2026 ASEE ANNUAL CONFERENCE June 21–24, 2026 | Charlotte Convention Center, NC
Host Sponsor UNC Charlotte
Paper ID #54077

Collaborative Additive Manufacturing Project for Engineering Students: Design and Fabrication of a Functional Toy Car

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1. Introduction

Additive Manufacturing (AM) has evolved from a rapid prototyping tool into a production-ready manufacturing technology with applications across aerospace, automotive, biomedical, and consumer industries [1–3]. As AM adoption increases, engineering graduates are expected to demonstrate proficiency not only in AM processes, but also in design-for-additive-manufacturing (DfAM), tolerance control, material–process compatibility, and system-level integration [4–6]. Traditional lecture-based instruction often falls short in addressing these competencies, particularly when students must reconcile geometric freedom with process constraints such as anisotropy, print resolution, and post-processing requirements [7].

Project-based learning (PBL) has been widely adopted in engineering education to address such challenges by embedding learning in authentic, open-ended design tasks [8,9]. Prior work has shown that PBL enhances student engagement, conceptual understanding, and retention of manufacturing knowledge when compared with traditional instructional methods [10,11]. In the context of AM education, PBL has been used to introduce students to part optimization, lightweighting, and process selection [12–14]. However, many AM-focused educational projects emphasize isolated component design or individual assignments, providing limited exposure to system-level integration and inter-team coordination—skills that are central to industrial manufacturing practice [15].

This study presents a collaborative, system-level PBL experience implemented in an undergraduate Additive Manufacturing course. Students worked in coordinated teams to design, fabricate, and assemble a fully functional miniature SUV using AM technologies. Each team was responsible for a specific subsystem—chassis and axles, wheels, body frame, or connectors and accessories—while coordinating interfaces, tolerances, and assembly constraints across teams. This structure intentionally mirrors real-world product development environments, where multiple engineering teams contribute to an integrated system [16].

The novel contribution of this work lies in embedding structured cross-team interface coordination, tolerance stack-up management, and system-level validation within a constrained four-week instructional module, an aspect that remains underreported in prior AM PBL literature. While earlier studies demonstrate the effectiveness of hands-on AM projects, few explicitly integrate subsystem interdependence with formal multi-level assessment tied to accreditation outcomes.

Assessment was conducted at three levels: individual contribution, subgroup performance, and full-system functionality. This multi-tiered approach was designed to reinforce both technical competence and collaborative accountability, consistent with best practices in engineering education assessment [17–19]. The objectives of this study are to describe the instructional design and implementation of the project, evaluate student performance and learning outcomes, and assess the project's effectiveness as a scalable model for AM education.

2. Literature Review / Background

2.1 Project-Based Learning in Engineering Education

Project-based learning has a long history in engineering education, particularly in design, manufacturing, and capstone courses [8,10]. PBL emphasizes student-centered learning, authentic problem contexts, and iterative design, allowing students to develop both technical knowledge and professional skills such as teamwork, communication, and leadership [11,18]. Studies consistently report that PBL improves student motivation and supports deeper conceptual understanding when projects are sufficiently structured and aligned with course objectives [9,20].

In manufacturing education, PBL has been shown to be particularly effective due to the inherently hands-on nature of manufacturing processes [12]. Students gain a more concrete understanding of tolerances, material behavior, and process limitations when required to fabricate and test physical artifacts [13,21].

2.2 Additive Manufacturing Education and DfAM

The rapid industrial adoption of AM has driven increased attention to DfAM within engineering curricula [4,5]. DfAM principles (such as part consolidation, orientation optimization, support minimization, and tolerance-aware design) require students to think beyond conventional manufacturing paradigms [6,14]. Educational studies demonstrate that hands-on AM projects significantly improve students' understanding of these principles compared to purely theoretical instruction [7,22].

Despite this progress, many AM assignments remain limited to single components or independent team projects. As a result, students often lack experience with interface compatibility, assembly planning, and system-level constraints, which are critical in real-world AM-enabled products [15,23].

