis of opportunities, synthesis of advanced technologies and improved interoperability related to these concept areas of SM.

NOTE 2 Annex A provides additional information about the concepts areas and the use of semantic modelling.

NOTE 3 Clause A.2 provides user perspective for URMSM.

6 Reference model concepts

6.1 SM modelling

Modelling is a very effective approach to systematize system development and operation activities by use of advanced information technology. The digital transformation of modelling activities over the past 30 years now offers processing power and breadth of repository functions necessary to manage representation of very complicated systems in ways not previously possible. However, to reduce the unnecessary duplication of effort and assure the interoperability of components and systems, identification of and understanding of the commonalities within the many models of SM is necessary.

A reference model provides insight into the aspects of a system to consider when developing a new system or modifying an existing system and can provide mechanisms for conducting that development or modification. Reference models based upon the URMSM provide a common basis for the development of individual systems and enable their interpretation as a whole system by reuse of the common characteristic of the individual systems.

NOTE 1 Figure 7 and Figure C.1 illustrate ways in which reference models provide content from generic through more specific to particular models of SM initiatives.

NOTE 2 Annex B provides details regarding the structure of URMSM conforming SMRM.

This document recognizes that not all SMRM conform to URMSM requirements and recommendations: however, the intent of this document is to enable the creation of URMSM conforming SMRM as either new models or by elaboration of existing SMRM, usually by articulating the associated semantic models and establishment of coherence criteria.

The use of the term SMRM in this document always refers to SMRM that conform to URMSM requirements and recommendations. Many existing SMRM do at least partially conform to URMSM.

An SMRM conforming to URMSM specifies its intended use in a relevant manufacturing domain, with appropriate abstractions, including activities, processes, resources and information, and their relationships. Starting from the specification of a unifying reference meta-model (see IEC TR 63319 [9]), models that are more specific with respect to purpose can be derived in a systematic manner for achieving the target system configuration and implementation.

NOTE 3 Annex D provides an overview of the meta-model used in IEC TR 63319 [9] for analysing commonalities of several different reference models for SM.

EXAMPLE 1 The principles embodied in the URMSM underpin the structure of ISO/IEC TR 63306-1 [8].

URMSM specifies that relevant aspects of manufacturing with appropriate abstractions include their constituent activities, processes, resources and information, and their relationships. Starting from an SMRM, models that are more specific can be derived in a systematic manner for achieving the target system configuration and implementation.

Clarification and standardization of the URMSM at various extents of abstraction in SMRM are necessary to improve the efficiency of development processes by reusing constituent resources in system development and operations. This document can also be used as a guide for effective use of existing standards, and in finding gaps for missing standards.

NOTE 4 Annex D provides an overview of the meta-model used in IEC TR 63319 [9] for analysing commonalities of several different reference models for SM.

To improve coherence of semantic models and clarify the relevant relationships between production, product and the externalities of both, an SMRM should accommodate a wide variety of perspectives and offer ways to filter out those perspectives of little or no relevance for a particular purpose (see 6.9).

Much of the text in Clause 6 and Clause 7 paraphrases text from ISO/IEC/IEEE 42010 [15] and ISO 15704 [18]. Knowledge of these two standards can help users of this document better understand the conceptual basis for URMSM as a specification for SMRM. Annex D is also based upon these two standards.

6.2 Modelling purpose

A precursor for any activity that includes the generation of a model is the clear understanding of the purpose for undertaking the modelling activity. Further, since every model is an abstraction, either physically or logically, of an identifiable artefact, that purpose needs clear association to one or more aspects of that artefact.

Great care is necessary to clearly distinguish between the model of the artefact and the instantiated artefact itself. This distinction is often morphed from correspondence to merged identity, i.e. the model is treated as if it were the artefact rather than a representation of the artefact. This distinction is very important in the context of analysis and synthesis regarding the purpose of reference models where the artefact is usually another model rather than real-world instantiation. An aspect specified in a reference model likely refers to properties of an instance that is twice or more removed from its domain specific logical, physical or descriptive identification. The bundle of properties for the aspect appear in successive models associated with the life cycle phases, or appear in modelling elements in implementation models.

