CAD to CAM Competency Progression Framework for Manufacturing Education: Constructive Alignment of Digital Design, Machining and Assessment

Ruzy Haryati Binti Hambali [1,*], Nuralina Farhani Binti Kamaruzaman [1]

[1] Faculty of Industrial & Manufacturing Technology & Engineering, Universiti Teknikal Malaysia Melaka, 76100 Durian Tunggal, Melaka, Malaysia

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ABSTRACT

CAD and CAM are commonly introduced in manufacturing programmes as related subjects, but students may still experience them as separate software activities. This paper proposes a CAD to CAM Competency Progression Framework that makes the complete learning pathway explicit, from conceptual understanding and parametric design to engineering documentation, manufacturing planning, CAM execution, and digital validation. A structured analysis of course documents was conducted using the official teaching plan, course learning outcomes, laboratory activities, assignment guidelines, assessment rubric and lecture materials from an eight-week diploma CAD/CAM course delivered using Autodesk Fusion. Constructive alignment, competency-based assessment and manufacturing practice informed the analysis. Course documents were coded according to learning action, technical artefact, manufacturing decision, assessment evidence and intended learning outcome, and the resulting codes were consolidated into six proposed competency levels. The mapping suggests an intended sequence in which constrained 2D sketches and feature-based 3D models support engineering drawings. These digital representations subsequently support machining strategy, toolpath generation, milling and turning operations, simulation, verification and NC program generation. A competency assessment alignment matrix is proposed to enable instructors to identify where each competency is introduced, practised and assessed. Unlike approaches that focus primarily on CAD proficiency, digital modules, isolated CNC simulation or broad Industry 4.0 competencies, the proposed framework explicitly links design, documentation, process planning, CAM implementation and validation as one assessable manufacturing workflow. The framework offers a practical curriculum-design and continuous-quality-improvement tool for engineering and TVET programmes. A supplementary summary of 37 complete CAD assessment records showed mean percentages of 91.4% for 2D sketching, 87.6% for 3D modelling and 79.0% for engineering drawing. These observations are preliminary and do not validate the framework or establish student learning gains.

Keywords: CAD CAM education; competency progression; constructive alignment; manufacturing education; TVET

INTRODUCTION

Digital manufacturing requires engineers and technologists to work across a connected product-realisation chain rather than within isolated software functions. CAD creates and communicates product geometry, while CAM transforms digital models into process plans, toolpaths, simulations and numerical-control (NC) instructions. Consequently, manufacturing education must help learners understand not only how to model a component, but also how design information is progressively converted into manufacturable and verifiable production information.

Recent engineering-education research supports the continued importance of CAD competency while also highlighting the need for more systematic assessment. Venkatason and Sivaguru [1] examined CAD course outcomes through a structured attainment approach, while Venkatason et al. [2] reaffirmed the continuing relevance of CAD education in the digital era. In TVET, Anuar et al. [3] demonstrated that a structured

CADCAM digital learning module can support learning engagement and competence. These contributions are important, but they address CAD attainment, the relevance of CAD instruction, or module effectiveness rather than explicitly modelling the full competency transition from design creation to manufacturing validation.

This distinction matters because Industry 4.0-oriented engineering education increasingly emphasises integrated and transferable competencies. Industry 4.0 curriculum research has argued for competency-based curricular innovation [4], while systematic literature has identified continuing gaps between the competencies developed in engineering education and those required in digitally transformed industry [5]. Learning-factory research similarly stresses authentic, action-oriented environments that connect technical learning with realistic production problems [6]. A CAD/CAM course can serve as a compact digital manufacturing environment when its learning sequence intentionally connects geometry, documentation, process planning, toolpaths, simulation and NC output.

Constructive alignment provides the educational logic for such integration. It requires intended learning outcomes, teaching and learning activities, and assessment tasks to activate compatible forms of learning [7]. Malaysian quality guidance likewise defines constructive alignment as designing activities and assessment around the action verbs of learning outcomes and treats continuous assessment as evidence that can support curriculum improvement [8]. Engineering studies continue to report the value of explicit alignment between laboratory activities, outcomes and assessment [9,10].

