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Additive manufacturing for construction — Qualification principles — Structural and infrastructure elements

Fabrication additive pour la construction — Principes de qualification — Éléments de structure et d'infrastructure

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Foreword

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This document was prepared by Technical Committee ISO/TC 261, *Additive manufacturing*, in cooperation with ASTM Committee F42, *Additive Manufacturing Technologies*, on the basis of a partnership agreement between ISO and ASTM International with the aim to create a common set of ISO/ASTM standards on Additive Manufacturing and in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 438, *Additive manufacturing,* in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

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

The construction sector is increasingly facing challenges with respect to labour shortages, project delays, increased lead times, excessive material use, large amounts of waste and adverse CO_2 footprint impacts. Furthermore, from a market perspective, the global construction demand is increasing especially as the housing crisis continues and infrastructure projects (whether new or sustaining existing structures) are on the increase. Additive construction (AC) also known as additive manufacturing for construction (AMC) and 3D construction printing (3DCP) has the potential to address these issues directly.

Of late, AC has made great strides. Printed elements could potentially prove to be more durable, more sustainable, more eco-friendly, cheaper (en masse), and faster to deliver than conventional construction approaches. However, without AC standards, approval, certification, and risk mitigation are unattainable.

The purpose of this document is to outline the requirements necessary as a basis for production and delivery of high quality additively manufactured structures (residential or infrastructure) in the construction sector.

Important steps of the AC process are specified. These steps will be controlled and monitored to ensure high quality printed structures for on-site or off-site use. This document is not intended to be technology- or material-specific, and therefore sub-processes are applicable depending on the approach used. However, it should be noted that printed element(s) should be approved by a locally certified engineer and adhere to both local and regional specifications and requirements.

Additive manufacturing for construction — Qualification principles — Structural and infrastructure elements

1 Scope

This document specifies quality assurance requirements for additive construction (AC) concerning building and construction projects in which additive manufacturing techniques are used for construction. The requirements are independent of the material(s) and process category used.

This document does not apply to metals.

This document specifies the criteria for additive construction processes, quality-relevant characteristics, and factors along AC system operations. It further specifies activities and sequences within an AC cell (additive construction site) and project.

This document applies to all additive manufacturing technologies in building and construction (load bearing and non-load bearing), structural and infrastructure building elements for residential and commercial applications and follows an approach oriented to the process.

This document does not cover environmental, health and safety aspects that apply to printing facility setup, material handling, operating of robotic equipment, and packing of equipment and/or elements for shipping but should be applied based on material supplier guidelines, robotic solution operating guidelines, and local and regional requirements.

This document does not cover design approvals, material properties characterization and testing.

2 Normative references

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

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

ISO/ASTM 52950, *Additive manufacturing — General principles — Overview of data processing*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in 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
additive manufacturing for construction
AMC
process to join materials to make structural and non-structural elements/components and systems from 3D model data usually by depositing material layer upon layer as opposed to subtractive and formative manufacturing methodologies

3.2
additive construction
AC
term to describe all relevant disciplines and knowledge for the construction segment using additive manufacturing process categories

Note 1 to entry: The use of the technologies covers all relevant construction sectors, for example large scale real estate projects, entire buildings and building elements, civil infrastructure, and disaster relief.

Note 2 to entry: AC describes all relevant knowledge disciplines, for example: architecture, engineering, structural engineering, materials engineering, robot operator, project management, construction management, facility management, etc.

Note 3 to entry: Other terms used interchangeably are: Digital Construction (DC), Construction 4.0, Advanced Manufacturing in Construction (AMC), Construction 3D Printing (C3DP) and 3D Construction Printing (3DCP).

Note 4 to entry: Building materials include:

— cementitious variations such as concrete and mortar, polymer modified pastes,

— composite materials.

Note 5 to entry: Intrinsic to the current definition is a high degree of robotic automation, a reduced degree of human intervention during the construction process, and minimal waste due to as-needed material delivery systems.

