

# Research on Strategies, Methods and Approaches for Applying CAD/CAM/CAE Technologies and Their Integration in Cyber-Physical Production Systems

Galena Slavova<sup>1</sup>, Stanislav Slavov<sup>2\*</sup>

<sup>1</sup>Changzhou Institute of Mechatronic and Information Technology Changzhou, China/Sofia  
University, Sofia, Bulgaria

<sup>2</sup>University of Chemical Technology and Metallurgy, 8 Kliment Ohridski, Sofia 1797, Bulgaria

Received 07 February 2026, Accepted 05 March 2026

DOI: 10.59957/see.v11.i1.2026.7

---

## ABSTRACT

*Cyber-Physical Production Systems (CPPS) have emerged as one of the most important technological paradigms in Industry 4.0, enabling manufacturing systems to become intelligent, interconnected, and adaptive. A key foundation for CPPS development is the integration of engineering technologies such as Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), and Computer-Aided Engineering (CAE). These tools provide digital representations of products, processes, and system behaviour, but remain fragmented in many industrial contexts.*

*This paper investigates strategies, methods, and standards supporting CAD/CAM/CAE integration in CPPS architectures. A multi-level integration framework is proposed, linking engineering backbone systems, semantic interoperability models, real-time operational connectivity, analytics, and closed-loop optimization. The role of industrial standards such as OPC UA, AutomationML, STEP-NC, Asset Administration Shell, FMI, and ISO digital twin frameworks is analysed. Extended case studies from automotive machining, robotic welding, and smart assembly demonstrate the practical benefits of closed-loop manufacturing integration.*

***Keywords:** CAD/CAM/CAE, Cyber-Physical Production Systems, Industry 4.0, Digital Twin, Digital Thread, OPC UA, AutomationML, STEP-NC, Asset Administration Shell, FMI.*

---

## INTRODUCTION

The rapid evolution of smart manufacturing requires production environments that are capable of real-time monitoring, decision-making, and adaptation. Cyber-Physical Production Systems (CPPS) represent the convergence

of computational intelligence with physical manufacturing resources, enabling factories to operate as interconnected ecosystems rather than isolated automation cells.

At the core of modern engineering workflows are CAX technologies:

- CAD systems describing product geometry

---

\*Correspondence to: Stanislav Slavov, University of Chemical Technology and Metallurgy, 8 Kliment Ohridski, Sofia 1797, Bulgaria, e-mail: stanislavslavov@uctm.edu

and tolerances;

- CAM platforms defining manufacturing operations and toolpaths;
- CAE tools modelling physical behaviour through simulation.

Despite their importance, these tools often remain disconnected from operational manufacturing systems such as SCADA, MES, or machine-level control, resulting in incomplete digital continuity.

Recent research highlights two critical Industry 4.0 concepts:

- Digital Thread, ensuring traceability of information throughout the life-cycle,
- Digital Twin, enabling synchronized virtual replicas of manufacturing systems.

ISO 23247 provides a structured framework for implementing digital twins in manufacturing environments, emphasizing information exchange and life-cycle integration [1].

The challenge is not whether CAD/CAM/CAE technologies should be applied, but rather how they can be integrated effectively into CPPS architectures, supporting interoperability, semantic consistency, and feedback-driven optimization.

This paper explores strategies, standards, and methods that enable CAD/CAM/CAE tools to become fully embedded into cyber-physical production ecosystems.

## EXPERIMENTAL

This work applies a systematic literature-driven approach combined with architectural synthesis. The research methodology consists of the following steps:

1. Analysis of CPPS reference architectures such as RAMI 4.0 [2];
2. Review of international standards and protocols enabling interoperability between engineering and production layers;
3. Classification of CAD/CAM/CAE integration strategies across multiple CPPS levels;

4. Development of a mapping table linking standards to their functional roles;
5. Synthesis of an integration framework enabling closed-loop manufacturing workflows;
6. Extension through industrial case studies, demonstrating practical implementation in general manufacturing domains.

The paper focuses on widely adopted standards (Table 1) including OPC UA (IEC 62541) [3], AutomationML (IEC 62714) [4], Asset Administration Shell [5], STEP-NC [6], and FMI 3.0 [7].

## RESULTS AND DISCUSSION

### A Multi-Level Framework for CAD/CAM/CAE Integration in CPPS

A structured five-layer architecture is proposed, covering transformation from engineering models to closed-loop production control.