2.3 Collaborative and System-Level Design in Manufacturing Courses

Collaborative system-level projects have been shown to enhance students' understanding of engineering trade-offs, interface management, and tolerance stack-up [16,17]. Such projects more closely resemble professional engineering workflows, particularly in manufacturing and product development contexts. However, their implementation in process-focused courses (such as Additive Manufacturing) remains relatively underreported in the literature [19]. The present study addresses this gap by introducing a structured, collaborative AM project that requires coordination across multiple subsystems and teams, while remaining feasible within a four-week instructional window.

3. Methodology / Approach

3.1 Course Context and Participants

The project was implemented in an undergraduate Additive Manufacturing course offered within a mechanical engineering curriculum. The course includes instruction on AM processes, materials, design considerations, and post-processing techniques. Students enrolled in the course were primarily junior- and senior-level undergraduates with prior experience in CAD modeling and introductory manufacturing concepts. Students were divided into four teams, each consisting of three to five members. Each team selected a team lead responsible for communication, coordination, and submission of required information to the instructor.

3.2 Project Structure and Design Constraints

The core assignment required students to collaboratively design, fabricate, and assemble a fully functional miniature SUV using additive manufacturing. The overall vehicle dimensions were constrained to approximately 8.5–10 inches in length, 4.7–5.9 inches in width, and 4–5.1 inches in height, with ground clearance between 0.5 and 0.8 inches to reflect SUV characteristics.
Each team was assigned responsibility for a specific subsystem:

- Chassis & Axles: structural frame, axle mounts, wheel alignment, and body mounting interfaces
- Wheels: tires, wheel rim, rotational fit, and axle compatibility
- Body Frame: SUV-style body with appropriate clearances and mounting features
- Connectors and Accessories: connectors, bumpers, spoilers, and auxiliary components

Explicit dimensional guidelines and assembly clearances were provided for all interfaces (e.g., wheel–axle, axle–chassis, body–chassis) to ensure functional compatibility. Teams were required to coordinate interface dimensions across subsystems prior to fabrication, reinforcing communication and system-level thinking.

3.3 Additive Manufacturing and Fabrication

Students designed their components using CAD software and exported STL files for printing. Available AM technologies included FDM, SLA, and PolyJet systems, subject to laboratory availability. Each team was permitted one prototype print before final fabrication, encouraging iterative design and tolerance refinement. Material selection, print orientation, and support strategies were left to student discretion, provided safety and laboratory guidelines were followed. Post-processing techniques such as sanding, polishing, or painting were allowed but optional.

3.4 Assessment Strategy

Project assessment was structured across three levels to capture technical, collaborative, and individual learning outcomes:

- Group Performance (40%): evaluation of subsystem quality, collaboration, and peer feedback within each team
- Overall Project Evaluation (40%): assessment of full-system assembly, dimensional compatibility, motion functionality, and print quality
- Individual Performance (20%): determination of individual contribution based on peer evaluations

Additional qualitative data were collected through individual reflection summaries and instructor observations during the final live assembly and demonstration.

3.5 Data Collection and Evaluation

Student learning outcomes were evaluated using a combination of performance-based assessment, peer reviews, and reflective feedback. Observations focused on students' ability to apply DfAM principles, manage tolerances, resolve interface conflicts, and collaborate across teams. These data formed the basis for evaluating the effectiveness of the project as a teaching model for additive manufacturing education.

4. Results and Outcomes

This section presents the outcomes of the collaborative additive manufacturing (AM) project using four complementary assessment lenses: (1) team-level project execution, (2) individual contribution and professional skills, (3) student self-assessment and feedback, and (4) manufacturing and design-for-AM performance metrics. Together, these results provide both qualitative and quantitative evidence of learning effectiveness aligned with manufacturing education objectives.

4.1 Team-Level Project Execution and Coordination

All four teams successfully completed the design, fabrication, and integration of their assigned subsystems within the four-week project duration. Figure 1 shows the different subassembly parts designed by the teams.

