INTERNATIONAL STANDARD

ISO 23704-3

First edition
2023-03

General requirements for cyber-physically controlled smart machine tool systems (CPSMT) —

Part 3: Reference architecture of CPSMT for additive manufacturing

Reference number
ISO 23704-3:2023(E)

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Foreword

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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 documents 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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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT), see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 184, *Automation systems and integration*, Subcommittee SC 1, *Industrial cyber and physical device control*.

A list of all parts in the ISO 23704 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

According to ISO/ASTM 52900, additive manufacturing (AM) is the process of joining materials to make a part from 3D model data usually layer by layer. With the advancement of various feedstocks, process technologies, and product design methodologies, AM contributes to realizing customized production, which is the key objective of Industry 4.0. Also, AM allows construction of complex geometry and other features that were previously impossible or impractical to manufacture.

Many institutions have long been devoted to technological development from the viewpoint of reducing downtime and defects and are considering smart technologies such as Internet-of-Things (IoT) as a new means to achieve this.

From the market perspective, many institutions have released various smart additive manufacturing systems (SAMS) based on their own concepts and local terminologies. This makes stakeholders confused about the common concept of SAMS, including end-users. For this reason, standards and substantial modelling for a SAMS are needed.

From the standards perspective, for standards on contemporary AM technology, there is a set of standards and a roadmap from ISO TC261/ASTM F42. For standards on smart manufacturing, RAMI 4.0 (IEC/PAS 63088) and IEC TR 63319 TR-SMRM provide a reference model for smart manufacturing on a high level. Even though some standards deal with Industry 4.0 enabling technologies, e.g. OPC-UA (IEC/TR 62541-1 and Reference [67]), MTConnect (ANSI/MTC1.4-2018), ISO/IEC 30141, IEC 62769, there are no standards specifying the SAMS.

The ISO 23704 series specifies general requirements on smart machine tools for supporting smart manufacturing in the shop floor via cyber-physical system control scheme, namely cyber-physically controlled smart machine tool systems (CPSMT).

Figure 1 shows the overall structure of the ISO 23704 series, including:

— Overview and fundamental principles of CPSMT in ISO 23704-1;

— Reference architecture of CPSMT for subtractive manufacturing in ISO 23704-2;

— Reference architecture of CPSMT for AM in ISO 23704-3.

Other related parts such as implementation guideline or reference architecture for other types of manufacturing will be added if and when necessary

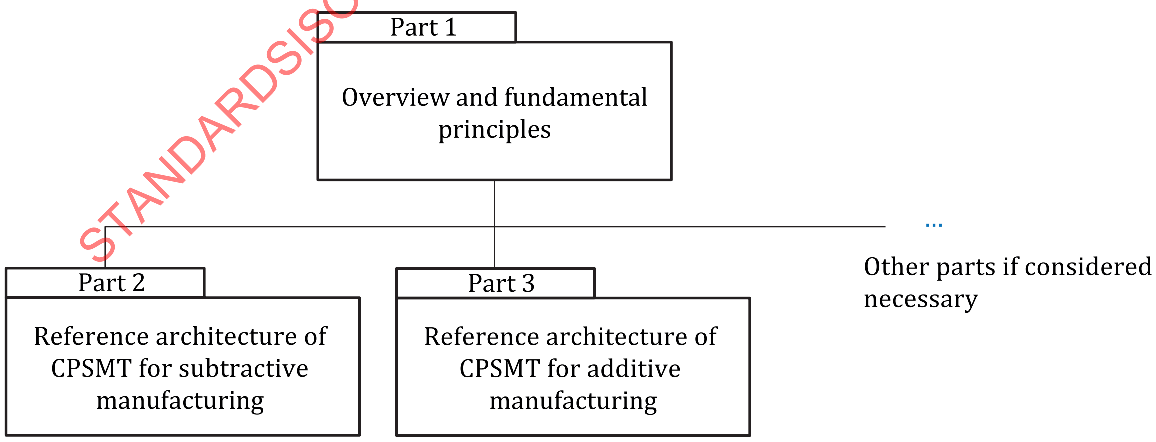


Figure 1 — Overall structure of the ISO 23704 series on general requirements for cyber-physically controlled smart machine tool systems (CPSMT)

This document can be used as a reference and guidelines for stakeholders such as, but not limited to:

— Design engineers in the area of SAMS,

— System architects in the area of SAMS,

— Software engineers working with the AM machine builders in the area of SAMS,

— Machine tool control vendors in the area of SAMS,

— Solution and service providers in the area of SAMS, and

— End users such as factory operators working with SAMS.

General requirements for cyber-physically controlled smart machine tool systems (CPSMT) —

Part 3: Reference architecture of CPSMT for additive manufacturing

1 Scope

This document specifies a reference architecture of cyber-physically controlled smart machine tool systems (CPSMT) for additive manufacturing (AM) based on the reference architecture of CPSMT as provided in ISO 23704-1 and the requirements for cyber-physically controlled smart additive manufacturing system.

The reference architecture of a CPSMT for AM includes:

— the technical requirements for the smart additive manufacturing system (SAMS),

— the reference architecture of the cyber-physically controlled machine tools (CPCM) for AM,

— the reference architecture of the cyber-supporting system for machine tools (CSSM) for AM, and

— the interface view of the CPSMT for AM.

This document also provides:

— stakeholder requirements for the SAMS,

— the concept of the digital thread,

— types of abnormality in AM, and

— use cases of reference architecture of a CPSMT for AM.

This document does not specify physical or implementation architecture.

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 for 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 23704-1, *General requirements for cyber-physically controlled smart machine tool systems (CPSMT) — Part 1: Overview and fundamental principles*

ISO 23704-2, *General requirements for cyber-physically controlled smart machine tool systems (CPSMT) — Part 2: Reference architecture of CPSMT for subtractive manufacturing*

ISO/ASTM 52900, *Additive manufacturing — General principles — Fundamentals and vocabulary*

3 Terms, definitions and abbreviated terms

For the purposes of this document, the terms and definitions given in ISO 23704-1, ISO 23704-2, ISO/ASTM 52900, 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, definitions and abbreviations

3.1.1
additive manufacturing component
AM component
single piece or group of pieces forming a functional unit within an additive manufacturing (AM) machine *unit* (3.1.15)

3.1.2
additive manufacturing function
AM function
function performed by an additive manufacturing (AM) machine *unit* (3.1.15) instance

3.1.3
additive manufacturing machine unit
AM machine unit
AMU
instance of a cyber-physically controlled machine tool (CPCM) for additive manufacturing (AM) in the reference architecture of cyber-physically controlled smart machine tool systems (CPSMT) for AM

3.1.4
additive manufacturing process
AM process
process of joining materials to make a part from a 3D model data layer by layer in the reference architecture of a cyber-physically controlled machine tool (CPCM) for additive manufacturing (AM)

Note 1 to entry: Definition is based on the ISO/ASTM 52900 definition of single-step AM process in Annex B.

3.1.5
additive manufacturing workflow
AM workflow
sequence of process steps involved in producing a physical part using additive manufacturing

Note 1 to entry: The AM workflow consists of a) product design, b) feedstock, c) build preparation, d) process control, e) post-processing, f) quality control, and g) part.

3.1.6
build motion
machine movements needed for creating a product with feedstock / support

Note 1 to entry: Feedstock and support are defined in ISO/ASTM 52900 in the context of additive manufacturing.

3.1.7
build process
realization of the material joining by providing a source of activation

Note 1 to entry: Joining means realization of consolidation of the raw material to create the final form using a material activation method.

Note 2 to entry: Example activation methods are binding mechanism, chemical reaction or heating.

3.1.8
cyber physical system unit
CPS unit
collection of functional entities responsible for advanced cyber-physical control

Note 1 to entry: ISO 23704-1:2022, 3.1.8 defines a CPS (Cyber-Physical System) as a physical and engineered system whose operations are monitored, coordinated, controlled and integrated by a computing and communication core.

Note 2 to entry: The CPS unit provides advanced control functionalities for the *machine tool unit* (3.1.13), interfacing with data from sensors, numerical control kernel / programmable logic controller, the cyber-supporting system for machine tool (CSSM), shop floor control system (SFCS), and unified interface system (UIS).

3.1.9
cyber-physically controlled smart additive manufacturing system
CPSAM
smart additive manufacturing system (SAMS) (3.1.14) viewed from the capabilities of cyber-physically controlled smart machine tool systems (CPSMT)

Note 1 to entry: See ISO 23704-1:2022, Clause 10 for the capabilities of CPSMT.

3.1.10
digital thread
framework that provides an integrated view of all data throughout the *AM workflow* (3.1.5)

Note 1 to entry: The digital thread manages a record of a product from its creation to its removal. The CAx chain (CAD, CAPP, CAE, CAM, CNC, CMM) is a key enabler for this, based on Reference [104].

Note 2 to entry: The data are interconnected in a series of feedback and feedforward loops.

Note 3 to entry: For more details on digital thread including the difference between digital thread and digital twin, see Annex B.

3.1.11
digital thread unit
instance of a *digital thread* (3.1.10), focussed on the operation phase, in the reference architecture of cyber-physically controlled smart machine tool systems (CPSMT) for additive manufacturing (AM)

3.1.12
feedstock / support handling
delivery (feeding), storage and management of the remaining feedstock / support on the machine, e.g. recoating and surface levelling mechanism in vat photopolymerization, powder feeding system in binder jetting

3.1.13
machine tool unit
unit (3.1.15) consisting of hardware that performs a series of machine tool functions

Note 1 to entry: According to ISO 14955-1, the machine tool function consists of machine tool operations (machining process, motion and control), process conditioning, *workpiece* (3.1.16) handling, tool handling or die change, recyclables and waste handling and machine tool cooling / heating.

3.1.14
smart additive manufacturing system
SAMS
additive manufacturing system that supports the vision, characteristics, and capabilities of smart manufacturing

Note 1 to entry: Details of smart manufacturing are described in IEC TR 63319[51].

3.1.15
unit
group of elements that constitutes part of the reference architecture of a cyber-physically controlled machine tool (CPCM) and a cyber-supporting system for machine tool (CSSM) for additive manufacturing

Note 1 to entry: The term “unit” here is used as an instance of a collection of elements.

3.1.16
workpiece
joined material forming a functional element that could constitute all or a section of an intended product

Note 1 to entry: The functional requirements for a workpiece are typically determined by the intended application.

[SOURCE: ISO/ASTM 52900:2021, 3.9.1, modified — term “part” changed to workpiece]

3.2 Symbols and abbreviated terms

For the purposes of this document, the abbreviated terms given in ISO 23704-1, ISO 23704-2, and the following apply.

AM	Additive Manufacturing
AMF	Additive Manufacturing File Format
CPCM	Cyber-Physically Controlled Machine tool system
CPS	Cyber-Physical System
CPSAM	Cyber-Physically controlled Smart Additive Manufacturing system
CPSMT	Cyber Physically controlled Smart Machine Tool system
CSSM	Cyber Supporting System for Machine tool
KPI	Key Performance Indicator
SAMS	Smart Additive Manufacturing System
SFCS	Shop Floor Control System
SFDS	Shop Floor Device System
STL	Standard Transformation Language
3MF	3D Manufacturing Format
UIS	Unified Interface System

4 Conformance with the CPSMT reference architecture for additive manufacturing (AM)

To claim conformance, a definition of specific system architecture provided by a vendor or system integrator should use the terminology, architectural concepts, and have the capabilities defined in this document, within the scope of their specific use cases.

5 Goals and objectives of the CPSMT reference architecture for AM

The CPSMT reference architecture for AM describes an architecture of smart machine tool systems for AM based on the generic reference architecture specified in ISO 23704-1. It provides guidance for designers developing smart machine tool systems for AM and aims to give a better understanding of smart machine tools to the stakeholders of such systems.

NOTE Examples of stakeholders are machine tool builders, CNC vendors, solution vendors, service providers, customers and end-users.

The CPSMT reference architecture for AM ensures the following important standardization objectives:

— transparent and unambiguous communication between all interested parties of an SAMS,

— the interoperability of an SAMS with related hardware devices, software, services, and manufacturing systems,

— the quality / capability of an SAMS,

— the use of an SAMS, and

— systematic development, modification of an SAMS.

Figure 2 illustrates the context of how the CPSMT reference architecture for AM is derived and viewed from various perspectives.