- Engineering Backbone Layer  
Integration of CAD/CAE/CAM with PLM and product lifecycle management.
- Semantic Interoperability Layer  
Standardized representations of assets, processes, and engineering data.
- Operational Connectivity Layer  
Real-time integration of machines, sensors, and OT systems with IT networks.
- Analytics and Optimization Layer  
Digital twin synchronization, simulation, AI-driven decision support.
- Closed-Loop Control Layer  
Feedback of operational results into engineering models and manufacturing plans.

Fig. 1 illustrates the five-level integration concept linking CAD/CAM/CAE engineering models with operational connectivity, semantic interoperability, analytics, and closed-loop optimization.

### Key integration methods identified

Digital Thread Implementation

Digital thread strategies ensure traceability

Table 1. Standards and Their Roles Across CPPS Levels.

Standard / Technology	Role in Integration	CPPS Level
ISO 23247 Digital Twin Framework	Digital twin lifecycle and information exchange	Analytics-Control
RAMI 4.0 Reference Architecture	Structural model for Industry 4.0 system layers	All levels
OPC UA (IEC 62541)	Secure machine-to-system interoperability	Operational layer
AutomationML (IEC 62714)	Engineering data exchange between tools	Semantic layer
Asset Administration Shell (AAS)	Digital passport of industrial assets	Semantic-Operational
STEP-NC (ISO 14649)	CAD/CAM/CNC integration and manufacturing continuity	Engineering-Semantic
FMI 3.0 Standard	Co-simulation interoperability for cyber-physical models	Analytics layer
MES/SCADA Systems	Production monitoring, scheduling, execution integration	Operational - Analytics
AI/ML Predictive Models	Process optimization and anomaly detection	Analytics-Control

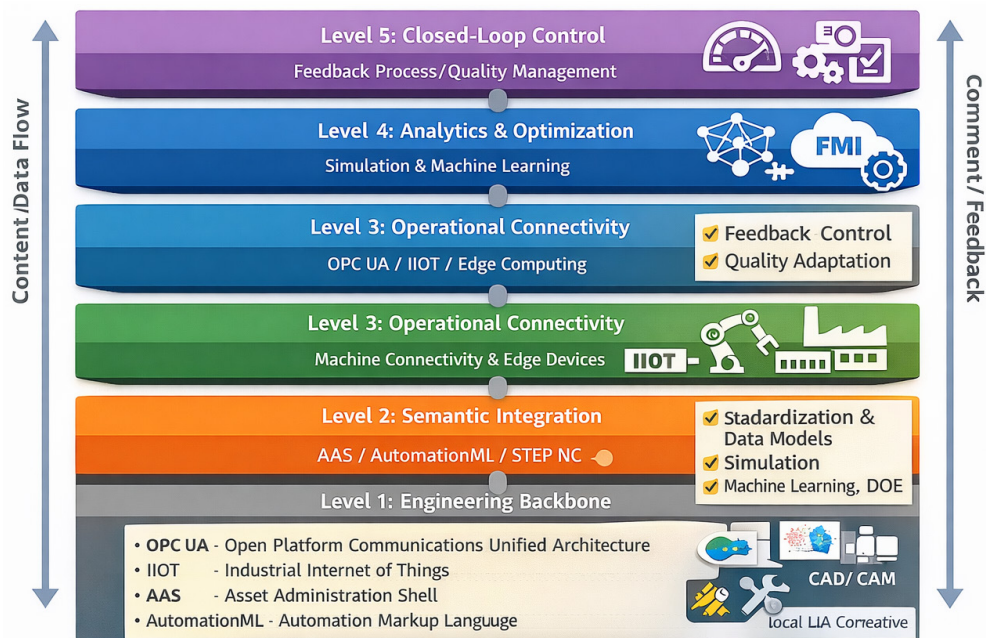


Fig. 1. Proposed CPPS integration architecture.

from design decisions to manufacturing results. STEP-NC provides a formal basis for linking CAD process intent to CAM execution contexts [6].

### Digital Twin Synchronization

ISO 23247 defines the manufacturing digital twin framework, supporting bidirectional

information flow between physical systems and their virtual counterparts [1].

#### Semantic Interoperability

Asset Administration Shell structures industrial asset data into interoperable submodels, enabling consistent communication between engineering and OT domains [5].

#### Closed-Loop Manufacturing Feedback

Closed-loop strategies return quality and performance feedback into process planning, enabling continuous improvement of CAM parameters and machining strategies [8].

### Case studies

#### *Case study 1: Closed-Loop Smart Machining in Automotive Production*

In automotive machining lines, CAM toolpaths are traditionally generated offline with limited integration to machine feedback. However, STEP-NC based digital machining approaches enable the linking of machining operations with real execution context [6].