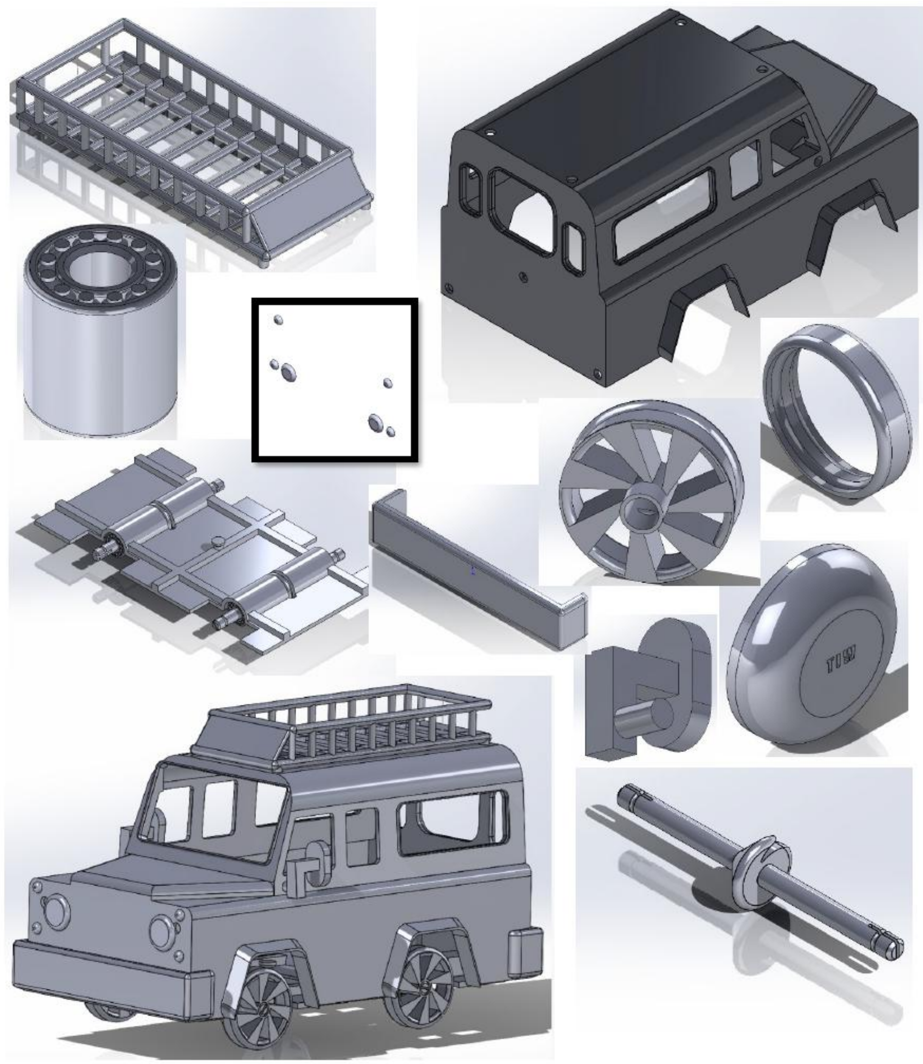

Figure 1. Subassembly parts designed by the student teams.

Instructor observations and weekly progress reports indicate that early-stage challenges were primarily associated with interface definition, tolerance allocation, and subsystem dependencies, rather than CAD modeling itself. Table 1 summarizes key manufacturing metrics collected during the project, including average print time, printed mass, and reprint frequency for each subsystem.

Table 1. Manufacturing Performance Metrics by Subsystem

Subsystem	Avg. Print Time (hrs)	Avg. Weight (g)	Reprint Required (%)
Chassis & Axles	5.8	210	75
Wheels	3.2	95	25
Body Frame	6.5	240	50
Connectors & Accessories	2.1	45	25

The chassis and axle subsystem exhibited the highest reprint frequency (75%), largely due to tolerance stack-up issues affecting wheel alignment and axle rotation. This result aligns with expected challenges in additive manufacturing of load-bearing components with functional interfaces and provided a meaningful learning opportunity related to dimensional accuracy, clearance design, and print orientation. In contrast, the wheels and connector subsystems demonstrated lower reprint rates, reflecting simpler geometries and fewer critical interfaces. These results highlight how subsystem complexity directly influences manufacturability in AM contexts—an important system-level insight for students. Figure 2. Demonstrates the 3d printed and assembled car parts together.