Note 6 to entry: As of this writing in 2023, the field of AC is rapidly evolving, and novel materials and methods are very likely to become included in this definition.

Note 7 to entry: AC is used on-site or off-site (e.g. modular factory-based production).

3.3
layer deposition
application of a single layer

3.4
AC cell
printing solution deployed on site for in-situ printing (includes material mixing and placement systems)

3.5
material deposition device
numerically controlled assembly, including mixing and delivery mechanisms for raw materials, binders, and additives; places the mixture based on a digital simulation entered in the assembly's electronic programs, without the need for direct human intervention or for using moulds

3.6
physical production
physical totality of the build space, elements located on the build space, and production related support structures and plant in the build space of the system

3.7
virtual production run
computer/digital simulation of the *physical production* (3.7) run (print file)

EXAMPLE Printing simulation.

3.8
dry production run
process of running the build program with no materials to verify the first layer toolpath and other critical points of the program; and can be part of calibration process

3.9
construction process
digital and physical AC operations, from setup of the robot through completion of the final printed element, including quality assurance testing and verification

3.10
mechanical, electrical and plumbing
MEP
building systems required for heating, ventilation, and air conditioning; electrical power and communication supply; and water supply and sewage removal, respectively

3.11
printed element
construction 3D printed component, whether constructed on-site (in-situ) or off-site, that gets incorporated into a building or structure, as a complete infrastructure component

EXAMPLE Walls, columns, beams, etc.

3.12
printability
ability of the material to be easily delivered to the print head, processed by the print head, e.g. *extrudability* (3.13), and meet consistent layer shape stability, *buildability* (3.14) requirements, and if applicable *pumpability* (3.15)

3.13
extrudability
ability of the material to smoothly be ejected through the printing nozzle without inducing any blockage of the conduits or significant damage to the material quality

3.14
buildability
ability of a print to preserve vertical and lateral stability under increasing loads coming from superposed/subsequent layers with controlled deformation

3.15
pumpability
material paste criterion that is related to the concrete extrusion and workability, as it is important to ensure that the materials have a continuous easy-flowing behaviour from the source to the printing material deposition device/nozzle

Note 1 to entry: Pumpability ensures the materials can be pumped easily and continuously without creating clogging issues inside the delivery system.

4 Constructability, assessment and review

4.1 General

Verification of the AC element requirements shall be specified and verified before the data preparation. The results shall be transferred in a definite sequence with associated production specifications including specific requirements in respect to the quality control (for load and non-load bearing elements). It is recommended that any asset monitoring and/or management be based on locally applicable standards/codes/regulations which could be based on numerical verification analysis.

If the production request is incomplete (for example missing technical drawing) or an initial commissioning is associated with restrictions, the customer shall be notified to correct the problem.

Figure 1 shows the individual steps for checking the feasibility and qualification phase as a pre-requisite for the serial production with AC.

