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CAD-CAM INTEGRATION IN INDUSTRY 5.0

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Abstract:
This paper analyses modern CAD/CAM systems within the context of Industry 5.0, with a focus on their integration with advanced digital technologies. Industry 5.0 emphasises human–machine collaboration, personalised production, and sustainability, where CAD/CAM tools such as SolidWorks play a key role in optimising design and manufacturing processes. The application of artificial intelligence enables design automation, structural optimisation, and predictive analysis, while augmented and virtual reality enhance visualisation, simulation, and operator training. The integration of these technologies positions CAD/CAM systems as central platforms for industrial digital transformation. In conclusion, the synergy between CAD/CAM systems and Industry 5.0 technologies represents a key factor in improving the efficiency, flexibility, and competitiveness of modern manufacturing systems.

Keywords: *CAD-CAM integration, Industry 5.0, artificial intelligence (AI), augmented reality (AR), virtual reality (VR)*

Introduction

Significant efforts have been made to automate numerical control (NC) code generation directly from CAD models in order to improve the efficiency and consistency of the design-to-manufacturing transition. Conventional approaches are largely based on geometry-driven feature recognition and rule-based process planning. In such frameworks, manufacturing features (e.g., holes, pockets, and slots) are identified from 3D CAD models, associated with appropriate machining operations, and used as a basis for generating toolpaths and tool selection data [1].

To further enhance this process, knowledge-based systems incorporate established machining rules and best practices, enabling partial automation in the selection of process parameters such as spindle speed, feed rate, and cutting depth. The resulting process plans are

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subsequently converted by post-processors into machine-specific G-code (or equivalent formats), ensuring interoperability across different CNC platforms.

Despite these advancements, traditional CAD/CAM integration remains largely deterministic and workflow-driven, often requiring expert intervention for fine-tuning and adaptation. Such systems can struggle to efficiently handle complex geometries, high variability in product design, and dynamic production environments. As manufacturing systems evolve towards greater flexibility and responsiveness, these limitations become increasingly pronounced.

In response, recent research has explored the integration of artificial intelligence (AI) techniques into CAD/CAM workflows. Methods based on deep learning and reinforcement learning (RL) have demonstrated potential in automating feature recognition, improving toolpath strategies, and enabling adaptive decision-making based on real-time data. Unlike conventional approaches, AI-driven systems can learn from historical and operational data, allowing continuous improvement and greater robustness in uncertain or changing conditions [2].

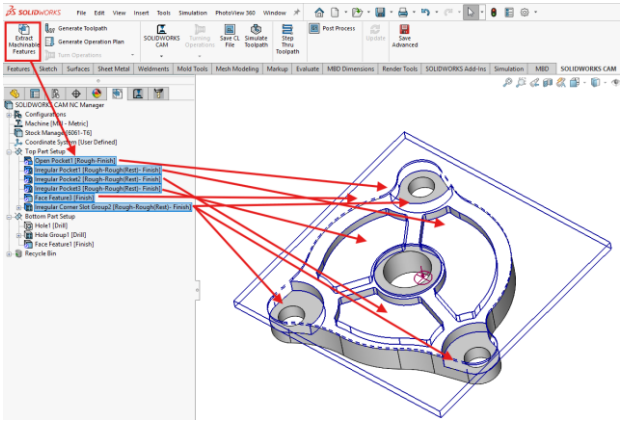
The incorporation of AI at key stages of the CAD-to-CAM pipeline opens the possibility for intelligent, self-optimizing manufacturing systems that reduce dependency on human expertise and shorten the overall product development cycle. This shift aligns closely with the principles of Industry 5.0, which emphasise human-centric, adaptive, and highly personalised production.

Nevertheless, despite the increasing interest in AI-enhanced manufacturing and the broader evolution of digital production technologies, a clear and systematic understanding of how to effectively bridge the CAD/CAM gap is still lacking. In particular, there is a need for more comprehensive research that critically examines both the technical challenges and the transformative opportunities associated with CAD/CAM integration within the Industry 5.0 paradigm.