The research gap addressed in this paper is therefore not the absence of CAD or CAM instruction, but the absence of an explicit, assessable progression model showing how competencies should develop across the complete CAD-to-CAM workflow within a compact manufacturing course. The present study addresses this gap through document-based curriculum analysis. Its objectives are to: (1) identify the technical competency sequence embedded in an existing CAD/CAM course; (2) evaluate constructive alignment among learning outcomes, laboratory activities and assessment tasks; (3) develop a six-level CAD-to-CAM Competency Progression Framework; and (4) establish an assessment mapping that can support subsequent empirical evaluation and continuous quality improvement.

LITERATURE REVIEW

CAD CAM and Digital Manufacturing Education

CAD mastery is more than the ability to reproduce geometry. Research comparing novice and more experienced CAD users indicates that expertise involves differences in modelling processes and problem representation, supporting the need to assess how students construct models rather than only the visual correctness of final outputs [11]. This is consistent with rubric-based assessment that makes constraints, modelling procedure and engineering documentation visible.

CAM and CNC learning introduce additional cognitive and procedural demands because learners must interpret geometry as manufacturing operations. Studies of CNC education have examined simulation-supported practice and its relationship with learning performance [12].

Simulation is educationally valuable because it permits learners to inspect tool motion, operation sequence and potential machining problems before physical execution. In an integrated CAD/CAM curriculum, however, simulation should be positioned as a validation stage following design and process planning rather than as an isolated software exercise.

Industry 4.0 further strengthens the case for integration. Reviews of engineering competencies identify digital, analytical and technical capabilities alongside the need for practical and experiential learning [5]. Industrial engineering curricula have also been shown to rely heavily on procedural knowledge when developing Industry 4.0 competencies [13]. These findings suggest that technical courses should deliberately structure progression from knowledge to procedural application and validation.

Constructive Alignment, Authentic Assessment and Competency Evidence

Constructive alignment is particularly relevant to technical courses because learning outcomes commonly use performance verbs such as create, apply, plan, generate, simulate and validate. Assessment should therefore require observable performance corresponding to those verbs. Malaysian work on technology-programme assessment has used document analysis to develop alignment guidance linking outcomes, knowledge profiles and assessment tasks [10]. Recent engineering research similarly shows that competency-based instruments can provide more diagnostic evidence than undifferentiated traditional assessment [14].

Authentic assessment strengthens this alignment when students produce artefacts resembling professional outputs. In CAD/CAM education these artefacts include constrained models, engineering drawings, setup decisions, machining strategies, toolpaths, simulations, NC programs and setup sheets.

Alternative engineering assessment research has shown the value of experiential and performance-oriented tasks for complex problem solving [15]. The present framework extends this logic by arranging authentic artefacts as evidence of successive stages in one digital manufacturing workflow.

Positioning and Novelty of the Present Framework

Prior emphasis	Representative evidence	Primary contribution	Gap relative to present study
CAD attainment	Venkatason & Sivaguru [1]	Structured measurement of CAD course outcomes	Focuses primarily on CAD performance rather than end-to-end CAD-to-CAM progression
CAD relevance	Venkatason et al. [2]	Review of the continuing role of CAD education	Does not provide a manufacturing competency progression and assessment map
CADCAM digital module	Anuar et al. [3]	ADDIE-based module; engagement and learning interest	Evaluates module experience rather than curriculum-level design-to-NC competency alignment
Industry 4.0 competency frameworks	Treviño-Elizondo and García-Reyes [4]; Rosas Quintero and Namuche Maldonado [5]	Broad competencies and curriculum implications	High-level competency framing; not specific to the CAD-to-CAM manufacturing chain
Learning factory / authentic production learning	Mohd Hanafiah et al. [6]	Action-oriented learning linked to industrial practice	Broader production environment; not a staged CAD/CAM assessment architecture
Constructive-alignment guidance	Love et al. [9]; Mokhtar et al. [10]	Alignment of outcomes, activities and assessment	General engineering/technology assessment rather than a domain-specific CAD-to-CAM progression
Present study	Proposed framework	Six assessable levels connecting design, documentation, planning, CAM execution and validation	Makes the complete digital manufacturing progression explicit and links each stage to assessment evidence

Table 1. Positioning of the proposed framework against related educational approaches.

METHODOLOGY

Research Design and Unit of Analysis

The main study used qualitative analysis of the documented course structure, including learning outcomes, teaching activities and assessment requirements. To provide a limited check against recorded assessment performance, the authors also prepared an aggregate descriptive summary of three CAD components from the same course (37 complete records). No names or student identifiers are reported. The assessment summary is supplementary: it was not used to derive the framework, test its effectiveness or infer progression to CAM competence.