A closed-loop CPPS machining workflow includes:

- CAD feature recognition;
- CAM generation using STEP-NC process models;
- OPC UA-based machine data acquisition;
- Adaptive parameter correction based on tool wear and surface quality.

A digital thread framework for intelligent machining based on ISO 14649 demonstrates improved traceability and cutting strategies optimization [8].

#### *Case study 2: Robotic Welding Optimization Using CAE and Digital Twins*

Robotic welding cells represent complex CPPS environments where quality depends on thermal behaviour, joint geometry, and real-time control.

CAE simulation models (thermal FEM) are combined with operational sensor data through FMI-based co-simulation [7]. This enables

predictive adjustment of:

- welding speed;
- heat input;
- robot trajectories.

An OPC UA-enabled CPPS architecture improves synchronization between virtual welding twins and real-time execution, enhancing defect prevention and energy efficiency [9].

#### *Case study 3: Smart Assembly Lines and Digital Twin Driven Control*

Assembly lines increasingly require adaptive coordination between humans, robots, and intelligent logistics.

The Asset Administration Shell provides digital identities for assembly assets, while OPC UA enables connectivity of tools, robots, and inspection systems [3, 5].

Digital twins are applied for:

- dynamic scheduling;
- predictive maintenance;
- quality inspection feedback.

Cloud manufacturing integration further expands CPPS capabilities, supporting distributed analytics and AI-driven assembly optimization [10].

The presented framework demonstrates that CAD/CAM/CAE integration into CPPS is enabled primarily through standardized interoperability and semantic consistency.

However, several challenges remain:

- Semantic misalignment between CAD models and operational data;
- Configuration management to keep digital twins synchronized;
- Real-time constraints of OT environments compared to cloud analytics”;
- Cybersecurity and trustworthiness of production lifecycle data;
- Scalability issues when extending integration across supply chains.

OPC UA provides strong foundations for secure industrial interoperability [3], but higher-level semantic standards such as AAS and

AutomationML must converge to achieve full CPPS consistency [4, 5].

Future research directions include:

- unified OPC UA + AAS semantic ecosystems;
- reduced-order CAE models for real-time adaptation;
- standardized KPIs for CPPS efficiency and sustainability assessment.

## CONCLUSIONS

This paper analysed strategies, methods, and approaches for integrating CAD/CAM/CAE technologies into Cyber-Physical Production Systems. A five-level architectural framework was proposed, linking engineering backbone environments with semantic interoperability, operational connectivity, analytics, and closed-loop control.

Key standards such as ISO 23247, OPC UA, AutomationML, STEP-NC, Asset Administration Shell, and FMI provide the foundation for implementing digital twins, digital threads, and adaptive manufacturing workflows.

Extended industrial case studies confirm that CAX integration in CPPS supports improved traceability, predictive optimization, and continuous closed-loop improvement in smart manufacturing environments.

## Acknowledgements

*This article draws upon research conducted within the scope of Procedure BG16RFOP002-1.016 “Development of Innovation Clusters”, under Contract No.*

*BG16RFOP002-1.016-0009-C01 for the project “Development of the Innovation Potential of the Automotive Cluster Bulgaria”. The project is co-financed by the European Regional Development Fund (ERDF) under the Operational Programme “Innovation and Competitiveness” 2014 - 2020.*

## REFERENCES

1. ISO 23247-1:2021, Automation systems and integration - Digital twin framework for manufacturing, ISO, 2021.
2. K. Schweichhart, Reference Architectural Model Industrie 4.0 (RAMI 4.0), European Commission Report, 2016.
3. IEC 62541-1:2025, OPC Unified Architecture - Overview and Concepts, IEC, 2025.
4. AutomationML e.V., AutomationML Specification (IEC 62714), 2022.
5. Plattform Industrie 4.0 / IDTA, Specification of the Asset Administration Shell, 2023.
6. ISO 14649, Industrial automation systems - STEP-NC data model for CNC machining, ISO, 2019.
7. Modelica Association, Functional Mock-up Interface FMI 3.0 Release, 2022.
8. Digital Thread Framework for Intelligent Machining Based on STEP-NC, ScienceDirect, Procedia CIRP, 2024.
9. Engineering Development of Cyber-Physical Production Systems, Springer, Int. J. Adv. Manuf. Technol., 2020.
10. Integration of Cloud Manufacturing and Cyber-Physical Systems Using OPC UA, Robotics and Computer-Integrated Manufacturing, ScienceDirect, 2024.