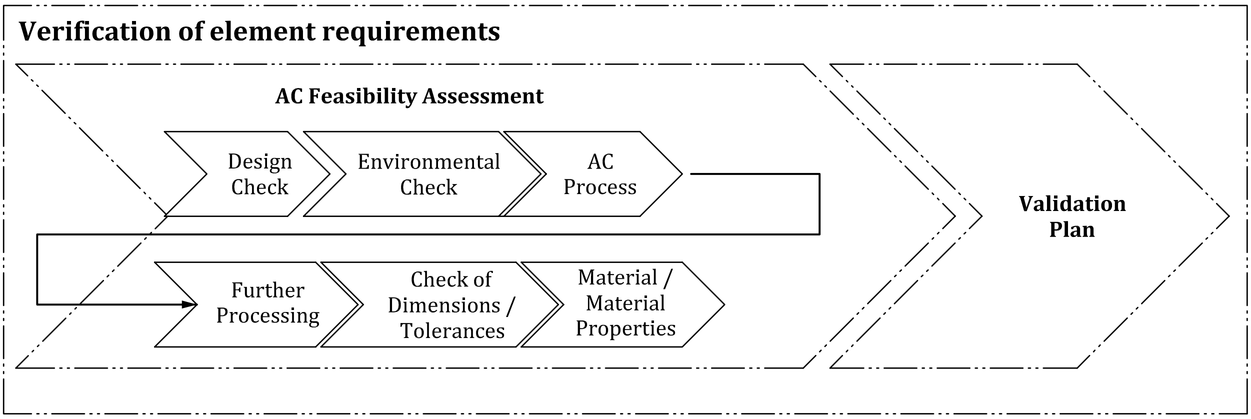

Figure 1 — Steps involved in verification of AC element requirement

4.2 AC feasibility assessment

AC feasibility, including AC element requirements, shall be evaluated by suitable personnel (e.g. technology experts or instructed persons, obtaining relevant permits from local authorities, classified and registered as required by authorities having jurisdiction and proven to have designed and accomplished successfully a specific number of 3D printed elements (e.g. 5) with the same construction process and comparable dimensions and complexity).

The necessary production competence is only available in the direct AC environment. It is important to include all element requirements in the feasibility check. The evaluation shall include the following steps:

a) **Design check**: the process-relevant design directives should be consulted to evaluate the design's AC feasibility and comply with national, regional, and local codes. In addition, process-relevant AC restrictions such as minimum wall thicknesses and reinforcement requirements shall also be taken into consideration.

b) **Environmental check**: for the environmental dimension, material selection and design stages are regarded as crucial to the sustainability performance of a built element throughout its life cycle. It is important to perform a sustainability assessment of the building material or the building product itself, in accordance with ISO 21930 and ISO 14001 following a cradle-to-grave approach of a life cycle analysis (LCA) and track macro-indicators, for both internal use and to elaborate Environmental Product Declarations (EPDs) of building products after validation. Environmental checks/studies shall be done in compliance with all national, regional, and local requirements.

   Core indicators to use are:

   — global warming potential (CO_2 equivalent emissions);

   — greenhouse gas (GHG) emissions that have a potential impact on the climate.

   Other relevant indicators may be:

   — Pollution potential: freshwater resources that have a potential impact on the depletion of freshwater resources (in case no metallic material will be used in the paste mix design, using other than freshwater, such as sea water, or treated water may be envisaged in the process, based on the usage of the printed element, and its interaction/exposure to end users).

   — Fossil fuel depletion potential (oil equivalent): consumption of non-renewable raw materials and non-renewable primary energy.

   — Ozone depletion potential (CFC-11 to air): release of gases that have a potential impact on the stratospheric ozone layer.

— Amount of waste generated by type: total volume of non-hazardous and hazardous wastes that has a potential impact on the generation of waste for disposal acidification potential (SO_2 to air) - potential impact on the acidification of land and water resources.

— Freshwater eutrophication potential (P to freshwater): potential impact on the eutrophication of water bodies.

c) **AC process**: it is also necessary for qualified engineers to check whether the desired element, and element properties to be attained, are AC feasible with the process parameters already qualified, or whether adaptations are necessary to attain AC feasibility. AC specific process category risks also need to be evaluated by qualified engineers to achieve dedicated component requirements. Refer to Table A.1 for specific processes and materials.

d) **Further processing**: if a further (semi-)automated manufacturing step occurs, it is necessary to check whether the design is appropriate for this, if auxiliaries cannot be used. If subtractive or finishing processes are then carried out to attain the required manufacturing tolerances, corresponding design details shall be provided as early as the data processing, if necessary.

e) **Check of dimensions/tolerances**: the tolerances specified in the design shall be attainable in the selected AC process. Post-treatment shall be considered before the start of the AC process.