Document Corpus

The document corpus comprised: (i) the official DMIM2122 CAD CAM teaching plan, including learning outcomes, weekly syllabus and assessment weighting; (ii) the Assignment 1 guideline and rubric covering 2D sketching, 3D modelling and engineering drawing; (iii) the CAM Turning laboratory activity; (iv) the individual Assignment 2 turning-operation guideline; and (v) lecture material describing CAD, CAM and their integration in manufacturing. Together these documents provide evidence of intended learning, instructional sequence, required technical actions and assessable outputs.

Coding and Framework Development Procedure

To improve transparency and reproducibility, the framework was developed through five explicit analytical steps. First, action verbs and technical tasks were extracted from each document. Second, each task was coded according to the principal learning action (explain, create, document, plan, execute or validate), technical artefact/output, and associated learning outcome. Third, tasks that represented the same underlying competency were clustered. Fourth, clusters were ordered according to technical dependency: a later stage was positioned after an earlier stage when successful completion required outputs or understanding produced by the earlier stage. Fifth, the resulting competency levels were checked against assessment tasks to determine whether each level had observable evidence.

Coding dimension	Question applied to each document item	Example from course documents
Learning action	What must the learner do?	Create, apply, plan, simulate, generate
Technical object	What engineering object/process is acted upon?	2D sketch, 3D model, drawing, turning operation
Output/artefact	What observable evidence is produced?	Constrained model, drawing, toolpath, simulation, NC code
Manufacturing decision	Does the task require a process decision?	Machining strategy, operation sequence, toolpath method
Learning-outcome link	Which intended outcome does the task evidence?	LO1–LO4
Dependency	What prior competency is needed?	Valid geometry before CAM; process plan before validation

Table 2. Analytical coding scheme used to derive the competency progression.

COURSE ARCHITECTURE AND DOCUMENT ANALYSIS

Learning Outcomes and Assessment Structure

The course specifies four learning outcomes that increase in applied complexity. LO1 requires students to explain CAD/CAM systems and applications in manufacturing. LO2 requires application of CAD CAM methodology to 2D sketches, 3D models, surface modelling and CAM operations. LO3 requires planning of

machining strategies and toolpath methods. LO4 requires investigation and simulation of machining operations before machining. The formal assessment structure comprises Assignment 1 on 3D part design and 2D drawing (20%), Assignment 2 on turning operations (20%), a milling project (30%) and a test (30%).

Outcome	Dominant competency demand	Primary assessment evidence
LO1	Conceptual understanding of CAD/CAM and manufacturing application	Test
LO2	Digital design and CAD/CAM application	Assignment 1; practical CAD/CAM activities
LO3	Machining strategy and toolpath planning	Assignment 2; milling project
LO4	Simulation, verification and pre-machining investigation	Assignment 2; milling project

Table 3. Learning-outcome and assessment alignment.

Instructional Sequence

The eight-week teaching plan follows a dependency-based sequence. Week 1 introduces CAD and CAM, Autodesk Fusion software, sketching fundamentals and dimensional constraints. Weeks 2 and 3 cover feature-based 3D modelling, transformation features and engineering drawing. Weeks 4 and 5 move to CAM milling, machining strategies, toolpath simulation, verification and NC code generation. Weeks 6 and 7 address CAM turning, process planning, simulation, validation and NC programming. The sequence therefore moves from representation to manufacture rather than presenting CAD and CAM as unrelated software topics.

Authentic Assessment Evidence

Assignment 1 requires students to create a reasonably complex 2D sketch with holes, radii and chamfers, use geometrical and dimensional constraints and construction or centre lines, produce a separate 3D mechanical part, and create detailed top, left, front, section and isometric views. The rubric separately recognises 2D sketching, 3D modelling and drawing, making the CAD foundation visible as distinct assessable competencies.

The CAM Turning laboratory then introduces facing, profile roughing and finishing, grooving, threading and parting in the Manufacture workspace. Required outputs include the Autodesk Fusion file, NC code and setup sheet. Assignment 2 extends these activities into an individual task requiring a turning part, multiple turning operations, machining simulation, NC program generation and part drawing. These outputs approximate professional digital-manufacturing artefacts and therefore provide authentic evidence beyond a conventional written test.