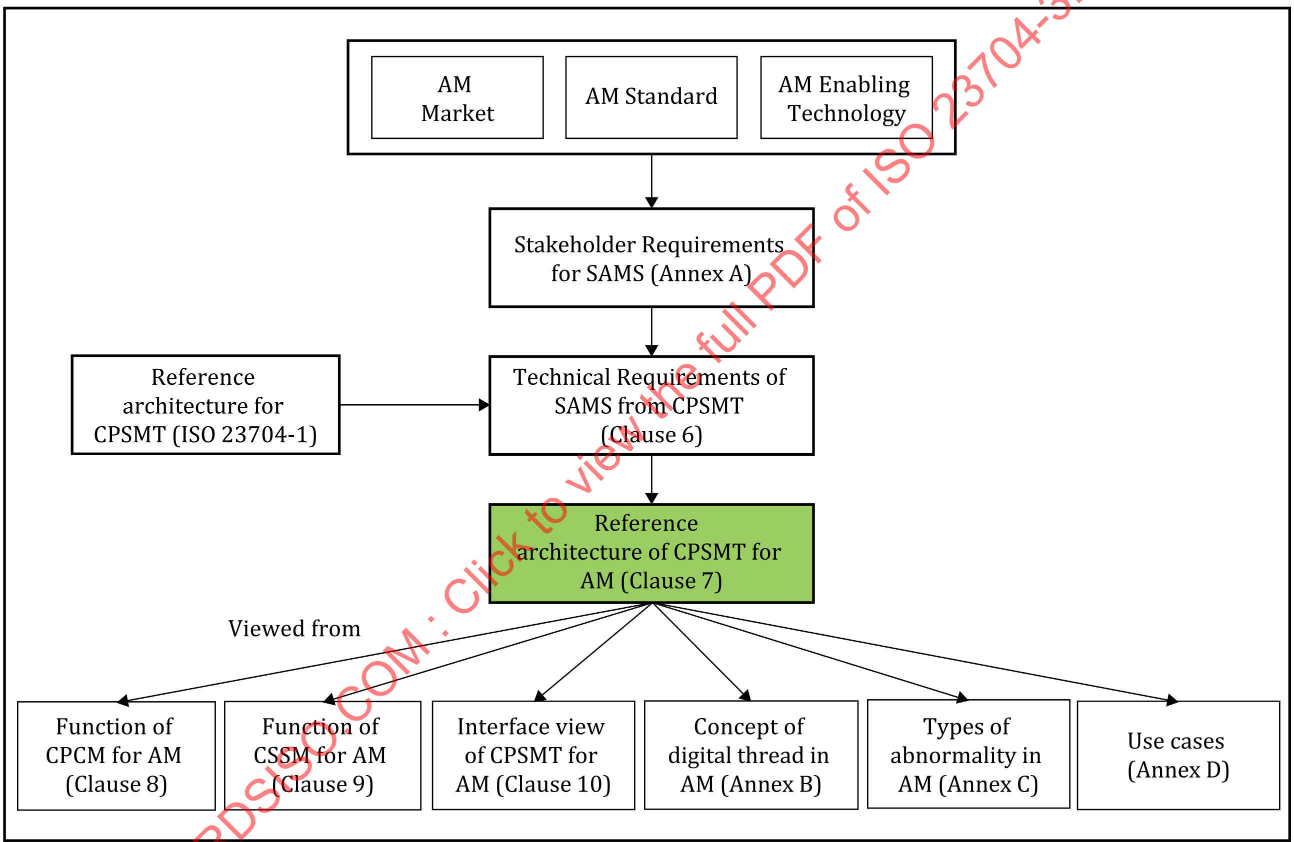


Figure 2 — Context of the CPSMT reference architecture for additive manufacturing (AM)

Based on Figure 2, this document has the following descriptions:

— The technical requirements of an SAMS from the CPSMT perspective in Clause 6,

— The reference architecture of a CPSMT for AM in Clause 7,

— The reference architecture of a CPCM for AM viewed from a functionality perspective in Clause 8,

— The reference architecture of a CSSM for AM viewed from a functionality perspective in Clause 9,

— The reference architecture of a CPSMT for AM viewed from the interface perspective in Clause 10,

— The stakeholder requirements on an SAMS in Annex A,

— The concept of digital thread in AM in Annex B,

— The types of abnormality in AM in Annex C, and

— Example use cases on the reference architecture of a CPSMT for AM in Annex D.

6 Technical requirements of a smart additive manufacturing system (SAMS) from the CPSMT perspective

6.1 General

This Clause describes the technical requirements of the SAMS mainly based on the AM stakeholder requirements described in Annex A from the perspective of a CPSMT as summarized in Table 1.

NOTE 1 In the view of 'systems engineering,' an advanced methodology for developing complex systems, the technical requirements described in Clause 6 correspond to 'system requirements,' the technical requirements to be satisfied by the reference (solution) architecture for the smart manufacturing system are specified in Clause 7.

NOTE 2 For details on systems engineering, see ISO/IEC/IEEE 15288, ISO/IEC/IEEE 12207, ISO/IEC/IEEE 42010.

In terms of the phase of the AM workflow, the technical requirements are functions to be fulfilled by the SAMS during the process control (operation) phase categorized into six capabilities of a CPSMT specified in ISO 23704-1:2022, Clause 10.

NOTE 3 The 'life cycle aspect' defined in ISO 23704-1 corresponds to 'AM workflow' in the AM domain.

The details of the technical requirements in each category are given in the following subclauses so that they can be used as the requirements to be satisfied by the reference architecture of a CPSMT for AM specified in Clause 7.

Table 1 — Technical requirements of Smart Additive Manufacturing System (SAMS) from the CPSMT capabilities

Categories based on the CPSMT capabilities (subclause number in this document)	Technical requirements (subclause number in this document)
Autonomous dealing with abnormalities (6.2)	6.2.2 Dealing with hard real-time scale abnormalities during an AM process
	6.2.3 Dealing with soft real-time scale abnormalities during an AM process
	6.2.4 Acquisition of data related to an AM process
	6.2.5 Data processing related to an AM process
	6.2.6 Extraction of value-added data
	6.2.7 AM process monitoring
	6.2.8 AM process status prediction
	6.2.9 AM process status diagnosis
	6.2.10 Making decisions about the AM system to enhance AM process performance
	6.2.11 Update of AM workflow data
	6.2.12 Dealing with abnormalities
Autonomous coordination with shop floor devices (6.3)	6.3.2 Coordination among shop floor devices
	6.3.2 Supporting the combination of finish cutting in subtractive manufacturing and AM process

Table 1 *(continued)*

Categories based on the CPSMT capabilities (subclause number in this document)	Technical requirements (subclause number in this document)
Autonomous collaboration with shop floor control system (6.4)	6.4.2 Receiving a coordinated process plan
	6.4.3 Providing the AM process data for shop floor operation
	6.4.4 Interoperability for the data interface
Interface with an AM workflow (6.5)	6.5.2 Interaction with AM workflow
	6.5.3 Interoperability for interface with AM workflow
Interface with hierarchy level (6.6)	6.6.2 Interaction with a hierarchy level
	6.6.3 Interoperability for interface with hierarchy level
Interface with humans (6.7)	6.7.2 Interaction with humans
	6.7.3 Interoperability for interface with humans

6.2 Technical requirements of autonomously dealing with abnormalities

6.2.1 General

This subclause describes the technical requirements of an SAMS from the "autonomously dealing with abnormalities" capability perspective.

NOTE 1 See ISO 23704-1:2022, 3.1.1 for the definition of abnormality.

NOTE 2 As noted in ISO 23704-1:2022, 10.1, the capability of dealing with abnormalities is emphasized due to the fact that:

— In principle, total optimization of the manufacturing process, in essence, is done by: a) off-line optimization (e.g. via CAx, DfAM), followed by b) on-line 'faithful' execution.

— Faithful execution can be done by autonomously dealing with abnormalities; the deviations from the normal status optimally planned off-line.

6.2.2 Dealing with hard real-time scale abnormalities during an AM process

This technical requirement means dealing with abnormalities during the AM process in a hard real-time fashion. Hard real-time means the result of data handling is incorrect unless the measure meets the specified timing requirements.

NOTE 1 See ISO 23704-1:2022, 3.1.17 for the definition of hard real-time.

NOTE 2 Hard-real time does not mean the process itself, but the controller task, i.e. even a slow process is operational in real time.

There are abnormalities occurring abruptly during the build process, e.g. within a layer, between layers, immediately adversely affecting the AM system when measures are not taken within the time limit. In order to detect and take action for these abnormalities, the AM process needs to be checked and handled in hard real-time.

Explicitly, an SAMS should have a means for dealing with the abnormalities in a hard real-time scale.

NOTE 3 Example abnormalities to be dealt with in the hard real-time scale include inappropriate melt pool geometry and thermal distribution, servo disturbance, clogging.

6.2.3 Dealing with soft real-time scale abnormalities during an AM process

This technical requirement means dealing with abnormalities during the AM process in a soft-real time fashion. Soft real-time means the result of data handling is degraded unless the measure meets the specified timing requirements.

NOTE 1 See ISO 23704-1:2022, 3.1.28 for the definition of soft-real time.

There are abnormalities occurring during the build process, e.g. within a layer, between layers, gradually adversely affecting the AM system. In order to detect and take action for the abnormalities, the AM process needs to be checked and handled in soft-real time.

Explicitly, an SAMS should have a means for dealing with the abnormalities in a soft-real time scale.

NOTE 2 Example abnormalities to be dealt with in the soft real-time scale include gradual energy overconsumption, gradual reduction of the remaining useful life of the motor in the nozzle.

6.2.4 Acquisition of data related to an AM process

This technical requirement means the process of collecting data related to the AM system to determine and to analyse its status.

All data in the AM domain are related to the AM workflow. The representative sources of data include, e.g. the AM machine (e.g. sensor, controller), office floor (e.g. order management system), a CAx system (e.g. CAD, CAM, CAE), human input. Those data are a valuable asset and have the potential for enhancement of the operational performance.

Explicitly, an SAMS should have a means for acquiring data related to the AM process.

NOTE 1 Example sensors include infrared camera, thermocouple, strain gauge.

NOTE 2 Example process parameters, in the case of powder bed fusion, include heat source energy, scanning feed, scanning spot size, chamber preheat temperature, chamber pressure.

NOTE 3 Example CAx data includes part program which conforms to the ISO 14649 series, ISO 6983-1, or 3D modelling format (e.g. AMF, 3MF, STL).

6.2.5 Data processing related to an AM process

This technical requirement involves the systematic performance of operations upon AM data.

NOTE 1 See Reference [1] for more details on data processing.

In practice, it is difficult to use the acquired data (See 6.2.4) immediately as they often include unorganized, inaccurate, and incorrect data. In order to make them usable, they need to be processed in some fashion. Data processing functions for supporting this include, e.g. cleansing, formatting, and grouping.

Explicitly, an SAMS should have a means for data processing related to the AM process.

NOTE 2 Examples of data cleansing include dealing with missing and noisy thermocouple values.

NOTE 3 Examples of data formatting include organizing the sensor, controller, and CAx data into pre-defined AM workflow data models.

NOTE 4 An example of data grouping is the insertion of formatted data into a group, e.g. porosity abnormality dataset.

6.2.6 Extraction of value-added data

This technical requirement means generating data of added value through data processing, which is described in 6.2.5.

Data processing provides the foundation for further analysis and utilization of data with specific purpose. These value-added data, through further processing, can contribute not only to enhancing the complexity and predictability of the AM machine behaviour, but also to making accurate decisions and generating control inputs for an AM machine, entities such as humans, CAx system, office floor systems, and shop floor systems.

Explicitly, an SAMS should acquire and utilize extracted value-added data.

NOTE Example value-added data includes the amount of deviation of energy supply from activation source compared with the reference value and estimated amount of the melt-pool geometry with thermal distribution.

6.2.7 AM process monitoring

This technical requirement means assessing whether or not an abnormality is occurring during an AM process in the time span of control.

During the AM process, various types of abnormality can occur. Early detection of abnormalities helps to shorten the time for making decisions to maintain or enhance the operational performance of the AM process.

Explicitly, an SAMS should have an AM monitoring function.

NOTE Examples of AM process monitoring include detection of insufficient energy supply to the laser power source, detection of laser overheating, detection of energy overconsumption during the AM operation, detection of thermal distortion / warping, calculating the thermal distribution of the melt pool, detection of porosity inside the AM product.

6.2.8 AM process status prediction

This technical requirement means prediction of future signs of abnormalities.

Various types of abnormality can occur during the AM process. If the symptoms of abnormalities can be identified in advance it can contribute to the improvement of AM process performance by shortening the time for making decisions and increasing the chance of pre-emptive action.

Explicitly, an SAMS should have an AM process status prediction function.

NOTE Examples of AM process status prediction include predicting the energy consumption during the AM operation, predicting the thermal distribution of the AM product during the AM process, predicting the cycle time of the AM process.

6.2.9 AM process status diagnosis

This technical requirement involves the identification of the root causes of malfunctions and the appraisal of their relevance for the AM process.

NOTE 1 For more details on diagnosis, see ISO 20077-1[22].