Figure 2. Representation of the 3d printed and assembled car parts.

Commonly reported challenges included:

- Misalignment between wheel hub and axle interfaces
- Insufficient clearance between body frame and rotating wheels
- Print-induced dimensional deviations due to material shrinkage or support removal

Despite these challenges, iterative problem-solving was evident. Three out of four teams required at least one prototype iteration prior to final submission, consistent with authentic manufacturing workflows. Teams that proactively coordinated interface dimensions early in the project exhibited fewer reprints and smoother final assembly. Table 2 summarizes reported challenges and resolution strategies by subsystem.

Table 2. Common Manufacturing Challenges and Mitigation Strategies by Subsystem

Subsystem	Primary Challenge	Resolution Strategy
Chassis & Axles	Axle misalignment	Increased bearing clearance
Wheels	Loose press-fit	Hub redesign, tolerance tightening
Body Frame	Wheel interference	Increased wheel well clearance
Connectors & Accessories	Assembly misfit	Standardized connector geometry

4.2 Individual Contribution and Professional Skill Development

Peer evaluation results demonstrate consistently high levels of individual accountability across teams. Mean scores for contribution, reliability, and technical work quality exceeded 4.0 on a 5-point scale for most students, indicating strong engagement and ownership of assigned tasks. Communication scores showed slightly greater variability, particularly in teams managing multiple interfaces, suggesting that inter-team coordination presents a higher cognitive and organizational demand than intra-team collaboration. Figure 3 presents the average peer-evaluation scores across assessed categories.

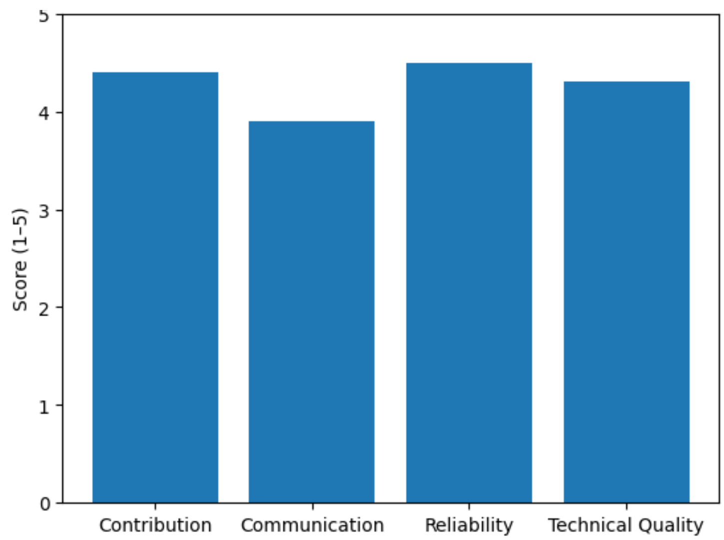

Figure 3. Average Peer Evaluation Scores Across Professional Skill Categories

Key observations include:

- Contribution (4.4/5) and reliability (4.5/5) were consistently rated highest
- Communication (3.9/5) scored lowest on average, though still above neutral
- No significant outliers indicating disengagement were observed

These results support the effectiveness of structured peer evaluation in reinforcing professional behaviors essential to manufacturing practice. Overall, students rated their teammates highly, particularly in reliability and technical quality. The comparatively lower communication score reflects common coordination challenges in multi-team, system-level projects and reinforces the instructional importance of structured interface communication and documentation. From an accreditation perspective, these results directly support ABET Student Outcome (5): "An ability to function effectively on a team whose members together provide leadership, create a collaborative and inclusive environment, establish goals, plan tasks, and meet objectives."

4.3 Student Confidence, Perceived Learning, and Project Difficulty

Student self-assessment surveys reveal strong perceived learning gains, particularly in the application of additive manufacturing tools and collaborative design practices. The majority of students reported high confidence in using AM technologies by the end of the project. Figure 4 summarizes student responses to Likert-scale survey items.