EXAMPLE 1 In the pharmaceutical industry, the notion of a vaccine (the instance) is a real world implementation. However, when considering the concept of a new vaccine, the steps of moving the vaccine from the laboratory to large scale production is very complicated. The "model" of making the vaccine requires careful supply chain integration from sourcing (glass vials, substrate for vaccine, etc.), reactors for vaccine production, filling and packaging of vials, tracking and tracing of vaccine ensuring proper environmental controls, and distribution through to the delivery to the public.

The artefact of an implementation model is the actual operational manufacturing system. Since that system has many aspects, many implementation models for the same manufacturing system can exist. Each implementation model relates to one or more aspect of the artefact that is the manufacturing system.

Because of the limited cognitive capacity of those generating models and of those using generated models, each modelling activity shall begin with a well-defined purpose that specifies the context, objectives of the modelling effort and focuses the modelling activity.

NOTE Objectives can be expressed in a number of ways, for example requirements, goals, opportunities as well as desired effects. Achieving objectives is more difficult when use cases are not available to elaborate objectives and shape viewpoints.

While a reference model can sometimes be used in the same manner as an implementation model, in most situations a reference model provides the basis for the generation of more specific implementation models. Thus a reference model can serve more than one possible implementation model purpose. Therefore, within this document the purpose of a reference model is to enable the creation and comprehension of implementation models within the domain of SM.

EXAMPLE 2 See Annex C for a description of the position the URMSM occupies in a hierarchy of specifications relevant to SM practitioners.

As a consequence of the extremely wide variety that today's manufacturing systems exhibit, many domain specific reference models are in use today. Some of these domain specific reference models are the subject of International Standards and consortia specifications [62]. The purpose of the URMSM is to establish criteria to guide in development of future domain specific reference models, whether for reference or implementation, across the entirety of manufacturing with particular attention for the incorporation of and evolution to the SM paradigm.

6.3 Modelling dimensions

Manufacturing enterprises are a complicated and often complex assortment of resources, people, processes and products, each composed of many distinct variables. To operate effectively and efficiently within the manufacturing context that applies knowledge of design and management of production to add value to products, goods and services, an understanding of the extent and relationships among these variables is necessary.

These variables should be captured in models that can represent the extent and relationships between the variables. The modeller applies existing knowledge to craft one or more model to represent approaches to address the concerns of stakeholders using appropriate modelling techniques. These models are used to generate model views aligned with viewpoints determined by the modeller to best elaborate one or more than one concern and possible ways to satisfy the concern.

These model views, perhaps as partitions or extracts of a larger model, comprise a collection of concepts in a particular context and thus meet the definition of aspect. Some aspects result from the aggregation or composition of views from more than one model. The multitude of possible aspects constitute a solution space corresponding to the problem space identified by the concerns. However, most often not all stakeholder concerns nor all aspects incorporating views are relevant to the purpose of the modelling effort.

To best analyse and utilize the knowledge present in aspects of manufacturing, the aspects shall be arranged into collections of aspects partitioned from all identified aspects such that the collection of aspects is characterized by coherence among the model views that distinguish the aspects. A coherent collection of aspects composed of model views is a modelling dimension of manufacturing. Many such dimensions of manufacturing are found in standards.

EXAMPLE The ISO/IEC 62264 series of standards [3] identifies several dimensions, i.e. functional hierarchy, role-base equipment hierarchy, and physical asset equipment hierarchy. ISO 15704 identifies in the generalized enterprise reference architecture of its Annex B various dimensions of an industrial enterprise, e. g. life cycle phases, modelling viewpoints, and genericity (instantiation).

As understanding of SM matures, and new technologies bear significant opportunities, and manufacturing systems evolve, modelling dimensions are likely to change in response. The URMSM accommodates both existing modelling dimensions, evolution of existing modelling dimensions, and ways for new dimensions to become available.