Since the AM process is a new and dynamically changing process, establishing root cause analysis for the various abnormalities in a variety of states and contexts is crucial for sustainable controllability and reproducibility.

Explicitly, an SAMS should have a mechanism for the diagnosis for the enhancement of the reliability and reproducibility, of the AM process.

NOTE 2 Examples of AM process status diagnosis include finding out the cause of balling phenomena in the direct energy deposition process, root cause analysis on thermal distortion / warping of an AM product, finding out the cause of inconsistent microstructure on the AM product.

6.2.10 Making decisions about the AM system to enhance AM process performance

This technical requirement involves: a) making decisions for dealing with abnormalities, and b) reflecting those decisions to the AM machine operation to alleviate the abnormalities and increase the AM operational performance.

Since the AM process is a new and dynamically changing process, making decisions on the AM system and reflection to it is crucial for a sustainable enhancement of AM process performance.

Explicitly, an SAMS should have a mechanism for the enhancement of the operational performance to realize the capability of autonomously dealing with abnormalities.

NOTE Examples of decision-making on the AM system include modifying parameters for reducing the chance of warp / distortion and verifying the changed parameter set, the transmission of modified parameter sets for reducing the chance of warp / distortion to the AM machine with the modification of path data of part program.

6.2.11 Update of the AM workflow data

This technical requirement involves updating the AM workflow data based on data processing (see 6.2.5), monitoring (see 6.2.7), prediction (see 6.2.8), diagnosis (see 6.2.9), and making decisions (see 6.2.10) on the AM process and AM system.

As a key enabler of personalized production, the AM process needs to be updated in a shorter cycle in conjunction with CAx activity compared with other types of manufacturing. To support more rapid updates, updating the AM workflow data based on the result of data handling (including data processing, monitoring, prediction, diagnosis and decision making) is necessary.

Explicitly, an SAMS should have a means to adapt to the change of the AM workflow data in a rapid and systematic fashion.

NOTE Examples of updating the AM workflow data include modifying parameters for reducing the chance of warp / distortion, changing the part orientation and support deployment in build preparation.

6.2.12 Dealing with abnormalities

6.2.12.1 General

This technical requirement involves a) monitoring abnormalities during operation, b) predicting abnormalities and diagnosing their cause, c) making decisions about appropriate countermeasures accordingly and d) reflecting these to the AM system.

Advanced data processing can be utilized for monitoring, diagnosis, prediction and making decisions on the various issues. Smart technologies such as the Internet-of-Things (IoT) can also be used to provide support by accessing data from other sources as well.

6.2.12.2 Abnormalities on an AM machine

During the AM process, according to stakeholder requirements in Annex A, there are issues on the AM machine components, including inappropriate feedstock / support delivery, path disturbance, insufficient energy supply from the activation source.

Explicitly, an SAMS should have a means for enhancing the operational performance of the AM process by dealing with abnormalities on the AM machine.

NOTE See C.2 for more details on the abnormalities of an AM machine.

6.2.12.3 Abnormalities on an AM feedstock / support

During the AM process, according to stakeholder requirements in Annex A, there are issues on the microstructure scale on the feedstock / support, such as mechanical (e.g. strength and ductility), chemical (e.g. reaction enthalpy and impurity), optical (e.g. absorptance and reflectance), rheological properties (e.g. surface tension and melting viscosity).

Explicitly, an SAMS should have a means for enhancing the operational performance of the AM process by dealing with abnormalities on the AM feedstock / support.

NOTE See C.3 for more details on the abnormalities of an AM feedstock / support.

6.2.12.4 Abnormalities on an AM workpiece

During the AM process, according to stakeholder requirements in Annex A, there are issues on the workpiece quality, such as surface roughness, geometric inaccuracy, warp / distortion, balling, insufficient bonding between layers.

Explicitly, an SAMS should have a means for enhancing the operational performance of the AM process by dealing with abnormalities on the AM workpiece.

NOTE See C.4 for more details on the abnormalities of an AM workpiece.

6.2.12.5 Abnormalities on environment and safety

During the AM process, according to stakeholder requirements in Annex A, there are issues from the environment and safety perspective, such as explosions and energy overconsumption. Environmental effects are complex and depend on the nature of the process and machine, hence are not detailed here.

Explicitly, an SAMS should have a means for enhancing the operational performance of the AM process by dealing with abnormalities in the environment and safety.

NOTE See C.5 for more details on the abnormalities of an AM environment and safety.

6.3 Technical requirements of autonomous coordination with shop floor devices

6.3.1 General

This subclause describes the technical requirements of an SAMS from the "autonomous coordination with an SFDS" capability perspective.

NOTE See ISO 23704-1:2022, 10.2 for “autonomous coordination with shop floor device” capability.

6.3.2 Coordination among shop floor devices

In a smart manufacturing environment, an SAMS needs to be integrated with the shop floor and should not work as a standalone device. Coordination among shop floor devices, including, e.g. an AM machine and a post-processing device, implies automatic interaction among them based on each device’s status and process plan for increasing production efficiency.

In a process chain involving AM the post-processing largely affects the production capabilities and overcoming the capabilities limit is the one of key issues in the AM domain. In terms of shop floor operation, not only enhancing the operational performance of each machine itself but also the operation performance of the interaction among them is important.

Explicitly, an SAMS should have a means for coordination among shop floor devices.

NOTE 1 A shop floor composed of, e.g. an AM machine, robot, machining centre, is an example of an automated shop floor where the shop floor devices are coordinated in some fashion[62].

NOTE 2 Loading feedstock to the AM machine, unloading the finished product, and requesting finishing job after build operation are examples of interactions with the shop floor.

6.4 Technical requirements of autonomous collaboration with a shop floor control system

6.4.1 General

This subclause describes the technical requirements of an SAMS from the "autonomous collaboration with the shop floor control system" capability perspective.

NOTE See ISO 23704-1:2022, 10.3 for “autonomous collaboration with shop floor control system” capability.

6.4.2 Receiving a coordinated process plan

This technical requirement means receiving the coordinated process plan, by which the optimization of shop floor operation is taken into consideration.

NOTE 1 Process planning is defined in ISO 18629-1[21] as the analysis and design of the sequences of processes, resources requirements needed to produce goods and services.

For coordination, the data from, e.g. the AM machine, CAx data system, human, can be incorporated.

As described in 6.3.2, increasing process capabilities is one of the key issues in the AM domain. Operation of the shop floor under the coordinated process plan can contribute to shop floor operation performance enhancement.

Explicitly, an SAMS should have a means for receiving a coordinated process plan.

NOTE 2 Example data items of a process plan include job number, product number, start time, number of product, end time.

6.4.3 Providing the AM process data for shop floor operation

This technical requirement means transmitting the acquired and processed data related to the AM process as described in 6.2.5 to 6.2.10 to the entities that perform shop floor control.

The coordinated process plan on the shop floor should be changed, taking, e.g. shop-floor devices, shop floor operation, an AM process, into consideration. For this, data related to the AM process should be shared to the entities that perform shop floor control.

Explicitly, an SAMS should have a means for providing data related to the AM process to the entities that perform shop floor control operation to support the update of the coordinated process plan.

NOTE Examples of data that can be provided include AM machine status (e.g. idle, running, standby, fault) and sensors (e.g. pyrometer, CCD camera, thermocouple), monitoring, prediction, diagnosis results for abnormalities.

6.4.4 Interoperability for the data interface

Interoperability involves the ability of different data technology systems and software applications to communicate, exchange data, and use the data that has been exchanged.

NOTE 1 See Reference [23] for details on interoperability.

Providing data from the AM shop floor devices to the entities that perform shop floor control in platform independent fashion is key enabler for this.

Explicitly, an SAMS should have a means for independence from a specific platform.

NOTE 2 OPC-UA (IEC/TR 62541-1) server, MTConnect (ANSI/MTC1.4-2018) Adapter / Agent are examples of interoperability standards.

6.5 Technical requirements of interface with AM workflow

6.5.1 General

This subclause describes the technical requirement of an SAMS from the "interface with an AM workflow" capability perspective.

NOTE 1 See ISO 23704-1:2022, 10.4 for “interface with life cycle aspects” capability.

NOTE 2 The ‘life cycle aspect’ defined in ISO 23704-1 corresponds to ‘AM workflow’ in the AM domain.

6.5.2 Interface with AM workflow

This technical requirement means communication between the AM workflow and AM system for data exchange. This interface performs a) transmission of the data related to an AM system to the AM workflow, and b) transmission of the output of the AM workflow to an AM system.

The AM workflow data update is necessary not only to improve the AM process performance but also for supporting optimization throughout the whole AM workflow.

Explicitly, an SAMS should have a means for interaction with AM workflow.

6.5.3 Interoperability for interface with AM workflow

This technical requirement means providing data from the AM shop floor devices to the AM workflow in platform independent fashion. Otherwise, AM workflow needs to have separate communication protocols for each shop floor device supporting different protocols.

Explicitly, an SAMS should have a mechanism for independence from a specific platform when interfacing with AM workflow.

6.6 Technical requirement of interface with hierarchy levels

6.6.1 General

This subclause describes the technical requirements of an SAMS from the "interface with hierarchy levels" capability perspective.

NOTE See ISO 23704-1:2022, 10.5 for “interface with hierarchy level” capability.

6.6.2 Interface with a hierarchy level

This technical requirement means communication between the hierarchy level and shop floor devices including AM system.

It contributes to a) shortening the time to reflect the data from the hierarchy level to the AM process, and b) updating the hierarchy level data considering an AM process and shop floor status.

Explicitly, an SAMS should have a mechanism for interaction with hierarchy levels.

NOTE An example of interaction with a hierarchy level includes receiving updated product orders from the hierarchy level accompanying the build geometry file (e.g. STL,[93] AMF,[41] ISO 14649-17[15]).

6.6.3 Interoperability for interface with hierarchy level

This technical requirement means providing data from the AM shop floor devices to the hierarchy level in platform independent fashion. Otherwise, the hierarchy level needs to have separate communication protocols for each shop floor device supporting different protocols.

Explicitly, an SAMS should have a mechanism for independence from a specific platform when interfacing with the hierarchy level.

6.7 Technical requirement of interface with humans

6.7.1 General

This subclause describes the technical requirement of an SAMS from the "interface with human" capability perspective.

NOTE See ISO 23704-1:2022, 10.6 for “interface with stakeholders” capability.

6.7.2 Interface with humans

This technical requirement involves communication between humans and shop floor devices including AM systems. This interface performs a) receiving human input, and b) transmission of data generated from shop floor devices to humans.

Explicitly, an SAMS should have a mechanism to interact closely with humans

NOTE Examples include sharing the operation status with the human operator (e.g. the transmission of visualized diagnosis results on surface balling through the UIS), cooperation with human operators involving post-processing work in an AM machine shop (e.g. part removal performed by humans).

6.7.3 Interoperability for interface with humans

This technical requirement means providing data from the AM shop floor devices to the humans in platform independent fashion. Otherwise, humans need to have separate interfaces to communicate with different shop floor devices.

Explicitly, an SAMS should have a mechanism for independence from a specific platform when interfacing with interface humans.

7 Reference architecture of a CPSMT for AM

Based on the technical requirements of SAMS (Clause 6), its solution architecture is given in Clause 7 accommodating the generic reference architecture for a CPSMT given in ISO 23704-1.

Figure 3 displays the reference of a CPSMT for AM.

The structure is as follows:

— The CPSMT primary system for AM is composed of a cyber-physically controlled machine tool (CPCM) for AM and a cyber-supporting system for machine tools (CSSM) for AM. It has the primary function to deal with machine tool abnormalities in autonomous fashion (see ISO 23704-1:2022, 10.1).

— The CPSMT associated system for AM is composed of a shop floor device system (SFDS), a shop floor control system (SFCS) has various capabilities as described in ISO 23704-1:2022, 10.2 and 10.3.

— Through the UIS, the CPSMT for the AM interfaces with external entities, such as humans, life cycle aspects, and hierarchy levels according to ISO 23704-1:2022, 10.4, 10.5, and 10.6.