EXAMPLE 1 Any special considerations for reinforcement and/or MEP integration, starting, stopping, or skipping in the AC process.

f) **Material/material properties**: AC feasibility shall be considered beyond the selected technology, depending on the material, material mix design, and over the entire AC process. The specified material properties shall be incorporated here. Local standard tolerances for fire resistance, load/compressive strength, tension, shrinkage, creep, and resistance to environmental effects such as moisture, cyclic freezing, and ultraviolet (UV) radiation etc. should be followed.

EXAMPLE 2 Materials that exhibit different AC constraints.

An individual element evaluation shall then be conducted to define the necessary measures for quality assurance. Based on the method for quality assurance already implemented as well as the risk analysis for the relevant application, it is necessary to check whether separate measures for element-related quality control are necessary (see 7.4).

4.3 Validation plan

The requirements of the direct manufacturing environment include the qualification plan for the series element. The prerequisite is qualification of the material for a definite AC process. A qualification plan shall be formulated for the elements and associated test methods according to the relevant work and/or procedural steps as specified by the customer. The element(s) production is validated in a stage process (see A.2 or ISO/ASTM 52901). Each phase is successfully completed upon signing by suitable personnel.

The methodical recording of the element requirements can be derived from (e.g. ISO/ASTM 52901). This makes it possible to derive which validations can be necessary beyond this document.

5 Infrastructure of the AC cell

The following requirements are relevant for the infrastructure of the AC cell:

a) **Equipment:** EHS (Environmental, Health and Safety) checks and management should comply with existing local and regional statutory on-site and off-site standards for all equipment. Some examples are listed below:

— EN 12001;

— EN 12629-1;

— ISO 4413;

— ISO 4144;

— ISO 12100;

— ISO 13849-1;

— ISO 13849-2;

— ISO 13850;

— ISO 13854;

— ISO 13857;

— ISO 14118;

— ISO 14119;

— ISO 14120;

— EN 60204-1;

— ISO 10218-1;

— ISO 10218-2;

— EN 60204-1.

b) **Safety at work**: a safe working environment with consideration of the statutory regulations shall be ensured. This includes personnel instruction concerning the occupational safety measures and equipment.

The users of this document should refer to appropriate safety management guidance and local legislation and regulation to gain a full understanding of specific requirements.

The following is a summary of some of the safety management aspects AC should consider.

1) Safety legislation holds operators to account for the protection of their employees, the public and the environment in relation to their industrial activities. While legislation and regulations vary in each country or region, the basic principles of safety management are common and should be common practice for all AC companies.

2) Operators shall possess safety management arrangements that identify responsible and accountable persons within their organization. The safety management arrangements will also detail the processes in place to ensure that safety is achieved for all operations of the company and considering all hazards that are associated with AC. Safety management arrangements should be proportionate to risk and complexity of the operation.

3) The central aim of safety management is to identify all foreseeable hazards and reduce risks to a level that is tolerable and as low as reasonably practicable or achievable. Risk control measures are used to achieve this in various ways across the safety discipline.

4) As the operator of robotic AC equipment and associated machinery and materials, operator shall consider and ensure the safety of all aspects of operation including, but not limited to:

— the printing location, factory or site-based;

— the machinery being used and interfaces between machinery;

— emergency and accident arrangements and response including first aid requirements;

— safety signage;

— safe handling and storage of materials;

— construction site safety requirements and PPE requirements;

— process warnings and cautions;

— installation and use of barriers and guards;

— adequate safety training and provision of adequate safety information;

— safety discipline and safety culture;

— duty of care for workers;

— reporting near misses;

— learning from experience;

— consideration of public safety;

— keeping auditable records for safety decisions.

c) **System installation**: the AC system shall be installed by qualified personnel (see 7.2). Evidence of installed conditions shall be documented (e.g. service report, final acceptance report, reports on modification to the system, designation of the machine type including version status of the software components and, if applicable, version status of the hardware components, machine identification number, etc.). All staff delivering the product to be deemed appropriately trained with maintained and retained record as part of a QMS system with the process steps recorded.

d) **Maintenance**: all maintenance activities shall be completed and documented.