6.4 Dimension coherence

For a dimension to exhibit coherence, the dimension shall exhibit two primary criteria: 1) each aspect of the dimension has a well-defined context; and, 2) the contexts of the dimension's aspects have a well-defined common contextual relationship. The aspect and dimension context criteria can impose an ordering among the aspects although that ordering need not imply sequence, dependence or hierarchy among the aspects. The ordering of aspects can be as independent aspects of equal worthiness with respect to the modelling purpose arranged for that purpose and thus subject to rearrangement for a different purpose (see 7.2.1).

NOTE 1 The two primary criteria for context definition can occur without regard to order or sequence of achievement. Sometimes each aspect has a well-defined context and from that collection of contexts the dimension context is derived. At other times, the dimension context gets well-defined and individual aspects within that dimension context are identified with selection of that portion of their individual aspect context that fits the dimension context.

Models of aspect can range from very abstract graphical information models or textual descriptions to highly detailed data models or activity models. These kinds of models are among a wide variety of modelling and descriptive techniques that modellers can employ. Often different modelling techniques for the same context are necessary to effectively communicate with different groups of stakeholders and designers of manufacturing elements.

Common contextual relationships among aspect contexts can be as simple as identical model artefacts appearing in each aspect context, thus giving them a common element or relationship, or as complicated as a single semantic model that spans all of the dimension's aspects.

To serve the needs of SM practitioners and those developing SM standards, a well-defined context and associated detail are necessary at a modelling purpose appropriate extent of granularity and fidelity within that context. SM practitioners often are given a context that is ambiguous or overly broad, for example highly generalized, and at the same time are given detail without a proper context for its application. The result is that they get information without proper context and then assume a context that was not intended. This situation can arise using multiple standards that are not harmonized for interoperation, i.e. there is no condition under which the standards pertain to the same context.

NOTE 2 Sometimes the segments of a dimension can be adapted or rearranged to help align standards to a context.

EXAMPLE 1 Using the NIST AM model [42] the dimensions of machine, material, and product interoperate in the context of operations to produce a part, but are otherwise almost disjoint.

NOTE 3 Subclause 7.2.1 specifies requirements related to context more formally as common type, defined inter-relationships, and relevance to purpose.

The utility of the modelling dimension for analysis and synthesis in the domain of SM is directly related to the granularity and fidelity of the semantic models that provide the descriptions of aspect context and common contextual relationships among the aspects of the dimension. In addition, as the granularity and fidelity of the semantic models become more closely aligned with the actual manufacturing reality, the sensitivity of the models to detect and identify the consequences of disruptive change in the manufacturing environment increases.

EXAMPLE 2 Marketing needs a different dimension of granularity than fabrication, or, they can use the same dimension but at different extents of granularity. If the purpose of the modelling effort is to serve both of those stakeholders, then the semantic model needs to support both uses by enabling specific views extracted from one or more model that spans the concerns of both.

EXAMPLE 3 In pharmaceutical manufacturing, the production of the vaccine (the product) requires a detailed model for reactor design and operation; changes to the recipe for the vaccine can result in detailed reactor model changes, or a simpler set of operational recipe steps; changes to reactor design, can also affect the manufacturing line that fill and package the vaccine into vials.

NOTE 4 The emphasis and effort to construct 'digital twins' is a direct result of comprehending the utility of high granularity and high fidelity digital semantic models for extant manufacturing elements of the physical world.

6.5 Stakeholders

Among the many stakeholders with concerns relevant in an SM context, two kinds of stakeholders, SM standards developers and SM practitioners, are primarily involved in the use of this document, which serves as a reference for more detailed activities that do impact all kinds of stakeholders of a manufacturing enterprise and its supply and value chains.

SM standards developers are those individuals and organizations charged with specifying requirements related to conducting SM system activities. Their work ranges from reference models for enterprise and system architecture description through use case scenario development to techniques for the semantic modelling of manufacturing elements. SM standards developers should provide enabling resources, for example, tools and model documentation, for downstream SM initiatives.

SM practitioners are those individuals and organizations that participate in the application of tools, technology and methods, anywhere in the supply or value chain, for implementation of SM initiatives. Where gaps exist in existing standards or methodologies, SM practitioners should work with SM standards developers to define new SM requirements to address identified SM concerns.