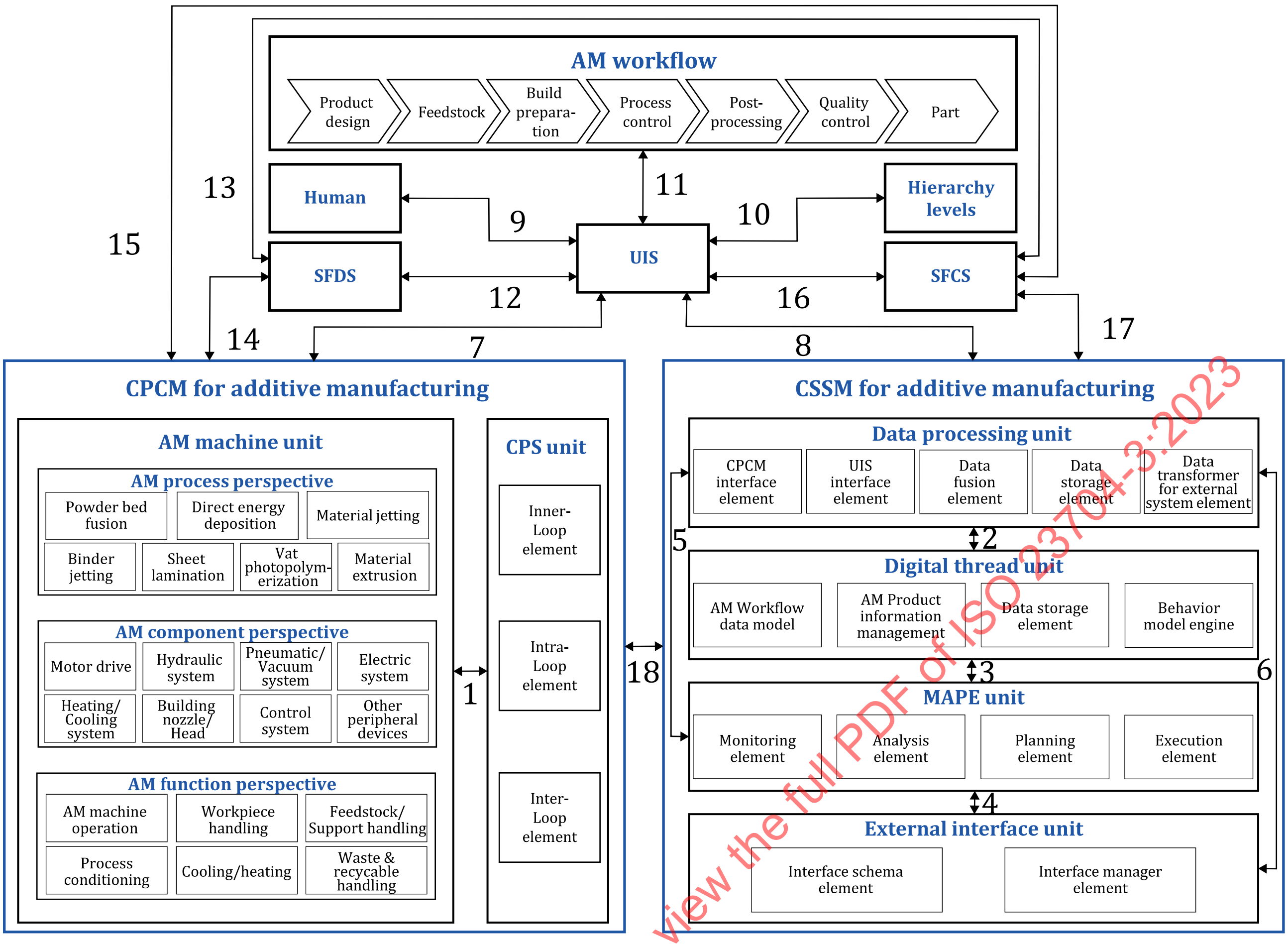
Largely speaking, compared with the reference architecture for subtractive manufacturing specified in ISO 23704-2:

— A CPCM for AM is distinguished from the AM machine unit (AMU), which is viewed from three perspectives; the AM process, the AM component, and the AM functions,

— A CSSM for AM is distinguished from the digital thread unit, which is composed of: the AM workflow data model, the AM workflow data management, the AM behaviour model, and the behaviour model engine, and

— The life cycle aspect for AM is distinguished from the AM workflow , which is composed of a) product design, b) feedstock, c) build preparation, d) process control, e) post-processing, f) quality control, and g) part.

Clause 8 specifies a set of requirements for the functional units and elements for a CPCM for AM, Clause 9 specifies a set of requirements for the functional units and elements for a CSSM for AM, and Clause 10 specifies the interface view of a CPSMT for AM.



Key

1 data exchange between an AM machine unit (AMU) and a CPS unit
2 data exchange between a data processing unit and a digital thread unit
3 data exchange between a digital thread unit and a MAPE unit
4 data exchange between a MAPE unit and an external interface unit
5 data exchange between a data processing unit and a MAPE unit
6 data exchange between a data processing unit and an external interface unit
7 data exchange between a CPCM for AM and a UIS
8 data exchange between a CSSM for AM and a UIS
9 data exchange between a human and a UIS
10 data exchange between a hierarchy level and a UIS
11 data exchange between AM workflow and a UIS
12 data exchange between a SFDS and a UIS
13 data exchange between a SFCS and a SFDS
14 data exchange between a SFDS and a CPCM for AM
15 data exchange between a CPCM for AM and a SFCS
16 data exchange between a UIS and a SFCS
17 data exchange between a SFCS and a CSSM for AM
18 data exchange between a CSSM and a CPCM

Figure 3 — Reference architecture of a CPSMT for additive manufacturing (AM)

NOTE The different process categories in the AM process perspective box are the categories defined in ISO/ASTM 52900 and do not refer to particular processes.

8 Functional view of a CPCM for additive manufacturing (AM)

8.1 General

This Clause specifies a set of requirements for the constituent elements of a CPCM for AM.

A CPCM for AM should consist of a) an AM machine unit (AMU), and b) a CPS Unit (see 8.3).

The specific configuration of a CPCM structure and related data items should be determined based on the purpose of implementation.

NOTE The functionality of a CPCM conforms to the reference architecture of a CPSMT (see ISO 23704-1:2022, Clause 7), but is adapted to the characteristics of AM.

8.2 AM machine unit (AMU) of a CPCM

8.2.1 General

The AMU is the physical system to be monitored, analysed, and for which decisions are made about possible abnormalities to enhance operational performance.

The AMU should be viewed from the perspective of a) an AM function, b) an AM process, and c) an AM component.

8.2.2 AM function perspective

From the AM function perspective, the AM function should be described as follows:

— AM machine operation, including build process, build motion , and machine control,

— Process conditioning,

— Workpiece handling,

— Feedstock / support handling,

— Recyclables and waste handling, and

— Machine cooling / heating.

NOTE Compared with machine function for subtractive manufacturing (defined in ISO 23704-2:2022, Clause 7), two attributes of the machine are replaced by the build process / build motion and feedstock / support handling due to the difference of manufacturing method.

8.2.3 AM process perspective

From the AM process perspective, according to ISO/ASTM 52900, process categories consist of: a) binder jetting, b) directed energy deposition, c) material extrusion, d) material jetting, e) powder bed fusion, f) sheet lamination, and g) vat photo polymerization. See ISO/ASTM 52900 for the definition of these processes.

8.2.4 AM component perspective

Based on ISO 17296-2, the AM components should be grouped into: a) the motor drive, b) hydraulic system, c) pneumatic / vacuum system, d) electric system, e) heating / cooling system, f) building nozzle / head, control system, and g) other peripheral devices.

NOTE 1 Compared with the machine tool component group described in ISO 14955-1, the building nozzle / head is added, and the lubricant and chip extraction system are excluded. This is due to the difference in the manufacturing method.

NOTE 2 Physical components of AMU can be grouped by the AM process and AM functions. The following are example components in terms of AM function for the powder bed process[64-66]:

- For build process in machine operation function:
  - Energy source (e.g. laser, electron beam), in building nozzle / head component type.
- For build motion in machine operation function:
  - Servo motor on, e.g. mirror, build platform, in motor drive component type.
- For machine control in machine operation function, e.g.:
  - Voltage transformer, power supply, lighting system, frequency converter, relays, in electric system component type,
  - Numerical control system, programmable logic controller, in control system component type, and
  - Display, sensors, decoder / encoder, camera, XCT, touch probe, in other peripheral devices component type.
- For process conditioning in machine operation function, e.g.:
  - Inert gas circulation system, vacuum pump, in pneumatic / vacuum system component type, and
  - Heating element for controlling the temperature in the chamber, laser heating / cooling element, mirror heating / cooling element, etc., in heating / cooling system component type.
- For workpiece handling in machine operation function, e.g.:
  - Pallet changer, product handling robot, the hydraulic clamping device, in hydraulic system component type,
  - Pneumatic clamping device, in pneumatic / vacuum system component type, and
  - Wire electro discharging machine, bandsaw, in other peripheral device component type.
- For feedstock / support handling in machine operation function, e.g.:
  - Motor in powder spreading device, powder feeding system, in motor drive component type, and
  - Feedstock container, in other peripheral device component type.
- For waste and recyclable handling in machine operation function, e.g.:
  - Air exhaust system, in pneumatic / vacuum system component type, and
  - Support removal system from the part and build platform, excess feedstock removal system from the build chamber, in other peripheral device component type.
- For cooling and heating in machine operation function, e.g.:
  - The heating element of the platform, frame, cooling system for control cabinet, in the heating / cooling system component type.

8.2.5 Abnormalities of an AM machine unit (AMU)

According to 6.2.12.2, functions of the AM machine can lose performance due to the degradation of mechanical properties (e.g. fatigue, hardness.) or malfunction.

According to 6.2.12.3 to 6.2.12.5, performance can also be degraded from the abnormalities of an AM feedstock / support, workpiece, and environment and safety.

In the capacity of a CPCM for AM, the abnormalities of the AM operation should be dealt with as follows:

— Function-wise, the machine control subfunction and their interface with the cyber-physical system unit should deal with the abnormalities to conform with technical requirements given in 6.2.12.2, 6.2.12.3, 6.2.12.4, and 6.2.12.5.

— Component-wise, the controller (including CNC and programmable logic control) together with actuators should deal with the abnormalities, and

— Process-wise, the abnormality resolution should be applied to all types of AM process, including a) binder jetting, b) directed energy deposition, c) material extrusion, d) material jetting, e) powder bed fusion, f) sheet lamination, and g) vat photopolymerization.

NOTE See Annex C for more abnormalities to be dealt with.

To this end, the machine control subfunction in the AM machine operation function should:

— Control the AM machine operation and all other functions of the AMU,

— Receive and manage the part program from a UIS to execute the AM process to conform with technical requirements given in 6.5.2 and 6.7.2,

— Generate status signals via sensors and I/O modules to conform with technical requirements given in 6.2.4,

— Transmit the collected data to the cyber-physical system unit, a CSSM, and a UIS, to conform with technical requirements given in 6.2, 6.5,

— Receive control instructions from the cyber-physical system unit to conform with technical requirements given in 6.2.2, 6.2.3 and 6.2.10, and

— Coordinate with the motion connected with the adjacent shop floor devices to conform with technical requirements given in 6.3.2.

8.3 Cyber-physical system (CPS) unit

8.3.1 General

Distinguished from the conventional stand-alone AM machine, the CPS unit of a CPSMT is the key player that controls and coordinates the AMU directly with a CSSM, an SFDS, an SFCS, and indirectly with external entities (AM workflow, Hierarchy levels, and Humans) via a UIS.

In terms of the six capabilities of a CPSMT, the CPS unit enables the CPCM to realize the two capabilities of a CPSMT:

— Autonomously dealing with abnormalities by interfacing with sensors, numerical control kernel / programmable logic controller, and a UIS, and a CSSM for realizing hard / soft-real time abnormality resolution, and

— Autonomously collaborating with the SFCS.

NOTE 1 Coordination with an SFDS is performed in a numerical control system, programmable logic controller, as described in 8.2.5.

To fulfil these tasks, a CPS unit should consist of:

— An inner-loop element,

— An intra-loop element, and

— An inter-loop element

The inner-loop element is the part of the CPS unit that detects and resolves abnormalities for the machine tool unit in hard real-time. See ISO 23704-1:2022, 3.1.17 for the definition of hard real-time

The intra-loop element is the part of the CPS unit that generates control instructions for the machine tool unit based on the data from a CSSM in soft-real time. See ISO 23704-1:2022, 3.1.28 for the definition of soft-real time.

The inter-loop element is the part of the CPS unit that generates event-driven control instructions for the machine tool unit based on data from an SFCS for the sake of collaboration.

NOTE 2 CPS control scheme means that all AM processes and AM functions are controlled with the AMU functions and three elements in the CPS unit.

The AM functionalities in the AMU are coordinated by the machine control subfunction of an AM machine operation.

Physical deployment of the CPS unit should be determined in the implementation phase. A CPS unit can be in the AM machine controller, outside of the AM machine controller, or both.

8.3.2 Inner-loop element

Inner-loop element is the part of the CPS unit that detects and resolves abnormalities for the sake of abnormality detection and resolution in hard real-time. This is to conform with technical requirements specified in 6.2.2.