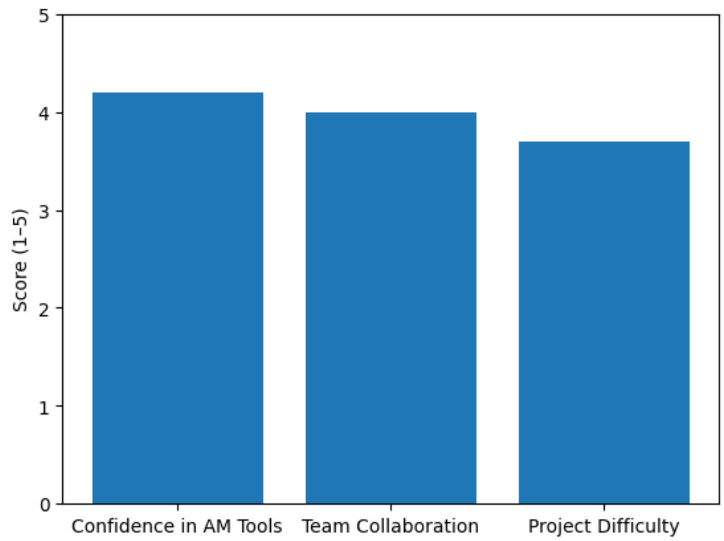

Figure 4. Student Self-Assessment of Confidence, Collaboration, and Project Difficulty

Key trends include:

- Confidence in AM tools: Mean ≈ 4.2/5
- Effectiveness of team collaboration: Mean ≈ 4.0/5
- Project difficulty: Mean ≈ 3.7/5

The moderate-to-high perceived difficulty suggests the project was sufficiently challenging without being overwhelming; an important balance for first-time exposure to system-level manufacturing design. Open-ended responses further reinforce these findings. The most frequently cited learning outcomes included:

- Understanding functional tolerances in AM parts
- Designing for assembly and motion
- Appreciating the impact of printer limitations on design decisions
- Recognizing the importance of early interface coordination

The high confidence score indicates that the project effectively reinforced practical AM skills, including CAD-to-print workflows, printer setup, material selection, and tolerance verification. The moderate difficulty rating suggests that the project was appropriately challenging for an upper-level undergraduate course, balancing technical rigor with achievability. These outcomes align strongly with ABET Student Outcome (1) (problem solving), Outcome (2) (engineering design with constraints), and Outcome (6) (experimentation, analysis, and interpretation of data).

4.4 Manufacturing Performance and Design-for-AM Outcomes

Objective manufacturing metrics provide direct evidence of student competency in design-for-additive-manufacturing (DfAM). Across all subsystems, most teams achieved functional clearances and successful assembly within one to two print iterations. Table 3 summarizes key manufacturing performance indicators.

Table 3. Manufacturing Metrics by Subsystem

Subsystem	Avg. Print Time (hrs)	Avg. Weight (g)	Clearances Achieved	Reprint Required
Chassis & Axles	5.8	210	Yes	Yes
Wheels	3.2	95	Yes	No
Body Frame	6.5	240	Partial	Yes
Connectors	2.1	45	Yes	No

Approximately 50–75% of teams required a reprint, most commonly due to insufficient clearances or unanticipated interference during assembly. Importantly, no team failed to achieve a functional final assembly, demonstrating effective learning through iteration. Figure 5 illustrates the frequency of reprints by subsystem.