The machine installation and maintenance refer to systems of the process control as well as all devices relating to systems and parts [e.g. material storage, mixer, pump, UV system (if applicable)].

e) **Production environment**: system manufacturer specifications shall be adopted with respect to ambient and installation conditions.

f) **IT infrastructure**: for an AC factory setup, ensure security of the server landscape, provision of the IT hardware, safety and archiving systems, etc. (e.g. according to ISO/IEC 27001) as outlined (but not limited) to the below shall be followed:

— floor load capacity and evenness of the ground, absence of vibration;

— extensive availability, minimum distance to neighbouring systems and equipment;

— controlled or permissible temperature, humidity, light conditions, air particle components;

— cleanliness of the AC environment;

— logged installation conditions and qualification of the production system;

— logs covering all other quality-relevant influencing factors regarding the function of a system.

The AC management system ensures that the correct steps occur in the qualified sequence with the corresponding parameters. This includes planning the machine capacity utilization and material stock corresponding to a specified minimum level. A system for planning the bottlenecks shall be demonstrated.

6 Qualification of the additive construction process

6.1 Quality-relevant process steps within the additive construction process

It is recommended that a quality management system (e.g. ISO 9001) is in place when the AC element manufacturer applies this standard. Additionally, this standard can be used to establish a quality management system specifically relevant to AC technology.

In order to ensure high quality within an AC cell, the complete process chain (see 6.2 to 6.7) of the production process and personnel requirements (see 7.2) shall be considered.

The relevant areas of the process chain are shown in Figure 2. These comprise:

— Quality assurance: preventive measures that ensure the required element quality over the entire process chain (see Annex B for a proposed approach for AC quality assurance);

— Data preparation: digital processing occurring before additive construction (see A.3);

— Material management: material flows occurring before and during the printing process (see B.3);

— System related pre-processing: manual activities occurring in the immediate environment of the printing system and serving to initiate the controlling of the process (see A.3);

— Process guidance (build cycle): complete machine cycle in which elements are produced additively (see A.3);

— Default post-processing: activities occurring in the environment of the production system and performed downstream of the process control (see A.1);

— Element specific post-processing: activities on the element after the process guidance (see Annex A, Annex B and Annex C).

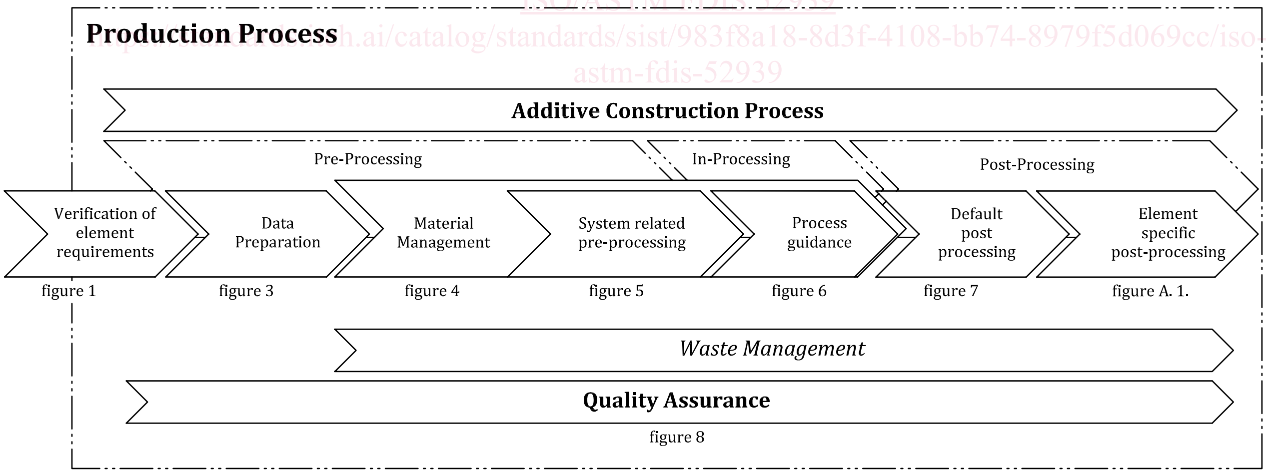

Figure 2 — Quality assured process in AC on-site or off-site

The assurance of the element quality requires comprehensive specification of the production process (Figure 2):