To this end, the inner-loop element should:

— Receive the data from the AM components (e.g. sensor and controller) and a UIS (e.g. a part program conforming with the ISO 14649 series, ISO 6983-1, 3D modelling file) to conform with technical requirements specified in 6.2.4, 6.5.2, 6.6.2 and 6.7.2,

— Identify the current CPCM for AM status based on data from the AMU,

— Compare the current state of the AMU with the reference state,

— Generate control instruction for improving operation of the AMU,

— Transmit the generated data to the UIS to conform with technical requirements specified in 6.5.2, 6.6.2 and 6.7.2, and

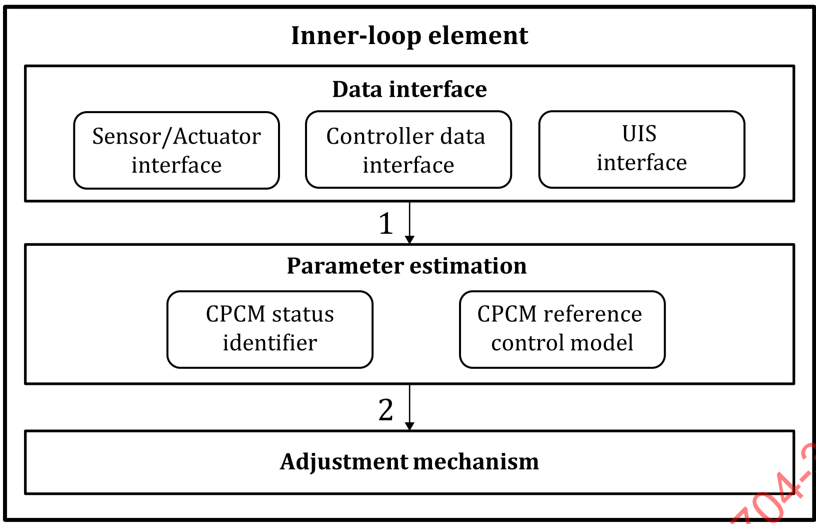
— Transmit the generated control instruction to the AMU to conform with technical requirements specified in 6.2.2 and 6.2.10.

NOTE 1 The example use case for the inner-loop element is adaptation of layer processing strategies taking thermal condition into consideration on the laser base powder bed fusion.

It is recommended to follow the inner-loop element structure shown in Figure 4 which is composed of a) data interface component, b) parameter estimation component, and c) adjustment mechanism component.

NOTE 2 The structure is similar to that of in ISO 23704-2:2022, 7.3.2, reflecting the characteristics of AM.

The data interface component conforms with technical requirements specified in 6.2.4, 6.5.2, 6.6.2, and 6.7.2, and should consist of controller data interface, sensor interface, and a UIS interface.



Key

1 transmission of collected data from the data interface to parameter estimation

2 transmission of generated feature from the parameter estimation component to the adjustment mechanism

Figure 4 — Functional structure of the inner-loop element

NOTE 3 Compared with ISO 23704-2:2022, Figure 4, the controller data interface is distinguished from numerical control kernel (NCK) / programmable logic controller (PLC) interface.

The parameters acquired from controller data interface vary over the AM process.

NOTE 4 In the case of material extrusion, example parameters are layer height, nozzle temperature, printing feed speed, layer width, cooling rate, bed / room temperature, humidity.

NOTE 5 In the case of vat photopolymerization, example parameters are layer thickness, light intensity, hatch spacing, blade with, fill cure depth, printing resin temperature.

NOTE 6 In the case of binder jetting, example parameters are binder set time, drying time, emitter output, target bed temperature, layer thickness, recoating speed, heater power ratio.

NOTE 7 In the case of material jetting, example parameters are layer height, layer thickness, dispensing apparatus temperature / light intensity, dispensing apparatus feed speed, humidity, chamber temperature.

NOTE 8 In the case of powder bed fusion, example parameters are heat source energy, scanning feed, scanning spot size, raster spacing, and pattern, chamber preheat temperature, chamber pressure, chamber oxygen level, build platform temperature, hatching space, layer thickness, layer height, scaling factors, recoating speed.

NOTE 9 In the case of direct energy deposition, example parameters are heat source energy, scanning feed, scanning spot size, raster spacing, and pattern, chamber preheat temperature, chamber pressure, chamber oxygen level, powder flow rate, shielding gas.

NOTE 10 In the case of sheet lamination, example parameters are laminator roll speed, laminator roll vibration amplitude, clamping force, tension force, layer thickness, layer height, material roll / stack speed.

For the sensor interface, various types of sensor data can be collected. Representative examples include data from, e.g. camera (IR, optical), photodiode, pyrometer, thermocouple, strain gauge.

For the UIS interface, the data received from a UIS include part program conforms with the ISO 14649 series and ISO 6983-1, 3D modelling file. For detailed contents of part program for AM domain, see ISO 14649-17. For standards on 3D modelling for the AM domain, see ISO/ASTM 52915.

The parameter estimation component should estimate the AM process's state based on the data from the data interface component. The difference between the estimated state and the reference state is provided by the parameter estimation component to conform with technical requirements given in 6.2.7 and 6.2.8.

NOTE 11 The example estimated parameters for the powder bed fusion process includes distribution amount of support, melt pool geometry, melt thermal pool distribution, residual stress, servo disturbance.

The adjustment mechanism component should generate a series of control input values based on the output from the parameter estimation component and transmit them to the controller to conform with technical requirements given in 6.2.2 and 6.2.10.

NOTE 12 The example control input for the powder bed fusion process includes laser power, scan feed, servo position control.

8.3.3 Intra-loop element

Intra-loop element is the part of the CPS unit that generates control instructions for the controller based on the data from a CSSM for the sake of optimization of the AM functions in soft-real time. This is to conform with technical requirements specified in 6.2.3 and 6.2.10.

Compared with the inner-loop element's capability, the intra-loop element can produce superior results in terms of, for example, predictability of AM machine behaviour.

To this end, the intra-loop element should:

— Receive the control command data from the CSSM for AM,

— Receive the status of the controller from the AMU to conform with technical requirement given in 6.2.4,

— Convert control commands for the AMU,

— Make a decision as to whether the proposed command can be accommodated, based on data from the AMU,

— Generate an override command for the AMU, and

— Transmit the generated command to the AMU to conform with technical requirements given in 6.2.3 and 6.2.10.

NOTE 1 The example use case for the intra-loop element is the change of the support structure to handle unsuitable thermal distribution or structural stability issues during AM process through the modification of part program.

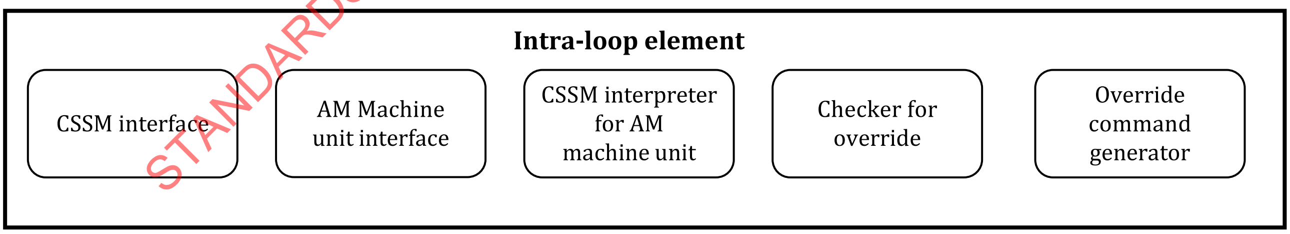


Figure 5 — Functional structure of the intra-loop element

It is recommended to follow the intra-loop element structure shown in Figure 5, which is composed of: a) CSSM interface, b) AMU interface, c) CSSM interpreter for AMU, d) checker for override, and e) override command generator.

NOTE 2 The structure is similar to that of ISO 23704-2:2022, 7.3.3, reflecting the characteristics of AM.

8.3.4 Inter-loop element

Inter-loop element is the part of the CPS unit that generates event-driven control instructions for the controller based on data from an SFCS for the sake of collaboration. This is to conform with technical requirements given in 6.4.2, and general requirements specified in ISO 23704-1:2022,10.3.

NOTE 1 See ISO 23704-1:2022, 3.1.16, for the definition of event-driven.

NOTE 2 Example use cases on an SFCS include a) resource reallocation or rescheduling of the shop floor devices due to failure and delay of some shop floor devices, b) special requests from manufacturing operation management, c) monitoring the shop floor performance comparing with the provided schedule, and d) diagnosing the cause of the problems on the shop floor such as bottlenecks.

To this end, the inter-loop element should:

— Receive outputs (e.g. task allocation plan) from an SFCS,

— Receive the status of the controller from the AMU to conform with technical requirement given in 6.2.4,

— Convert control commands for AMU,

— Make a decision as to whether the proposed command can be accommodated, based on data from the AMU,

— Generate override commands for the AMU, and

— Transmit the generated command to the AMU to conform with technical requirement given in 6.4.3

It is recommended to follow the inter-loop element structure shown in Figure 6, which is composed of: a) SFCS interface, b) AMU interface, c) SFCS interpreter for AMU, d) checker for override, and e) override command generator.

NOTE 3 The structure is similar to that of in ISO 23704-2:2022, 7.3.4, reflecting the characteristics of AM.

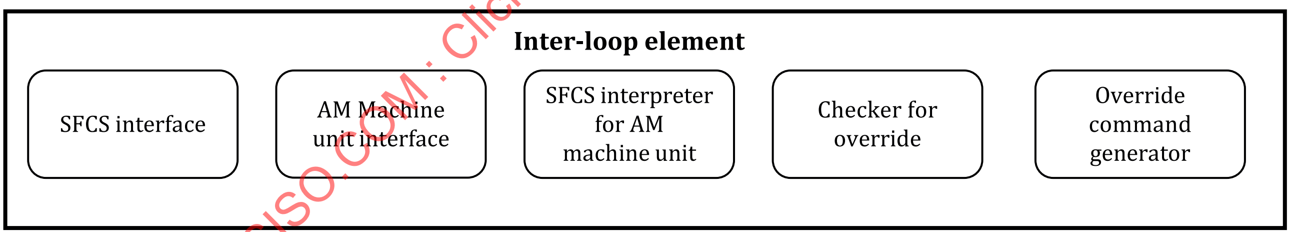


Figure 6 — Functional structure of the inter-loop element

9 Functional view of a CSSM for AM

9.1 General

This Clause specifies a set of requirements for the constituent elements of a CSSM for AM defined in Figure 3 of Clause 7.

A CSSM for AM should consist of:

a) The data processing unit,

b) Digital thread unit,

c) A MAPE unit, and

d) External Interface unit.

NOTE The functionalities of a CSSM conform to the reference architecture of a CPSMT (see ISO 23704-1:2022, Clause 7) reflecting the technical requirements of AM, given in Clause 7.

The specific configuration of a CSSM structure and related data items should be determined based on the purpose of implementation.

9.2 Data processing unit (DPU)

9.2.1 General

DPU is a set of functions to process the acquired data for the use of a digital thread unit, a MAPE unit, and external interface unit. A DPU is the foundation of a CSSM operation.

The DPU should consist of:

— a CPCM interface element,

— a UIS interface element,

— a Data fusion element,

— a Data storage element, and

— a Data transformer for external entities element.

9.2.2 CPCM interface element

The CPCM interface element is the element that acquires data related to the AM process status from sensors and controller, to conform with technical requirement given in 6.2.4.

To this end, the CPCM interface element should:

— Retrieve the data from a CPCM, mostly focusing on the controller / sensor data, and

— Transmit the retrieved data to the data fusion element.

NOTE 1 See 8.3.2 for the example data items from the controller for each AM process type.

NOTE 2 See 8.3.2 for the example sensor data.

NOTE 3 This document does not specify industrial communication protocols for the CPCM interface (e.g. Profibus, Modbus, and Ethernet).

9.2.3 UIS interface element

The UIS interface element is the element that acquires data from the external entities via a UIS to conform with technical requirements given in 6.2.4, 6.5.2, 6.6.2, and 6.7.2.

To this end, the UIS interface element should:

— Receive data from the AM workflow (e.g. part program conforms with the ISO 14649 series and ISO 6983-1, product 3D modelling.) via a UIS to conform with technical requirement given in 6.5.2,

— Receive data from the hierarchy level, such as order data via a UIS to conform with technical requirement given in 6.6.2,

— Receive human input to conform with technical requirement given in 6.6.2, and

— Transmit the retrieved data to the data fusion element.

NOTE 1 The AM workflow supports close linkage among the AM workflow data to achieve the major goals of AM from the perspective of Industry 4.0, such as reduction of time-to-market and personalized production.

NOTE 2 For the detailed contents of part program conforming with the ISO 14649 series in the AM domain, refer to ISO 14649-17. For standards on 3D modelling for the AM domain, see to ISO/ASTM 52915.

NOTE 3 For the detailed data contents on hierarchy level, see ISO/IEC 23510 (AM service platform).