Both SM standards developers and SM practitioners can conceive, construct or utilize models of various kinds.

6.6 Concerns

A concern is a substantive, focused expression of interest about one or more element of a manufacturing system from the perspective of one or more stakeholder. The primary focus of SM standards developers should be to accommodate the needs of SM practitioners by providing the means and methods for specifying a coherent viewpoint relative to those concerns.

The concerns of SM practitioners generally relate to domain specific and purpose specific information, methods and expectations for modelling outcomes they can apply directly to support SM initiatives. Because SM practitioner concerns result from highly focused practical application perspectives, SM standard developers should provide a comprehensive reference model with a broad range of capabilities for expressing, examining, and enabling SM practitioner activities.

The expression of a concern can take many forms. Most useful are concerns stated as questions about features or characteristics, as a keyword label for many related matters, and as expected quality attributes of the manufacturing system or its products and services. Concerns also arise from detailed use cases that can elaborate many distinct concerns related to an SM scenario.

6.7 Use case

An effective way for SM practitioners to document their concerns is to prepare a use case that employs one or more scenario(s) to convey how a manufacturing element interacts with the end users or other manufacturing elements to achieve a specific goal. A use case offers the opportunity to elaborate one or more concern(s) to provide guidance to the SM modellers, whether standards developers or practitioners, as they identify viewpoints and create views meaningful to a variety of stakeholders. A use case is particularly effective for identifying and presenting behaviour for innovative new technologies or novel application of existing technologies.

To aid the SM standards developer, SM practitioners should prepare use cases that detail to an appropriate extent a manufacturing scenario and expected outcomes to serve as a source of SM practitioner perspective concerns.

Multi-scenario and multi-concern use cases often use more viewpoints to address the use case. These more complicated use cases can provide modellers with additional information relative to the fit of viewpoints into a satisfactory modelling paradigm for the purpose of the SM modelling effort.

NOTE 1 The use case is most relevant when the scope of the use case falls completely within the purpose of the SM modelling effort for which it is submitted, and the outcomes described in the use case are unambiguous.

A use case can take one of several forms depending upon the granularity and fidelity of the purpose for which it is generated. A use case can cover abstract situations or very specific situations. Business use cases tend to be more abstract with a common set of terms from the business sector and can exist at different layers of an organization; however, as use cases add detail, the terminology and methodology starts to diverge and linkage to a business case becomes less clear.

While use case application scenarios can be across industry, a repository of use cases is often most useful across enterprises within an industrial sector.

NOTE 2 The topic of use case repository is not covered in the URMSM explicitly.

Several use case templates and a growing number of use case repositories are available, for example IEC 62559 [5]. Use case templates and repositories can be resources for adaptation to specific domain concerns.

Manufacturing facilities include a range of different stakeholders and different use case perspectives and requirements, some of which can often be shared or overlap. IEC TR 63283-1 [7] discusses this overlap as it pertains to terminology.

NOTE 3 Since an aspect is related to the view derived by application of a viewpoint, and a viewpoint draws upon use case content, a use case is conceptually a basis for an aspect of SM.

SM standard developers and SM practitioners should utilize use case techniques to verify concerns and validate proposed model views with stakeholders.

6.8 Viewpoints and views

A modelling viewpoint serves to collect subject matter in the form of clearly stated stakeholder concerns, and to establish conventions for the creation, interpretation, analysis and use of model views with respect to the collected concerns. That viewpoint should capture relevant practitioner concerns and accommodate known modelling concerns to assure a well-defined opportunity for enabling the creation of models and modelling views that address those particular concerns. Viewpoint conventions can specify one or more modelling paradigm or model kind to use when constructing a relevant model, usually in some form of engineering model. The conventions can also include less formal descriptors to guide view expression.

The model views, either as an entire model or portions of one or more model, should provide stakeholders with the outcome information necessary to make informed decisions about further modelling activities or implementation activities.