a) Quality-relevant characteristics as well as test methods and intervals for monitoring each individual process outlined in Figure 1 should be detailed;

b) Work equipment and any applicable ambient conditions required for and during the printing process shall be in place;

c) System-related maintenance and servicing activities; (see Table D.1 for specific process examples) should be taken into account;

d) Qualification measures for determining relevant input variables (e.g. material properties) and resultant output variables, which are derived from a combination of the previously specified characteristics over the entire process should be defined;

e) Defining the measurement, geometric dimensioning, and tolerancing regarding AC usage shall be specified by application specificity and/or based on user requirements (see Annex B).

6.2 Data preparation

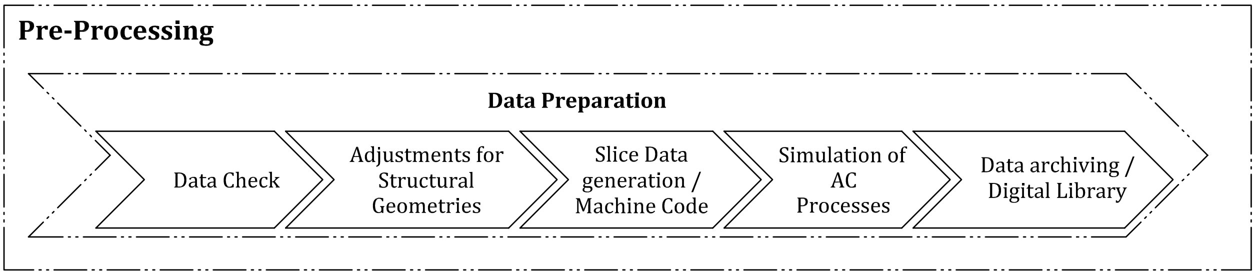

Figure 3 — Data preparation steps

Data structure principles of ISO/ASTM 52950 shall be applied. The definitions of ISO/ASTM 52900:2021, 3.4 shall be followed.

If technically applicable, the following process steps from Figure 3 shall be specified and their testing and documentation defined:

a) **Data check**: an inspection regarding error-free, process ability of the 3D data shall be completed. If errors are found, a data repair shall be carried out with close collaboration and approval of the engineering team especially if any geometric modification is required;

If applicable, documentation of the file format (e.g. STL, AMF) conversion (tessellation) parameters is required.

b) **Adjustment for element geometries**: allowances for temporary support (e.g. overhangs) and MEP integration if applicable. 3D data changes are allowed as they relate to element changes if all adaptations are documented in comprehensible and verifiable form (this requires version control of the modified data set), and proper approvals are sought and agreed upon prior to changes being made.

Slice data generation/machine code (e.g. g-code): conversion into machine-specific slice data with complete process parameters based on the approach and material.

In case of software updates, input and output data should be used to check that the generated data corresponds to the referenced output data.

The parameters for the data conversion shall be specified and complied with in the corresponding process description, under the consideration of the key quality assurance characteristics of the particular AC process category used.

c) **Simulation of additive construction process**: virtual production run to predict printability and print performance based on the geometry, material, and AC process categories/characteristics (see Table D.1 for specific examples).

Furthermore, a mock-up for a complex part of the element to be 3D printed should be constructed to demonstrate that the element is printable, and that the material is flowable, extrudable, buildable, pumpable, and that the extruded material's open time (the period of time in which the workability is consistent within certain tolerances acceptable for the process) is all as designed, to achieve required shape within allowable tolerances.