Supplementary Descriptive Assessment Evidence

To complement the curriculum-document mapping, a descriptive summary of 37 complete assessment records from the same course was considered for three CAD related components. Scores were reported only in aggregate; no names, student identifiers or individual marks are presented. The 2D sketching component was marked out of 40, 3D modelling out of 35 and engineering drawing out of 25. Component means were divided by their respective maximum scores to permit descriptive percentage comparisons. Because some marks may represent shared or group work, the records cannot automatically be treated as independent individual competency measures. No inferential tests or causal claims were made.

CAD assessment component	Records (n)	Mean raw score	Mean of maximum (%)
2D sketching	37	36.54 / 40	91.4
3D modelling	37	30.65 / 35	87.6

Engineering drawing	37	19.76 / 25	79

Table 4. Supplementary descriptive assessment results from available complete CAD records (n = 37).

Table 4 presents descriptive results from 37 complete CAD assessment records. Values are descriptive and are not measures of validated framework-level attainment. The pattern shows a lower average percentage in engineering drawing (Level 3) than in the two digital-design components (Level 2). This illustrates how disaggregated course assessment evidence may identify a component worth examining in future curriculum review. It does not demonstrate that the proposed framework improved learning, establish why the difference occurred, or validate CAM-related Levels 4–6.

Proposed Cad-To-Cam Competency Progression Framework

Level	Competency domain	Core capability	Observable evidence
1	Conceptual CAD/CAM knowledge	Explain CAD/CAM systems, integration and manufacturing applications	Conceptual responses / test evidence
2	Digital design competency	Create constrained 2D sketches and feature-based 3D models	Sketches, constraints, feature history and 3D part
3	Engineering documentation	Communicate design intent using standard views, sections and dimensions	Engineering drawing and projection views
4	Manufacturing planning	Select machining strategy, operation sequence and toolpath method	Process/operation plan and setup decisions
5	CAM execution	Generate milling and turning operations and toolpaths	CAM operations, toolpaths and machining parameters
6	Digital manufacturing validation	Simulate and verify operations and generate machine-oriented output	Simulation evidence, NC program and setup sheet

Table 5. Six-level CAD-to-CAM Competency Progression Framework.

Figure 1. Dependency logic of the proposed competency progression.

L1	L2	L3	L4	L5	L6
Conceptual Knowledge	**Digital Design**	**Engineering Documentation**	**Manufacturing Planning**	**CAM Execution**	**Validation & NC Output**

Constructive Alignment Matrix

Framework level	Introduced / practised through	Assessed through	Related LO
1 Conceptual knowledge	Introductory lectures; CAD/CAM integration	Test	LO1
2 Digital design	Sketching and 3D modelling laboratories	Assignment 1	LO2
3 Engineering documentation	Drawing-generation laboratory	Assignment 1	LO2
4 Manufacturing planning	Milling and turning strategy activities	Assignment 2; Project	LO3
5 CAM execution	Milling and turning toolpath activities	Assignment 2; Project	LO2–LO3
6 Validation & NC output	Simulation, verification and NC generation	Assignment 2; Project	LO4

Table 6. Constructive alignment of framework levels, learning activities and assessment.

DISCUSSION

The principal contribution of the framework is the explicit representation of CAD CAM learning as a competency chain rather than a set of software topics. Existing CAD education research provides useful evidence on CAD attainment and relevance [1,2], while CAD CAM module research demonstrates the value of structured digital learning resources [3]. The proposed framework adds a different layer: it identifies the technical dependency between design, documentation, manufacturing planning, CAM implementation and validation and makes each dependency assessable.

This end-to-end structure is educationally important because later CAM performance depends on earlier design quality. A learner cannot meaningfully plan machining without interpretable geometry, and generated toolpaths cannot be considered complete manufacturing evidence until they are simulated or verified. The framework therefore places simulation at Level 6 rather than treating it as a stand-alone learning technology. This position is consistent with NC education research showing that simulation changes the nature of machining practice and learning demands [12].

The framework also operationalises constructive alignment in a domain-specific manner. The course learning outcomes move from explaining to applying, planning and simulating, while the assessment artefacts move from conceptual responses to constrained geometry, drawings, machining strategies, toolpaths and NC output. This correspondence is consistent with Malaysian quality guidance on activating learning-outcome verbs in assessment [8] and with engineering studies calling for clearer alignment among outcomes, laboratory activities and assessment [9,10].