NOTE See ISO/IEC/IEEE 42010 [15] for more information about viewpoints, model kind, model and view as applied to enterprise and system architecture description.

6.9 Perspectives

6.9.1 Use of perspective

The URMSM provides ways to arrange or examine the semantic model(s) from several perspectives relative to a particular modelling purpose. The term 'stakeholder perspective' signifies the way in which a stakeholder conceptually thinks about the SM system of interest.

A semantic model of an SM system of interest shall include consideration of the elements of each aspect of manufacturing that are important to the purpose of the modelling activity as expressed by the stakeholder concerns relative to that purpose.

To present the many aspects of the system of interest relative to modelling purpose, and to satisfy the concerns of stakeholders, a modeller groups the representation of manufacturing elements into models relating those elements to each other. From these models the modeller projects views to articulate aspects of the system of interest that comprises the manufacturing elements, and are consistent with the specified modelling purpose. Often highly related aspects are collected into modelling dimensions to aid comprehension of those relationships by stakeholders. The term 'analytic perspective' signifies the way in which the modeller groups manufacturing elements into aspects of manufacturing.

NOTE 1 Often the relevant aspects of a model are arranged into a descriptive framework to satisfy a stakeholder perspective for decision support. A modelling framework typically arranges relevant aspects to satisfy a modelling purpose, which can provide several stakeholder perspectives by projecting relevant aspects of interest to the stakeholder, or can provide the analytic frameworks necessary for particular analytic techniques and methodologies.

Stakeholder perspectives are usually external or at the boundary of an SM system because perspectives are ways of thinking about the system. The analytical framework usually has internal considerations resulting from modelling activities driven by those external perspectives.

NOTE 2 The stakeholder perspective can be thought of as input to the modelling activity while the analytical framework can be thought of as the output of the modelling activity. During the modelling activity, modelling viewpoints specify the manner in which stakeholder perspectives result in the creation of the analytical framework.

6.9.2 Stakeholder perspectives

Stakeholder perspectives of SM initiatives are the result of their responsibilities, authorities, training and experience in manufacturing. These stakeholder perspectives drive the development of use cases and concerns from which viewpoints are derived that capture those drivers.

6.9.3 Analytical framework

An analytical framework deals with the creation and arrangement of aspects into collections identified as dimensions of SM. Each dimension or intersection of dimensions forms an analytical orientation that complements the stakeholder perspectives. An analytical framework arranges the results of viewpoint modelling to enable examination of aspects in relation to modelling purpose.

6.10 Aspects

An aspect is a way of characterizing the structure, quality or behaviour of a manufacturing element as a single conceptualization potentially composed of many concepts. A label or name identifies the aspect conceptualization that usually includes many more particular concepts. That characterization usually applies to the manufacturing element with respect to a particular context and the characterization can change when the context changes. Therefore, most often aspects are given broad characterizations that can apply in many contexts while retaining focus on those features or properties that distinguish the aspect. Well-specified aspects offer a way to categorize features and properties of elements so they can be referenced collectively and assessed in different situations, which are different views of the same aspect but in different contexts.

Each aspect within an SMRM shall be expressed by a semantic model that specifies the context and any constituents of that context applicable for the aspect as used in the SMRM. The semantic model should be sufficient to enable inclusion of the aspect into a coherent collection of aspects.

Because aspects are applicable in different situations, they are often identified as 'cross-cutting concerns', i.e. they are embedded into many different concerns of stakeholders with the same basic characterization but elaborated for concern context. A viewpoint can make use of this embedding to specify aspects for inclusion when constructing a model to produce one or more view(s). Conversely, a viewpoint can specify one or more view(s) to characterize an aspect. An aspect can be characterized by views from more than one distinct viewpoint.

NOTE In some situations an aspect can be considered to be the view according to a viewpoint.

Aspects are often labelled by reference to a context using a succinct term, for example, security, safety, element features. Aspects are usually decomposable into sub-context for specific domains, for example physical safety. The context associated with an aspect can be functional or more often non-functional as with the –ilities for various attributes of quality, such as sustainability and compatibility. Aspects are the primary discriminants in modelling frameworks, for example the OMG Unified Architecture Framework [30].