1. Artificial intelligence in CAM programming

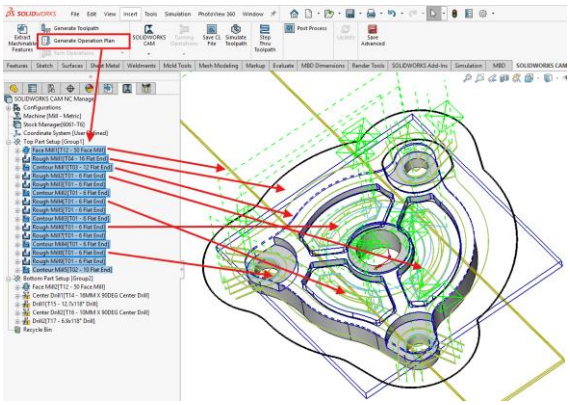
In the domain of modelling machining operations (both conventional and non-conventional) and operations for manufacturing parts using additive technologies, artificial intelligence (AI) methods have significant applications in the following areas [1]:

1. One of the most challenging aspects in applying AI methods, when discussing the modelling of machining operations using computers, is the automation of selecting the method and sequence of clamping and the orientation of the workpiece. Implicitly, this challenge also encompasses another problem that AI methods must solve: decision-making regarding the type and sequence of operations required to manufacture a part. At present, most commercial CAD/CAM applications, i.e. AI methods embedded in software, are not capable of successfully performing this task without the assistance of an engineer.
2. Once machining operations are determined, regardless of whether this is done by AI or an engineer, AI methods can then be used for recognising and categorising geometric-technological features on the workpiece. This categorisation serves as a basis for determining machining steps and tools (Picture 1).



Picture 1. *Automatic recognition of machining geometry in the context of modelling machining operations in the CAM module of SolidWorks software*

3. AI methods can be employed to select the required operations and machining steps based on the classification of geometric, functional, and technological characteristics of the workpiece. Such AI applications are already feasible (Picture 2).
4. In the tool selection phase, AI methods are already widely used for "guided search" through large databases of tools and machining parameters in order to identify optimal tools and cutting conditions. In this context, so-called expert systems are most commonly utilised.



Picture 2. *The SolidWorks CAM module independently recognizes and models the processing operations that can be applied and, in doing so, independently selects tools and processing modes*

5. AI methods can be applied during the modelling of machining steps:

   a) AI reasoning methods based on analogies can be used for automated categorisation of the target surface, and on the basis of this categorisation, AI can decide on the type of machining step that can be applied.

   b) Determination of tools and technological parameters (intelligent database searching based on expert rules embedded within CAD/CAM applications).

   c) Tool path generation:
   - determination of the optimal combination of parameters defining the characteristics of the relative motion between the tool and the workpiece in accordance with manufacturing constraints; and
   - selection of auxiliary entry and exit tool motions within a machining step.

6. AI methods can also be applied during the execution of CNC programmes:

   a) AI methods based on statistical processing of large datasets are typically an optimal choice for processing data obtained from numerous sensors in the machining zone, as well as from sensors in the preparation phase.

   b) AI provides an ideal set of tools for automating the sequencing of operations and machining steps in order to achieve maximum equipment utilisation. In this domain, AI methods can determine far

more quickly than humans which sequence of operations and machining steps yields maximum utilisation of tools, machines, or groups of machines.

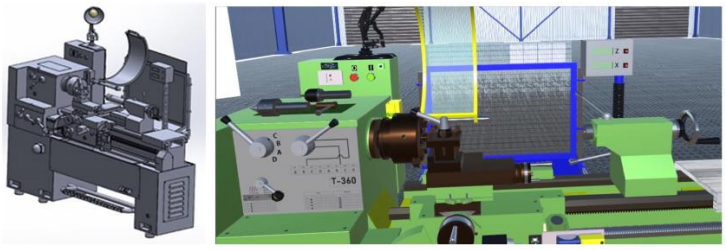
c) Post-processing of modelled operations into error-free CNC programmes represents another challenge that AI methods are expected to address.

Finally, in this brief overview of AI applications in the modelling of CNC machining operations, it should be emphasised that the most commonly used AI methods include: expert systems, machine learning, neural networks, semantic networks and analogy-based reasoning.

2. Virtual reality and Augmented reality in CAM

Virtual Reality (VR) technology enables users to become fully immersed in a computer-generated digital environment. Through the integration of hardware devices and software applications, VR creates a real-time virtual space that stimulates multiple human senses—primarily visual, auditory, and haptic—producing the illusion of physical presence within that environment. By effectively engaging these sensory channels, VR "captures" the user's perception and simulates reality. Interaction within this environment is achieved through bidirectional communication between the user and the system, using controllers or gesture-based inputs.