Authenticity is another strength. The assessment tasks require technical artefacts that resemble outputs produced in a digital manufacturing workflow. This is aligned with learning-factory literature, where realistic production contexts and action-oriented learning are used to develop industrial competencies [6], and with alternative engineering assessment approaches that emphasise experiential evidence of complex performance [15]. Although the present course is software-centred rather than a full physical learning factory, the digital workflow can function as a preparatory layer before machine-level implementation.

The six levels are intentionally framed as competencies rather than software commands. This improves transferability. Autodesk Fusion is the implementation platform in the analysed course, but the framework can be implemented with other integrated CAD CAM systems because the underlying sequence geometry, documentation, planning, toolpath execution, simulation and NC generation is platform independent. This is important in Industry 4.0 education, where an excessive focus on specific technologies can produce narrow skills that age quickly [4,16].For continuous quality improvement, the framework provides a diagnostic structure that a final course grade cannot provide. If assessment evidence is mapped to individual levels, instructors can determine whether difficulty emerges in parametric design, engineering documentation, process planning, CAM execution or validation. Competency-based assessment research supports this more granular approach because different assessment instruments can reveal different dimensions of engineering performance [14].

Practical Implications for Engineering and TVET Education

The framework can be used in three ways. First, it can guide curriculum sequencing: advanced CAM tasks should not be introduced before learners demonstrate sufficient design and documentation competence. Second, it can guide rubric design by separating geometry definition, modelling procedure, technical drawing, machining strategy, toolpath execution and validation. Third, it can guide CQI by locating weak attainment at a specific competency level rather than attributing poor performance to the CAD/CAM course as a whole.

The framework is particularly suitable for compact diploma and TVET courses because it prioritises technical dependency. Malaysia's TVET machining programmes similarly combine engineering drawing, CAD, CAM and CNC machining, illustrating the broader relevance of integrating these capabilities rather than teaching them as disconnected topics [17].

LIMITATIONS

The framework is derived from the documented architecture of one eight-week diploma-level course at one Malaysian technical university. It should therefore be interpreted as a context-grounded curriculum framework rather than evidence that the approach improves student achievement. Document analysis can establish intended alignment but cannot determine whether all students experienced the curriculum identically or attained the competencies at the expected level.

The present paper also does not compare software platforms or evaluate transfer from digital simulation to physical machining. A limited supplementary descriptive analysis of existing CAD assessment components illustrates a potential application for curriculum diagnosis but does not establish framework effectiveness.

FUTURE WORK

Future work will empirically evaluate the proposed framework using course assessment evidence. Anonymised marks from Assignment 1, Assignment 2, the milling project and the course test can be mapped to the six competency levels to quantify attainment and progression. Rubric-level analysis can examine 2D sketching, 3D modelling and engineering drawing separately, while CAM evidence can be decomposed into manufacturing planning, toolpath execution, simulation and NC program generation. Relationships between adjacent competency levels can then be tested to determine whether earlier CAD competencies predict later CAM performance. A subsequent multi-cohort or multi-institution study could further test the framework's transferability and its usefulness for continuous quality improvement.

CONCLUSION

This paper developed a six-level CAD-to-CAM Competency Progression Framework through structured analysis of an integrated manufacturing course. The framework connects conceptual CAD CAM knowledge, digital design, engineering documentation, manufacturing planning, CAM execution and digital validation as one dependency-based and assessable workflow. Its novelty lies not in introducing a new CAD or CAM technology, but in making the complete design-to-NC learning progression explicit and constructively aligning each stage with authentic assessment evidence.

The framework offers engineering and TVET educators a practical tool for curriculum sequencing, rubric development and future competency analytics. The supplementary CAD mark summary suggests that engineering drawing merits closer scrutiny, but does not demonstrate improved learning or validate the proposed progression. Further evaluation across CAM tasks and cohorts is required.

DECLARATIONS

Data Availability

The study analysed institutional course documents and assessment instruments, together with a descriptive summary of 37 complete CAD assessment records. Only aggregated component-level statistics are reported; individual marks and student identifiers are not included in this manuscript. The underlying course documents and assessment records are institutional materials and are not publicly available.

Conflict of Interest

The authors declare no conflict of interest.

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