EXAMPLE The aspects of the product specification for a part (manufacturing element) can have a set of features and a material specification. Features based on a product design context are considered in the production system context. Market requirements drive product design specifications, such as materials and features for the part. A change in the material and features will change the manufacturing processes needed to make the part; a material change could affect the speeds and feeds of a machining process. Tooling, fixturing, energy consuming, scraping, and material handling are processes related to the primary machining process. Requirements for the volume and throughput for the part could allow for other considerations, such as additive manufacturing. A one-off manufacturing lot versus a large lot size or specific material properties affects those considerations, as well as the size, weight, whether multiple machines and processes are required for the product features. For a high-volume product, a specialized machine can be considered. Modelling of the part based on those specifications, as well as the production systems, can enable tradeoffs to be made more expediently if the product model and the production model have corresponding semantic models.

Identifying and characterizing aspects of a manufacturing element in the proper context, whether that element is an entire manufacturing enterprise or the capability of a component, is essential to configuring and utilizing URMSM to create an SMRM or implementation model.

To maximize the potential for semantic models of aspects to enable the analysis and synthesis of aspect interactions in the context of SM, models of aspects should use the most semantically expressive digital representation available.

6.11 Life cycle modelling

The notion of life cycle is taken from biology where every living thing experiences the same pattern – birth, growth, maturity, decline and death – the cycle of life. This pattern dominates all living things and can be extended by abstraction to conceptual things, e.g. systems. By extension, the notion of life cycle applies to SM enterprises, services and products where each instance thereof exhibits the life cycle pattern during its lifetime. The same basic life cycle pattern articulates in many different ways for different purposes and situations. Since many different things comprise every enterprise or system, there are many life cycles occurring, one for each thing. Every project, every component, every artefact and every product have a life cycle and because some are constituents of others, life cycle activities appear in repetition and are almost always overlapping.

SM recognizes that the characterization of life cycle is a segmentation into life cycle phases with respect to mutual dependencies and similarity of model content rather than a presumed chronological sequence. Different life cycle phases can have different models and different models can exist at an individual life cycle phase. Life cycle phase models can be concurrent, repeated, or empty as the modelling situation necessitates.

A SMRM should clearly delineate the life cycle phases, as identified by the using organization, pertaining to the particular SMRM.

NOTE 1 Feeding model information forward and backward in life cycle phase activities enables value added iteration of processes that improves quality. A phase activity can modify or extend the model of a previous phase activity to the evolving needs of a subsequent phase activity.

The notion of life history captures the chronology of life cycle phase activities as they occur during a lifetime. The life history is often segmented into stages. While a reference model most often specifies static model representations, understanding the consequences of change can require knowledge of chronological sequence of activities experienced by a particular entity during its entire lifetime. ISO 15704 [18] presents an extended explanation of life cycle and life history concepts.

NOTE 2 Other standards, particularly those aligned with ISO/IEC/IEEE 15288, use the term life cycle stage instead of life history stage.

6.12 SM semantic modelling

6.12.1 Semantic modelling overview

To understand what it means for aspects to interact, some common form of expression is necessary for use to compare and contrast their respective properties and behaviour. Digital models provide syntactic forms of expression that enable human examination to occur more quickly over a broader range of situations. To take full advantage of digital technologies to supplement or go beyond human examination of aspect interactions, the form of expression needs to be suitable for machine computation. With very few exceptions, digital modelling languages only provide the semantic, or meaningfulness, complementary form terminology, but not the axioms necessary for inference processing based on these models that enables automation of analysis and synthesis.

For most models that are based upon graphic images, the meaning of model elements and their relationships is limited to syntactic expressions, which are suitable for interaction when the semantics is unambiguously stated as text but not suitable for analysis and synthesis when the meaning is only revealed through implication or inference. Model meaning then depends upon interpretation by a human observer, often resulting in different interpretations.

NOTE 1 Many graphical modelling tools provide a non-graphical expression of the model as well, but most often without explicit semantically informative content and complete specification of semantics.