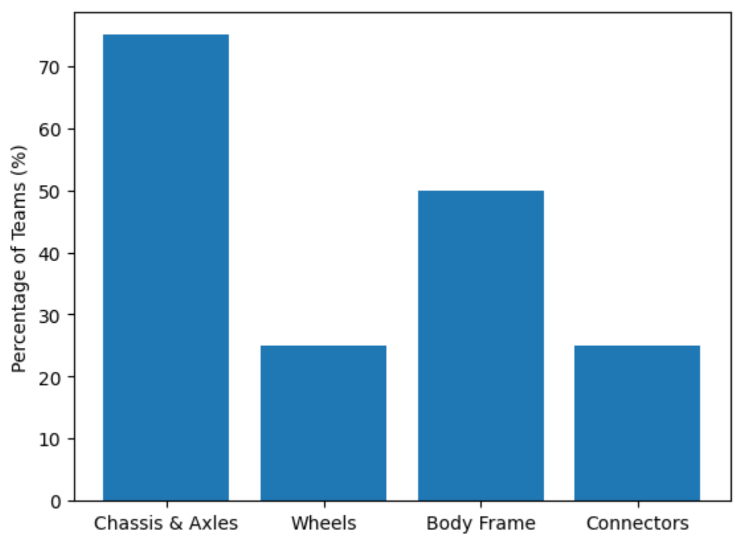

Figure 5. Reprint Frequency by Subsystem

Subsystems involving motion and structural integration (chassis and body frame) exhibited higher reprint rates, aligning with known challenges in AM tolerance control and assembly-fit design. This system-level validation phase reinforced ABET Student Outcome (7): “An ability to acquire and apply new knowledge as needed, using appropriate learning strategies.”

4.5 System-Level Integration and Final Demonstration

During the final live demonstration, all subsystems were successfully integrated into a fully assembled, rolling miniature SUV. Functional testing confirmed:

- Free rotation of wheels
- Proper axle alignment
- Stable body-to-chassis attachment
- No obstruction of moving components

The final assembly served as a tangible validation of system-level thinking, reinforcing the importance of interface management and manufacturing constraints in real-world engineering design.

4.6 Technical Performance and System Integration

All student teams successfully designed, fabricated, and assembled their assigned subsystems within the four-week project duration. Final assembly of the miniature SUV demonstrated full rotational functionality of the wheels, adequate ground clearance, and proper alignment between the chassis, axles, and body frame. Minor dimensional mismatches were observed in early prototype prints, particularly at wheel–axle and body–chassis interfaces; however, these issues were resolved in the final prints through tolerance adjustments and iterative redesign.
Students demonstrated a clear improvement in their application of DfAM principles between the prototype and final iterations. Common design refinements included increased fillet radii to reduce stress concentrations, adjustment of hole diameters to account for printer-specific shrinkage, and modification of part orientation to improve surface quality and dimensional accuracy. These outcomes align with prior findings that iterative AM projects reinforce process-aware design thinking [7,14].

4.7 Team Collaboration and Interface Coordination

Cross-team coordination emerged as one of the most impactful learning outcomes. Teams were required to exchange interface dimensions, negotiate tolerance ranges, and adapt designs based on constraints imposed by other subsystems. Instructor observations indicated that students initially underestimated the importance of interface definition but quickly recognized its critical role following early assembly challenges. Peer evaluations reflected strong engagement within teams, with most students rating their group collaboration as effective or highly effective. Several students explicitly noted that coordinating with other teams was more challenging, and more realistic, than working within a single group, reinforcing the value of system-level collaboration.

4.8 Assessment Outcomes

Analysis of grading data showed that the majority of teams performed consistently across subgroup and system-level assessments. While some discrepancies were observed (particularly where individual contributions varied within teams) the three-tier assessment structure helped mitigate free-rider concerns and provided a more nuanced evaluation of student performance.

4.9 Student Feedback and Reflections

Qualitative analysis of individual reflection summaries revealed several recurring themes:

- Increased understanding of tolerances and fit in AM
- Greater appreciation for communication and coordination in engineering design
- Improved confidence in applying CAD and AM tools to real-world problems

Many students highlighted the satisfaction of producing a fully assembled, functional product, noting that this experience differed significantly from typical single-part assignments. These reflections support prior research indicating that tangible system-level outcomes enhance student motivation and perceived learning value [10,11].

5. Discussion

The results of this study indicate that a collaborative, system-level PBL assignment can effectively enhance student learning in undergraduate Additive Manufacturing education. By requiring students to design interdependent subsystems and coordinate interfaces, the project extended learning beyond component-level DfAM principles to include system integration, tolerance management, and collaborative engineering practices.

More specifically, the observed reduction in reprint frequency following early coordination efforts directly supports ABET Student Outcome (1) through iterative problem-solving and analytical adjustment of tolerances. Successful subsystem integration aligns with ABET Student Outcome (2), as students designed components under realistic manufacturing, geometric, and process constraints. Peer evaluation results and documented coordination challenges map clearly to ABET Student Outcome (5), reflecting measurable growth in teamwork, leadership, and collaborative task planning. Finally, prototype iteration and adaptation to print-induced dimensional deviations demonstrate ABET Student Outcome (7), as students independently acquired and applied new knowledge to resolve emergent fabrication issues.