NOTE 4 This document does not specify industrial communication protocols for the UIS interface (e.g. Profibus, Modbus, and Ethernet).

9.2.4 Data fusion element

The data fusion element is the element in the data processing unit that integrates multiple data sources from a CPCM and a UIS interface elements in order to produce consistent, accurate, and useful data to accomplish technical requirement given in 6.2.5.

Data that has gone through data fusion should conform to the AM workflow data model in the digital thread unit for the usage of organized data in the digital thread unit and MAPE unit.

To this end, the data fusion element should perform:

— Data cleansing to search for and correct (or remove) a) corrupted or inaccurate data items in the collected data, b) identifying incomplete, incorrect, or irrelevant parts of the data, and c) replacing, modifying, or deleting the data,

— Data formatting to organize cleansed data to fit in a predefined specification that is defined by the AM workflow data model in the digital thread unit,

— Data grouping to group the data items involved in each abnormality, and

— Transmission of the output to the a) data storage, b) data transformer for external interface unit, and c) the AM workflow data management in digital thread unit.

NOTE Example use cases on the data fusion element include a) the storage, pre-processing, integration and management of big data in sustainable and smart AM,[89] b) the collaborative data management system through the entire AM lifecycle and value chains,[90] and c) data pre-processing and cleansing in the form a heatmap for the wall and chassis for large-scale AM[91].

9.2.5 Data storage element

The data storage element is the element in the data processing unit that stores the deliverables of a CSSM, including the output of data fusion, behaviour model in digital thread unit, the output of monitoring, analysis, and the planning function.

To this end, the data storage element should store and manage:

— The processed data from the data fusion element (see 9.2.4),

— The output of the MAPE unit (see 9.4), and

— The output of the behaviour model engine (see 9.3.5) in the digital thread unit.

9.2.6 Data transformer for external entities element

The data transformer for external entities elements is the element in the data processing unit that transforms the output of the data fusion element to fit into the data structure in the external interface unit.

The data transformer for the external entities element should transform the data processing unit data to fit into the data structure based on the interface schema element (see 9.5.2) of the external interface unit to conform with technical requirements given in 6.4.3, 6.4.4, 6.5.2, 6.5.3, 6.6.2, 6.6.3, 6.7.2, and 6.7.3.

NOTE Usage of 'Adapter' in MTconnect for transforming the acquired data to the MTconnect data model[92] is an example of data transformation for external entities.

9.3 Digital thread unit

9.3.1 General

From the CPSMT perspective, the digital thread unit organizes the AM workflow data based on data which has gone through data fusion (see 9.2.4) in the data processing unit. Also, the digital thread unit provides functions that generate value-added data to conform with technical requirement given in 6.2.6.

NOTE 1 Compared with the inner-loop element, the digital thread unit has advanced means to deal with abnormalities in a deeper way for the accuracy of prediction.

NOTE 2 The digital thread unit supports monitoring, analysis, planning, and execution in a structured fashion within the allowed soft-real time.

As a key enabler of personalized production, the AM process needs to be updated in a shorter cycle in conjunction with CAx activity compared with other types of manufacturing. Digital thread unit contributes to this by providing value-added data in view of operation phase, utilizing data from other AM workflow phases in comprehensive manner. Therefore, data models covering whole AM workflow phases is necessary.

NOTE 3 For this reason, digital thread unit is distinguished from the digital twin unit in ISO 23704-2 in that digital thread unit utilizes data from all AM workflow phases. For digital twin unit, it mainly utilizes the operation phase data (state data model) with circumstance given (context data model).

In addition, the digital thread unit supports abnormality resolution from a soft-real time point of view by providing value-added data to a MAPE unit. The types of abnormality during operation, based on Annex C and technical requirements given in 6.2.12.2, 6.2.12.3, 6.2.12.4, and 6.2.12.5, can be summarized into four categories as a) AM machine, b) feedstock / support, c) workpiece, and d) environment and safety.

NOTE 4 As specified in 3.1.15, the term "workpiece" is utilized rather than "part" for consistency throughout the ISO 23704 series.

To this end, the digital thread unit should consist of:

— An AM workflow data model,

— AM workflow data management,

— An AM behaviour model, and

— Behaviour model engine.

9.3.2 AM workflow data model

9.3.2.1 General

The AM workflow data model is the data model describing the AM workflow data.

NOTE 1 See ISO 23704-2:2022, 3.1.3 for the definition of the data model.

The AM workflow data model should be used as a format for the operation of the data fusion element.

Based on the AM workflow defined in 3.1.5, the AM workflow data model should consist of:

— Product design,

— Feedstock / support,

— Build preparation,

— Process control, and

— Inspection.

NOTE 2 Distinguished from AM workflow in 3.1.5, post-processing is not included here in, as it is done in conjunction with an SFCS.

9.3.2.2 Product design

In the workflow of product design, data related to product design should be organized and managed. Representative examples are 3D model files such as STL, vertex, colour, design rationale, requirement[68].

NOTE 1 For details on STL, see Reference [93].

NOTE 2 For the product design requirements, guidelines and recommendations, ISO/ASTM 52910 can be used.

NOTE 3 For managed model-based 3D engineering, ISO 10303-242 can be used.

9.3.2.3 Feedstock / support

In the workflow of feedstock / support, data related to feedstock / support specifications involved in product manufacturing should be organized and managed.

NOTE 1 Representative feedstock / support properties include optical, chemical, physical, rheological, thermal properties. See C.3 for a detailed description of the representative properties of feedstock / support.

NOTE 2 For requirements on material extrusion of plastic feedstock, ISO/ASTM 52903-1 can be used.

NOTE 3 For qualification guidance for feedstock materials, ISO/ASTM 52907 can be used.

NOTE 4 For qualification of materials for laser-based powder bed fusion of polymers, ISO/ASTM 52925 can be used.

NOTE 5 For guidance for characterizing properties of metal powders used in AM processes, ASTM F3049-14 can be used.

9.3.2.4 Build preparation

In this workflow, data related to build preparation, including process parameters, part orientation, support distribution, should be organized and managed.

NOTE 1 Examples in this category include sliced files, support structures, orientation, and setup parameters[79-81].

NOTE 2 For process design recommendations for laser-based powder-bed fusion process of metal, ISO/ASTM 52911-1 can be used.

NOTE 3 For process design recommendations for laser-based powder-bed fusion process of polymer, ISO/ASTM 52911-2 can be used.

NOTE 4 For a standard guide for directed energy deposition of metals, ASTM F3187-16 can be used.

NOTE 5 For an overview of a data model for CNCs, ISO 14649-1 can be used.

NOTE 6 For an application interpreted model for CNCs, ISO 10303-238 can be used.

NOTE 7 For general process data for CNCs, ISO 14649-10 can be used

NOTE 8 For process data for CNCs for AM, ISO 14649-17 can be used.

9.3.2.5 Process control and inspection

9.3.2.5.1 General

In this workflow, the actual process is carried out, which is the main focus from the perspective of a CPSMT for AM. Contribution to the enhancement of AM operational performance can be achieved through abnormality resolution during the operation of the AM process.

The group of abnormalities dealt with in the CPSMT should be classified as follows:

— AM machine body,

— Feedstock/support,

— Workpiece, and

— Environment and safety.

NOTE 1 See Annex C, for a detailed description on each type of abnormality.

NOTE 2 Abnormality types vary depending on the type of AM process. Examples taken in these subclauses are for the powder bed fusion (PBF) and direct energy deposition (DED).

9.3.2.5.2 AM machine body

The abnormalities of the AM machine body (e.g. print head, feed motor) are mainly due to degradation of machine components, which cause various phenomena such as path disturbance, inappropriate feedstock / support distribution, and inappropriate energy supplement.

NOTE 1 See C.2 for details on abnormalities of AM machine body.

To deal with abnormalities in machine body, the data from CPCM should be organized and managed as specified in the technical requirement given in 6.2.12.1.

NOTE 2 For process equipment and operational parameter requirements for plastic parts using material extrusion, ISO/ASTM 52903-2 can be used.

NOTE 3 For requirements and test methods for the qualification and requalification of laser beam machines for metal powder-bed fusion, ISO/ASTM 52941 can be used.

9.3.2.5.3 Feedstock / support

The abnormalities of the feedstock / support are mainly due to unsuitable variation of mechanical, chemical, rheological, optical, thermal properties.

NOTE 1 See C.3 for the details on abnormalities of feedstock/support.

To deal with abnormalities in the feedstock / support, the data from CPCM should be organized and managed as specified in the technical requirement given in 6.2.12.2.

NOTE 2 For requirements on material extrusion of plastic feedstock, ISO/ASTM 52903-1 can be used.

NOTE 3 For qualification guidance on feedstock materials, ISO/ASTM 52907 can be used

NOTE 4 For qualification of materials for laser-based powder-bed fusion of polymers, ISO/ASTM 52925 can be used.

NOTE 5 For guidance for characterising properties of metal powders used for AM processes, ASTM F3049-14 can be used

9.3.2.5.4 Workpiece

The abnormalities of the workpiece are mainly due to low geometric accuracy, unsuitable surface roughness, warping / distortion, porosity, balling, un-fused material, insufficient bonding between layers, cracking, etc.

NOTE 1 See C.4 for the details on abnormalities of workpiece.

To deal with abnormalities in the workpiece, the data from CPCM should be organized and managed as specified in the technical requirement given in 6.2.12.3.

NOTE 2 For process equipment and operational parameter requirements for plastic parts using material extrusion, ISO/ASTM 52903-2 can be used.

NOTE 3 For principal requirements applied to test of parts, ISO 17296-3 can be used.

NOTE 4 For requirements for purchased AM parts, ISO/ASTM 52901 can be used.

NOTE 5 For geometric capability assessment of AM systems, ISO/ASTM 52902 can be used.

NOTE 6 For practice for metal powder bed fusion process to meet critical applications, ISO/ASTM 52904 can be used.

NOTE 7 For classification of part properties for AM of polymer parts, ISO/ASTM 52924[1)] can be used.

NOTE 8 For requirements and ensuring component properties on AM titanium-6aluminium-4vanadium (Ti-6Al-4V) components, ASTM F2924-14 can be used.

NOTE 9 For requirements and ensuring component properties on AM titanium-6aluminium-4vanadium with extra low interstitials (Ti-6Al-4V-ELI) components, ASTM F3001-14 can be used.

NOTE 10 For requirements and ensuring component properties on AM UNS N07718 components, ASTM F3055-14a can be used.

NOTE 11 For requirements and ensuring components on AM UNS N06625 components, ASTM F3056-14e1 can be used.

NOTE 12 For requirements and ensuring component properties on AM UNSS31603 components, ASTM 3184-16 can be used.

NOTE 13 For requirements and ensuring component properties on AM titanium alloy components, ASTMF3302-18 can be used.

NOTE 14 For a standard specification for Cobalt-28 Chromium-6 Molybdenum via powder-bed fusion, ASTM F3213-17 can be used.

9.3.2.5.5 Environment and safety

Abnormalities in the environment are mainly due to, e.g. unsuitable energy consumption, unsuitable inner atmosphere condition, insufficient reuse of materials, excessive waste, and abnormalities in safety are mainly due to, e.g. explosion, leakage.

NOTE 1 See C.5 for the details on abnormalities of workpiece.

To deal with abnormalities in the environment and safety, the data from CPCM should be organized and managed as specified in the technical requirement given in 6.2.12.4.

NOTE 2 For a standard guideline for the use of metallic materials from environmental health and safety perspective, ISO/ASTM 52931 can be used.

1) Under preparation. Stage at the time of publication: ISO/ASTM FDIS 52924:2023.

NOTE 3 For considerations for reduction of hazardous substances emitted during the operation of material extrusion, ISO/ASTM 52933[2)] can be used.

9.3.3 AM workflow data management

AM workflow data management includes a) managing the data transmitted from data fusion by time-stamp, and b) providing data to the behaviour model engine (see 9.3.5) for extraction of value-added data and a MAPE unit (see 9.4).

It is to accomplish technical requirements given in 6.2.5.

To this end, the AM workflow data management element should:

— Receive the data from the data fusion element,

— Maintain the data from the data fusion element by a timestamp value, and

— Transmit the right data to the behaviour model engine (see 9.3.5) and a MAPE unit (see 9.4).

9.3.4 AM behaviour model

The behaviour model is a set of models that describe the AM process behaviour for the MAPE unit to conform with technical requirements given in 6.2.6 for extracting value-added data.

To this end, the behaviour model should:

— Be able to generate value-added data about abnormalities occurring in the AM machine body, feedstock / support, workpieces and environment and safety, which it is difficult to obtain directly from the data processing unit,

— Be designed for calculating value-added data, which is utilized in the MAPE unit, and

— Be executed in the behaviour model engine (see 9.3.5) to generate outputs.