The effectiveness of VR relies on three key components: **immersion**, referring to the depth of sensory engagement; **interaction**, which allows users to manipulate and respond to the virtual environment; and **imagination**, which supports the user's cognitive acceptance and sense of presence within the virtual space. An example of VR environment for CNC lathe operator training is presented on Picture 4.



Picture 4. *VR environment for CNC lathe operator training [6]*

In contrast, Augmented Reality (AR) enhances the real-world environment by overlaying digital content onto the user's visual and, in

some cases, haptic field. This integration creates the perception that virtual elements coexist with physical reality, enriching the user's experience with additional visual and auditory information. In industrial applications, AR can provide real-time guidance, such as step-by-step instructions for operating CNC machines via AR visors (Picture 5-a), or safety warnings based on the operator's position relative to the machine (Picture 5-b).



(a) *(b)*

Picture 5. *Display of a sequence of instructions for working with a CNC machine that the user receives through the AR visor (a); warning that the AR device provides to the operator regarding his position in relation to the CNC machine (b) [1]*

Additionally, AR enables the insertion of virtual objects into the user's environment (Picture 6), often triggered by markers such as QR codes.



Picture 6. *Insertion of an object into the visual-haptic field of the user based on a marker in the form of a QR code*

3. CAD-CAM integration in Industry 5.0

CAM has evolved from simply generating toolpaths to serving as a digital, knowledge-driven platform supporting planning, strategy, simulation, and decision-making. Modern manufacturing demands short lead times, traceability, and process reliability pushing leaders to use CAM as a strategic tool for competitiveness.

AI-driven toolpath generation replaces guesswork with data-driven optimization. By analysing tool behaviour, materials, forces, and vibrations, AI creates stable cutting conditions while programmers guide strategy. This human-machine collaboration improves accuracy, surface quality, and efficiency especially valuable where skilled labour is scarce. The digital thread now connects design, programming, and production, ensuring automatic updates when models change. It eliminates data loss, reduces errors, and strengthens traceability essential for aerospace and medical sectors. Knowledge-based CAM further closes the skills gap by capturing best practices, automatically identifying features, applying proven strategies, and making new engineers productive faster.

Adaptive machining monitors temperature, vibration, and force to adjust parameters in real time, reducing tool wear and enabling reliable unmanned operation. Integrated smart-factory environments link CAM with MES, scheduling, and monitoring tools providing data feedback, predictive maintenance, and improved delivery performance. Human expertise remains central: professionals focus on analysis, process optimisation, and innovation rather than repetitive programming. Simulation and virtual validation ensure safe, efficient execution before machining starts. Smarter CAM and automation reduce waste, energy use, and tool wear while tracking lifecycle data for environmental compliance. In Industry 5.0, manufacturers that treat CAM and automation as strategic assets amplifying human capability rather than replacing it will lead the next era of intelligent, sustainable production.

4. Conclusion

Considering the prevalence of computers and other electronic devices as well as computer applications and their role in managing and controlling the implementation of technological processes, it is more than clear that modelling technological operations with the help of CAD/CAM applications, VR and AR occupies a central place in the set of activities that remain for humans in future production environments.

The integration of CAD/CAM systems in the context of Industry 5.0 marks a transition toward more intelligent, adaptive, and human-centric manufacturing. While traditional, rule-based approaches have improved efficiency and reduced programming effort, they remain limited in flexibility and responsiveness to complex production demands. The incorporation of artificial intelligence, particularly machine learning and

reinforcement learning, enables more advanced capabilities such as automated feature recognition, toolpath optimization, and continuous system improvement.

These developments support key Industry 5.0 objectives, including mass customization, enhanced quality, and closer human–machine collaboration. However, challenges persist, particularly in data integration, system interoperability, and the effective use of expert knowledge within automated frameworks. Future research should focus on hybrid approaches that combine human expertise with AI-driven adaptability, as well as on developing interoperable and scalable architectures. Bridging the CAD–CAM gap will be essential for achieving resilient, efficient, and sustainable manufacturing systems.

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