Compared to traditional AM assignments, this approach more closely mirrors industrial product development workflows, where multiple teams contribute to a shared system under schedule and compatibility constraints [15,16]. The observed improvements in student communication, iterative design behavior, and problem-solving align with established PBL outcomes reported in engineering education literature [9–11].

From an instructional perspective, the three-level assessment strategy proved particularly effective. Evaluating group performance, system-level integration, and individual contribution allowed the instructor to balance technical rigor with accountability, addressing common concerns associated with team-based projects [17–19]. Importantly, the project remained feasible within a four-week timeframe, suggesting that similar implementations could be scaled to other manufacturing or design-focused courses.

5.1 Transferability and Implementation Considerations

The project was intentionally designed to require only standard desktop AM equipment (e.g., FDM or SLA systems), making it adaptable to institutions with limited laboratory infrastructure. The four-week timeline can be adjusted to shorter or longer formats by modifying subsystem complexity, print iteration allowances, or prototype requirements. For larger enrollments, additional subsystems (e.g., steering mechanisms, suspension modules, or gear assemblies) can be introduced to maintain manageable team sizes while preserving interdependence.

However, several implementation constraints should be considered. First, printer availability and scheduling may limit prototype iteration frequency, particularly in resource-constrained environments. Second, effective coordination requires structured milestone check-ins and clear interface documentation; without instructor scaffolding, teams may delay communication until late-stage assembly. Third, peer evaluation systems must be carefully structured to ensure accountability and fairness. Institutions adopting this model should plan for clear interface templates, scheduled cross-team reviews, and defined dimensional governance protocols to ensure successful execution.

Despite these constraints, the modular nature of the project allows adaptation across mechanical, manufacturing, or interdisciplinary engineering programs seeking to integrate system-level additive manufacturing experiences.

Limitations of this study include reliance on a single course offering and a relatively small sample size. Future work may incorporate pre- and post-project surveys, direct comparison with non-collaborative AM assignments, or longitudinal assessment of skill retention. Additionally, incorporating digital collaboration tools or version-control systems could further enhance realism and traceability in future implementations. Overall, this work contributes to the growing body of literature on additive manufacturing education by demonstrating a practical, scalable model for integrating collaborative, system-level PBL into an undergraduate AM curriculum. The findings suggest that such projects not only strengthen technical competencies but also prepare students for the collaborative and interdisciplinary nature of modern manufacturing practice.

6. Conclusion

This investigation presented the design, implementation, and evaluation of a collaborative, system-level project in an undergraduate Additive Manufacturing course, in which students jointly designed and fabricated a functional miniature vehicle using AM technologies. By distributing responsibility across interdependent subsystems and requiring coordinated interface management, the project moved beyond traditional component-level assignments and more closely reflected contemporary manufacturing practice. Assessment results and student feedback indicate that the project effectively reinforced key manufacturing concepts, including design-for-additive-manufacturing principles, tolerance management, and process-aware design iteration. Equally important, students developed practical experience with collaboration, communication, and system integration; competencies that are critical for modern manufacturing engineers and explicitly aligned with ABET student outcomes.

The three-tier assessment framework, combining subgroup performance, system-level functionality, and individual contribution, provided a balanced and transparent evaluation of student learning while mitigating common challenges associated with team-based projects. Its structured subsystem architecture, scalable team distribution, and clearly defined interface governance model provide a transferable framework that can be adapted to varying institutional sizes, resource levels, and accreditation requirements. From an instructional standpoint, the project proved feasible within a four-week timeframe and required only standard desktop AM equipment, supporting its adoption in similar manufacturing-focused curricula. Future work will focus on expanding quantitative assessment through pre- and post-project concept inventories, incorporating metrology-based validation of printed components, and exploring the integration of industrial AM constraints such as cost modeling, build-time optimization, and quality control. Overall, the results suggest that collaborative, system-level AM projects represent an effective and scalable pedagogical strategy for manufacturing engineering education.

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