NOTE Example behaviour models are:

— Machine body, see Reference [94] for more details on temperature shutdown error in powder bed fusion and see Reference [95] for more details on seeded driving belt fault in material extrusion,

— Feedstock / support, see Reference [96] for more details on material flow analysis in binder jetting[96], for details on characterization of metal powders in AM,

— Workpiece, see Reference [98] for more details on porosity detection in direct energy deposition, see also Reference [99] for more details on surface roughness in material extrusion, and

— Environment, see Reference [100] for more details on energy consumption.

9.3.5 Behaviour model engine

The behaviour model engine is the element that runs the behaviour model with the input from 'AM workflow data management' (see 9.3.3) and 'data storage element' (see 9.2.5).

This is to conform with technical requirement given in 6.2.6 for extracting value-added data.

The behaviour model should be executed in the behaviour model engine for extracting value-added data.

To this end, the behaviour model engine should transmit the output of the behaviour model to:

— The MAPE unit, and

2) Under preparation. Stage at the time of publication: ISO/ASTM DIS 52933:2023.

— The data storage element in the data processing unit.

9.4 MAPE unit

9.4.1 General

The MAPE unit is the unit that monitors, analyses, plans, and executes for the machine tool based on the data and behaviour models for the enhancement of key performance indicators (KPI) of the AM process defined in the digital thread unit.

The output of the MAPE unit can be utilized for updating AM workflow data managed in the AM workflow (e.g. 3D model design, support deployment, part orientation).

To this end, the MAPE unit should consist of:

— Monitoring element,

— Analysis element,

— Planning element, and

— Execution element.

9.4.2 Monitoring element

The monitoring element is the element that calculates key performance indicator (KPI) values from the viewpoints of the AM machine body, feedstock / support, workpiece, and environment and safety for determining whether or not the abnormality occurs in the time span of control.

This is to conform with technical requirements given in 6.2.7.

To this end, the monitoring element should:

— Generate the KPI values at the moment of current AM operation from the perspective of an AM machine body, feedstock / support, workpiece, and environment and safety, and

— Evaluate the KPI values to determine whether the current operation state is abnormal or not.

NOTE Example use case on monitoring includes the measuring melt pool thermal distribution and temperature in powder bed fusion using camera and pyrometer.

9.4.3 Analysis element

The analysis element is the element that:

— Predicts the future KPI values from the viewpoint of an AM machine body, feedstock / support, workpiece, and environment and safety to conform with technical requirement given in 6.2.8;

— Conducts diagnosis for finding the cause of the problematic KPI values to conform with technical requirement given in 6.2.9.

To this end, the analysis element should:

— Generate the expected future KPI values from the perspective of an AM machine body, feedstock / support, workpiece, and environment and safety, to clarify whether or not the abnormality occurs in the future, and

— Diagnose the cause of inappropriate KPI values generated in the monitoring element.

NOTE 1 Example use case on analysis includes: a) the predicting the residual stress and distortion in the powder based AM,[72] b) predicting surface roughness in the material extrusion,[102] and c) process failure diagnosis based on acoustic emission in material extrusion[103].

NOTE 2 For more information on KPIs in shop floor operation, see Reference [25].

9.4.4 Planning element

The planning element is the element that:

— Redefines the AM workflow data including process parameters or decides the action to conform with technical requirements given in 6.2.10 and 6.2.11, and

— Verifies the planning output to conform with technical requirements given in 6.2.10 and 6.2.11 for the sake of the "autonomously dealing with abnormalities" capability.

To this end, the planning element should:

— Redefine the AM workflow data including process parameters or decide the action to take that contributes to the enhancement of AM operation from the viewpoint of the AM machine body, feedstock / support, workpiece, and the environment and safety, and

— Verify the redefined parameters via simulation.

NOTE Example use case on planning includes optimizing the path in terms of geometrical accuracy, build time, material usage, surface quality of part[1].

9.4.5 Execution element

The execution element is the element that:

— Transmits the output of planning elements to the CPCM to conform with technical requirement given in 6.2.10, and

— Transmits the output of monitoring, analysis, and planning elements to the data storage in DPU and external interface unit to conform with technical requirements given in 6.4.3, 6.4.4, 6.5.2, 6.5.3, 6.6.2, 6.6.3, 6.7.2 and 6.7.3.

To this end, the execution element should:

— Receive the output from the monitoring, the analysis and the planning element,

— Transmit the output to the intra-loop element of a CPCM, and

— Transmit the output of monitoring, the analysis, and the planning element to data storage element in DPU and external interface unit.

NOTE Example use case on execution includes transmission of modified laser power parameter value to the intra-loop element in the CPCM for AM.

9.5 External interface unit

9.5.1 General

The external interface unit is the unit that receives data from the data processing unit via the data transformer for the external entities' element and data storage element, a MAPE unit via execution element.

The external interface unit transmits that data to an SFCS and a UIS for the sake of a) collaboration with an SFCS, b) data exchange with AM workflow, c) data exchange with hierarchy level, and d) data exchange with humans with interoperable communication to conform with technical requirements given in 6.4.3, 6.4.4, 6.5.2, 6.5.3, 6.6.2, 6.6.3, 6.7.2, and 6.7.3.

NOTE 1 OPC-UA (IEC/TR 62541-1), MTConnect (ANSI/MTC1.4-2018)[52], are representative standards for ensuring interoperability.

NOTE 2 See References [87] and [88] for the example configuration of OPC-UA server for an AM domain, including system architecture, data model, a prototype system.

To this end, the external interface unit should consist of:

— Interface schema element, and

— Interface manager element.

9.5.2 Interface schema element

The interface schema element is the element that represents the data structure in a CSSM to share with the external entities such as a UIS and an SFCS.

The interface schema element makes the a UIS and an SFCS refer to and find the right data in a CSSM.

To this end, the interface schema element should:

— Manage the table of contents of a CSSM for an SFCS and a UIS, and

— Provide the data schema to the interface manager element.

NOTE Examples of the table of contents are: a) manifest in administration shell of IEC/PAS 63088, b) XML schema of OPC-UA (IEC/TR 62541-1).

9.5.3 Interface manager element

The interface manager element is the element that manages the collected data from the data processing unit, a MAPE unit, and transmits them to an SFCS and a UIS to conform with technical requirements given in 6.4.3, 6.4.4, 6.5.2, 6.5.3, 6.6.2, 6.6.3, 6.7.2, and 6.7.3.

To this end, the interface manager element should:

— Communicate with and transmit data to an SFCS and a UIS, based on the table of contents defined in the interface schema element,

— Receive the schema from the interface schema element, and

— Manage the collected data from the data processing unit and a MAPE unit.

NOTE OPC-UA server in IEC/TR 62541-1 and MTConnect agent in ANSI/MTC1.4-2018[52] are examples of interface manager element.

10 Interface view of a CPSMT for AM

10.1 General

This Clause specifies a set of requirements for the interface between components of a CPSMT from a data perspective, as shown in Figure 7.

Communication protocol of the interface is out of scope. It should be determined in the implementation phase based on the purpose of implementation, considering the required latency threshold, system configuration type (e.g. edge, fog, cloud), the amount of data.

NOTE 1 This clause describes mainly the internal and external interfaces on a CPCM and a CSSM, indicated by the key in Figure 3.

NOTE 2 This clause does not deal with interfaces between associated systems and external entities. See ISO 23704-1:2022, Clause 9 for those interfaces.

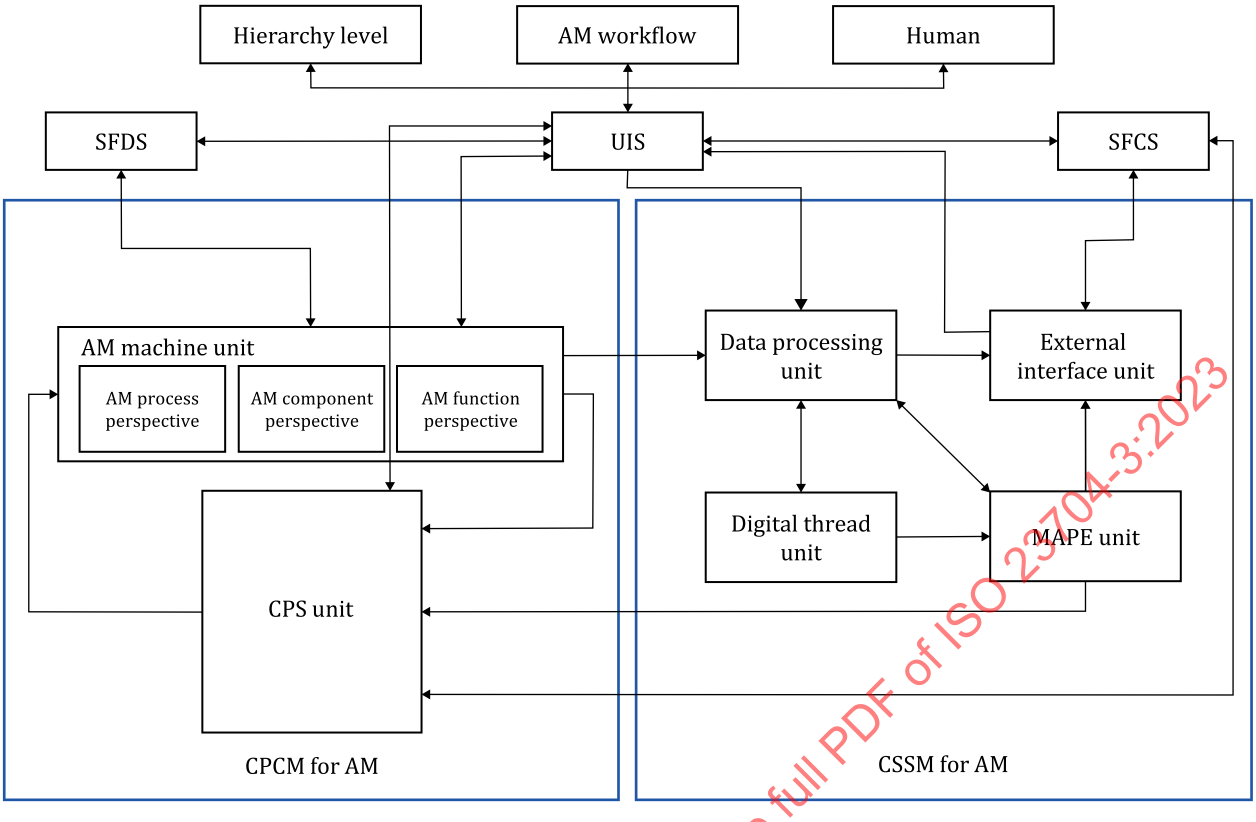


Figure 7 — Interface view of a CPSMT for AM

10.2 CPCM interface

10.2.1 General

This subclause deals with internal and external data interfaces on a CPCM.

10.2.2 External interface with a CPCM

10.2.2.1 General

This subclause deals with external data interfaces on a CPCM.

10.2.2.2 Interface between an SFDS and an AM machine unit (AMU)

To conform with technical requirements given in 6.3.2, this interface should exchange all controls and data for coordination between devices in an SFDS and an AMU.

For the interface for automated machine tending, see ISO 21919-1.

10.2.2.3 Interface between a UIS and a CPS unit

To conform with technical requirements given in 6.5.2, 6.6.2, and 6.7.2, this interface should transmit the data from the external entities (e.g. part program and AMF file) to the CPS unit via UIS.

To conform with technical requirements given in 6.5.2, 6.6.2, and 6.7.2, this interface should also transmit the parameter estimation output in the inner-loop element to the external entities via UIS. The parameter estimation output can be grouped by abnormality types described in 9.3.2.5.

10.2.2.4 Interface between a UIS and an AM machine unit (AMU)

To conform with technical requirements given in 6.5.2, 6.6.2, and 6.7.2, this interface should transmit the data from the external entities (e.g. part program) to the AMU.

To conform with technical requirements given in 6.5.2, 6.6.2, and 6.7.2, data values generated by controllers and sensors can be transmitted to the external entities via a UIS if necessary. For examples of relevant data items, see 8.3.2.

10.2.2.5 Interface between an AM machine unit (AMU) and data processing unit

To conform with technical requirements given in 6.2.4, this interface should transmit the data acquired from the AMU to a CPCM interface element in data processing unit.

For example data items, see 9.2.2.

10.2.2.6 Interface between a CPS unit and a MAPE unit

To conform with technical requirements given in 6.2.3 and 6.2.10, this interface should transmit the result of the planning element, which is performed by the execution element in MAPE unit, to the intra-loop element in the CPS unit.

Data from a CSSM to a CPCM can be grouped by abnormality types described in 9.3.2.5.

10.2.2.7 Interface between a CPS unit and an SFCS

To conform with technical requirement given in 6.4.2, this interface should transmit the output of an SFCS (e.g. task allocation plan) to the inter-loop element in the CPS unit.