Different representations like textual descriptions, abstract information models and data or activity models can model aspects that comprise functional or non-functional features of products or production. In the case of SM, the basic modelling artefacts are information, data and activity to be identifiable in aspect characteristics.

A unified semantic model, based on graph and data type algebras, should support the representation, analysis and synthesis of an interoperating SM network dealing with information, data and activities in the context of SM.

Models and their tools that use graph and data type algebras are semantic models that are symbolically executable and thus form the foundation for a semantic analysis and predictive maintenance.

NOTE 2 By applying the GUI of tools with underlying graph and data type algebras, a kind of language support for writing semantic expressions enables tool-supported analysis beyond the structural analysis provided by XML or OWL [36].

Several articles and white papers [50] [61] provide a thorough discussion of the issues involved in conceiving and using models with semantic content sufficient to support the interoperability of digital system representations. In particular, two modelling formalisms enable the exchange of information to support automated interoperation – XML Schema [32] and the OWL [33] modelling language, where the former is "intended to characterize syntactic structure and the latter is intended to characterize semantic structure (or meaning)" [66].

NOTE 3 OWL makes use of the RDFS (Resource Description Framework Schema) to represent knowledge about things, groups of things, and relations between things in a computational logic-based language. Knowledge expressed in OWL can be exploited by computer programs, e.g. to verify the consistency of that knowledge or to make implicit knowledge explicit [33].

EXAMPLE 1 In this simple example, which is concerned with a part of a design by itself, the class that is the impeller within pump model “WBX-456A” can be defined using an OWL Restriction as follows:

```
ex -des:ImpellerInWBX-456A
    owl:equivalentClass [
        owl:intersectionOf (
            ex-rdl:Impeller
            [ owl:onProperty lci:partOf;
              owl:allValuesFrom ex-des:WBX-456A ]
        )
    ];
    rdfs:subClassOf ex-des: WI-57SS .
```

From this restriction, it can be inferred that an impeller that is part of a pump of type “WBX-456A” is of type “WI-57SS” [19].

Modelling tools intended to support SM shall provide the means for exchanging model content in both human readable and machine interpretable forms for use by other modellers and models. At a minimum the syntax should be well-formed using an established standard.

EXAMPLE 2 Modelling paradigms that support XML Schema forms of expression are generally suitable for schema matching processes, whether through human examination or machine automation.

NOTE 4 Models that are or contain images with undifferentiated content, while useful for some applications involving aspects, are not well suited for analysis or synthesis automation. Image tagging or a means to 'parse' the image for encapsulated digital content related to one or more other aspect can add differentiated content to the image, which makes at least that portion of the image amenable to computation.

Moving beyond the simple syntactic representation requirement, modelling paradigms with a formal syntax, for example those defined using an EBNF specification of their modelling language syntax [10], can provide opportunities for identifying semantic relationships between aspects from the modelling patterns provided by the EBNF specification [22] [21]. Some model schema matching techniques take advantage of this feature.

The next step up in providing aspect semantic models involves the use of meta-models for a particular domain where the scope of the domain can be quite large. ISO 19440 [21] (in the domain context of model based control) specifies constructs for enterprise modelling using the UML modelling language [11], which has an XML Schema conforming representation feature, and then provides meta-models for both manufacturing-oriented and service-oriented enterprises as configurations of those constructs.

At the top of the semantic modelling hierarchy are ontological theories that give meaning to concepts in relation to other concepts. Unfortunately, general ontological theories are of marginal utility for large bodies of knowledge because such knowledge bases are networks of interrelated concepts. However, these theories do form the basis for very useful domain specific ontology of the kind implemented using the OWL specifications [37].

EXAMPLE 3 Digital representations can span from the use of formal languages like OWL, a combination of logic, and algebraic graph theoretical technologies.

A good understanding of the relationship of semiotic concepts with modelling concepts is necessary to achieve digital models that provide the semantic, or meaningfulness, complementary form necessary for inference processing, which enables automation of analysis and synthesis. Further, semantic models of modelling languages are themselves models and as such have a life history where meanings can change over time.