To this end, the SFCS delivers, for example, a device allocation plan to each device in an SFDS and a CPCM for AM based on the current status of the shop floor system.

10.2.3 Internal interface with a CPCM

10.2.3.1 General

This subclause deals with internal data interfaces on a CPCM.

10.2.3.2 Interface between an AM machine unit (AMU) and a CPS unit

To conform with technical requirements given in 6.2.4, this interface should transmit the data acquired from sensors and controllers in the AMU to the inner-loop element. For examples of related data, see 8.3.2.

To conform with technical requirements given in 6.2.2 and 6.2.10, this interface should transmit the control input generated by the adjustment mechanism component in the inner-loop element to the AMU.

To conform with technical requirements given in 6.2.3 and 6.2.10, this interface should transmit the converted commands from a CSSM in the intra-loop element to the controller in the AMU.

To conform with technical requirement given in 6.4.2, this interface should transmit the converted commands from an SFCS in the inter-loop element to the controller in the AMU.

10.3 CSSM interface

10.3.1 General

This subclause deals with internal and external data interfaces on a CSSM.

10.3.2 External interface with a CSSM

10.3.2.1 General

This subclause deals with external data interfaces on a CSSM.

10.3.2.2 Interface between a UIS and data processing unit

To conform with technical requirements given in 6.5.2, 6.6.2, and 6.7.2, this interface should transmit the data from the external entities (e.g. part program and AMF file) to the UIS interface element in the data processing unit. The acquired data is mapped and managed in the digital thread unit via data fusion element.

10.3.2.3 Interface between external interface unit and a UIS

To conform with technical requirements given in 6.5.2, 6.5.3, 6.6.2, 6.6.3, 6.7.2, and 6.7.3, this interface should transmit a) the output of monitoring, analysis, and planning function in the MAPE unit, b) the history data stored in the data storage element, and c) data from data transformer for external entities elements to the external entities via a UIS.

10.3.2.4 Interface between external interface unit and an SFCS

To conform with technical requirements given in 6.4.3 and 6.4.4, this interface should transmit a) the output of monitoring, analysis, and planning function in the MAPE unit, b) the history data stored in the data storage element, and c) data from data transformer for external entities elements to an SFCS.

10.3.2.5 Interface between a CPS unit and a MAPE unit

This clause is included for completeness but is the same connection as that already dealt with from the CPCM. For details, see 10.2.2.6.

10.3.2.6 Interface between an AM machine unit (AMU) and data processing unit

This clause is included for completeness but is the same connection as that already dealt with from the CPCM. For details, see 10.2.2.5.

10.3.3 Internal interface with a CSSM

10.3.3.1 General

This subclause deals with internal and internal data interfaces on a CSSM.

10.3.3.2 Interface between data processing unit and external interface unit

To conform with technical requirements given in 6.4.3, 6.4.4, 6.5.2, 6.5.3, 6.6.2, 6.6.3, 6.7.2, and 6.7.3, this interface should a) transmit the output of the data transformer for external entities element to the interface manager element in the external interface unit, and b) transmit the history data in the data storage element to the interface manager element for the interaction with a UIS, and an SFCS.

10.3.3.3 Interface between data processing unit and digital thread unit

To conform with technical requirement given in 6.2.6, this interface should transmit the data fusion result to the AM workflow data management element in the digital thread unit. The output of data fusion is the organized data mapped to the AM workflow data model.

This interface should transmit a) the data past a certain amount of time in AM workflow data management, and b) the output of the behaviour model engine to the data storage element for managing the history.

To conform with technical requirement given in 6.2.6, this interface should transmit data managed by the data storage element to the behaviour model engine as input for the behaviour model, which requires the history data.

10.3.3.4 Interface between data processing unit and a MAPE unit

To conform with technical requirements given in 6.2.7, 6.2.8, 6.2.9, and 6.2.10, this interface should transmit the stored data to the MAPE unit for the functions that require history data.

This interface should also transmit the MAPE unit's output to the data storage element for managing the history.

10.3.3.5 Interface between digital thread unit and a MAPE unit

To conform with technical requirements given in 6.2.7, 6.2.8, 6.2.9, and 6.2.10, this interface should transmit the value-added data from the behaviour model engine to the MAPE unit.

10.3.3.6 Interface between a MAPE unit and external interface unit

To conform with technical requirements given in 6.4.3, 6.4.4, 6.5.2, 6.5.3, 6.6.2, 6.6.3, 6.6.2, and 6.7.3, this interface should transmit the MAPE unit's output to the interface manager element.

Annex A
(informative)

Collected stakeholder requirements on smart additive manufacturing system (SAMS)

A.1 General

This annex contains the results of a pre-study to collect stakeholder needs and formalise them as requirements in this document.

The stakeholders addressed in this document are aimed at those who are directly involved in the development of the SAMS. As defined in ISO/IEC/IEEE 12207[10], a stakeholder is an individual or organization having a right, share, claim, or interest in a system or in its possession of characteristics that meet their needs and expectations.

NOTE According to ISO/IEC/IEEE 42010:2022, 5.3, the following stakeholders are recommended to be considered in the architecture description: users, operators, acquirers, owners, suppliers, developers, builders, and maintainers of the system.

A.2 The principle on the derivation of stakeholder requirements for the SAMS

The stakeholders for the SAMS can be largely divided into the supply industry and user industry. In the supply industry, there are machine builders, controller and drive makers, and system integrators. In user industries, there are process designers, the AM machine operators, mechanics, production managers.

To identify the key features of the SAMS for Industry 4.0, extensive interviews / workshops with experts, benchmarking / reverse engineering, comprehensive analysis of documents including market reports, R&D papers in the AM domain, have been conducted. The identified features are elaborated and organized, taking AM workflow defined in 3.1.5 and the perspective of the generic architecture of a CPSMT given in ISO 23704-1 into consideration. Figure A.1 shows the AM workflow and related stakeholders.

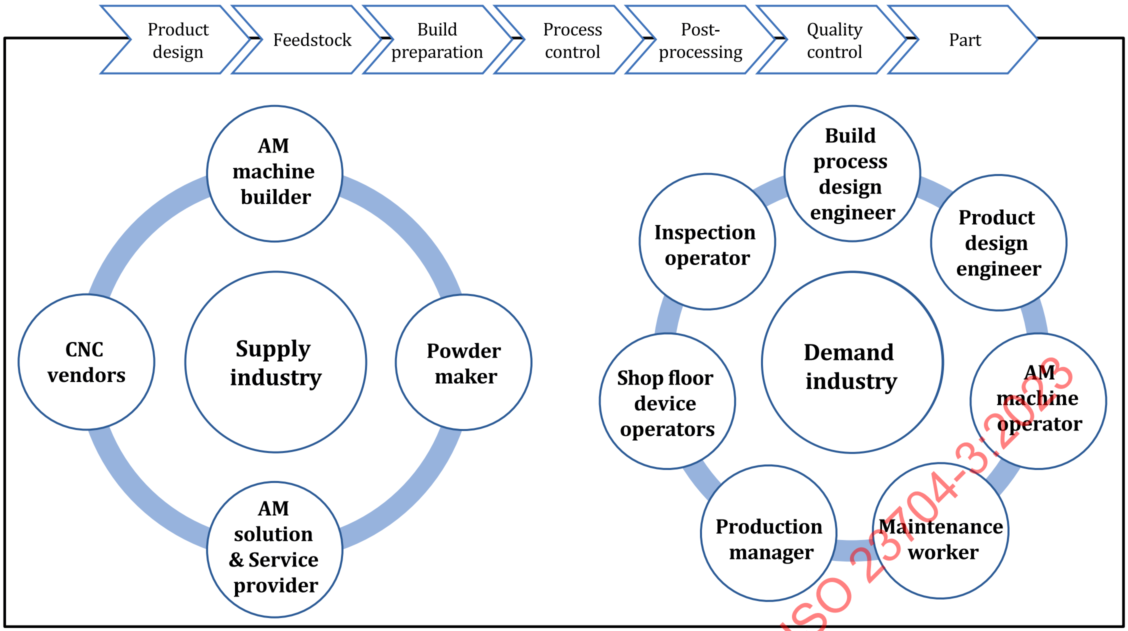


Figure A.1 — AM workflow and related stakeholders for identifying the key features of the SAMS

Despite the great potential for enabling the Industry 4.0 paradigm, mainly due to the immature state-of-the-art technology, there exist limitations in the AM domain, which can be thought of as the source of the requirements for an SAMS. Examples of limitations include the type of the materials, quality of the product, size of the product, cost of the product, production lead time including design, material setup, building / printing, post-processing.

NOTE A standard for data processing along the AM workflow is ISO/ASTM 52950.

From the perspective of operation of the AM process, the following have been identified as the key requirements that need to be fulfilled by the smart AM system:

— to handle various abnormalities in the AM domain that occur during the build process and inspection;

— to share continuously the various data on the whole AM workflow to the shop floor and vice versa to increase process performance;

— to interact with the various shop-floor devices, office floor system, and an AM machine to overcome the different communication methods, data specifications;

— to incorporate the concept of combination with a subtractive manufacturing process and an AM process into one machine.

Annex B
(informative)

Concept of the digital thread in AM

The key advantage of the AM process is short time-to-market and personalized production. In producing products, the production process needs to be updated in a shorter cycle in conjunction with CAx activity compared with other types of manufacturing through active feedback and feedforward among different life cycle information.

In this respect, the digital thread is the key enabler for achieving those objectives. Digital thread is the framework that provides an integrated view of all data throughout the life cycle of a product, which are interconnected in a series of feedback and feedforward loops. The digital thread manages a record of a product's or system's lifetime, from its creation to its removal. The CAx chain (CAD, CAPP, CAE, CAM, CNC, CMM) is a key enabler for this[63].

The digital thread can be realized throughout the whole AM life cycle, which is represented in AM workflow for emphasis on the life cycle management/update from AM perspective.

The digital thread can bring the following to the SAMS, as well as to an enterprise:

— Provision of an integrated view on the life cycle data,

— Reduction of time-to-market,

— Interoperable and bi-directional data flow among all life cycle phases,

— Optimization of operability, manufacturability on the product, and

— Enabling feedback loop for the life cycle monitoring and control of product, process, resources.

The digital thread and the digital thread unit as referenced in 9.3 have a common point in that they acquire and manage the AM product life cycle and use it in a comprehensive manner.

From the CPSMT perspective, the digital thread can:

— provide the life cycle information on products to CPSMT primary system (CSSM, CPCM) for the sake of the "autonomous dealing with abnormalities" capability;

— provide the life cycle information on products to CPSMT associated systems (SFDS, SFCS, UIS) for the sake of the "autonomous coordination with SFDS," and "autonomous collaboration with SFCS" capabilities;

— update their own life cycle information by a) receiving information with operation perspective generated from CSSM, CPCM, SFDS, SFCS, and b) bi-directional data flow among all life cycle phases. The capabilities of "interface with life cycle aspect, hierarchy level, humans," especially the life cycle aspect, support this function.

Annex C
(informative)

Types of abnormality in AM

C.1 General

A CPSMT is a smart machine tool system supporting smart manufacturing on the shop floor via a cyber-physical system control scheme. Given this, the CPSMT mainly focuses on the operation phase from the AM workflow perspective.

One of the main capabilities of the primary system of CPSMT is "Autonomous dealing with abnormalities".

To prevent abnormalities and enhance an AM operation from the CPS control scheme perspective, recognition of the symptoms of those types of abnormality and resolution in an autonomous fashion are key points.

In general, the types of abnormality during an AM operation are the following:

— Abnormalities on an AM machine body,

— Abnormalities on feedstock/support,

— Abnormalities on workpiece, and

— Abnormalities on environment and safety.

C.2 Abnormalities on AM machine body

For abnormalities on an AM machine body, ISO 11452-1 defines machine degradation as an undesired departure in the operational performance of any device, equipment, or system from its intended performance imposed on the AM machine.

NOTE 1 Inappropriate energy supplement is the variation of energy reaching the interaction zone out of allowable limits[82].

NOTE 2 Path disturbance is the phenomenon happening to a servo system that induces a gap between the planned path and actual path.

NOTE 3 Inappropriate feedstock / support distribution is the variation of feedstock / support supplement reaching the interaction zone out of allowable level.

NOTE 4 Other abnormalities can be incorporated in the implementation phase.

C.3 Abnormalities on feedstock/support

For abnormalities on the feedstock/support, unsuitable variation in mechanical, chemical, rheological, optical and thermal properties, is the major cause and the representative data related to this are:

— Optical properties including the absorbance, reflectance, transmittance[69];

— Rheology properties including surface tension, melting viscosity, wetting angle, thermal conductivity[70];

— Chemical properties including the reaction enthalpy, impurity[71,72];