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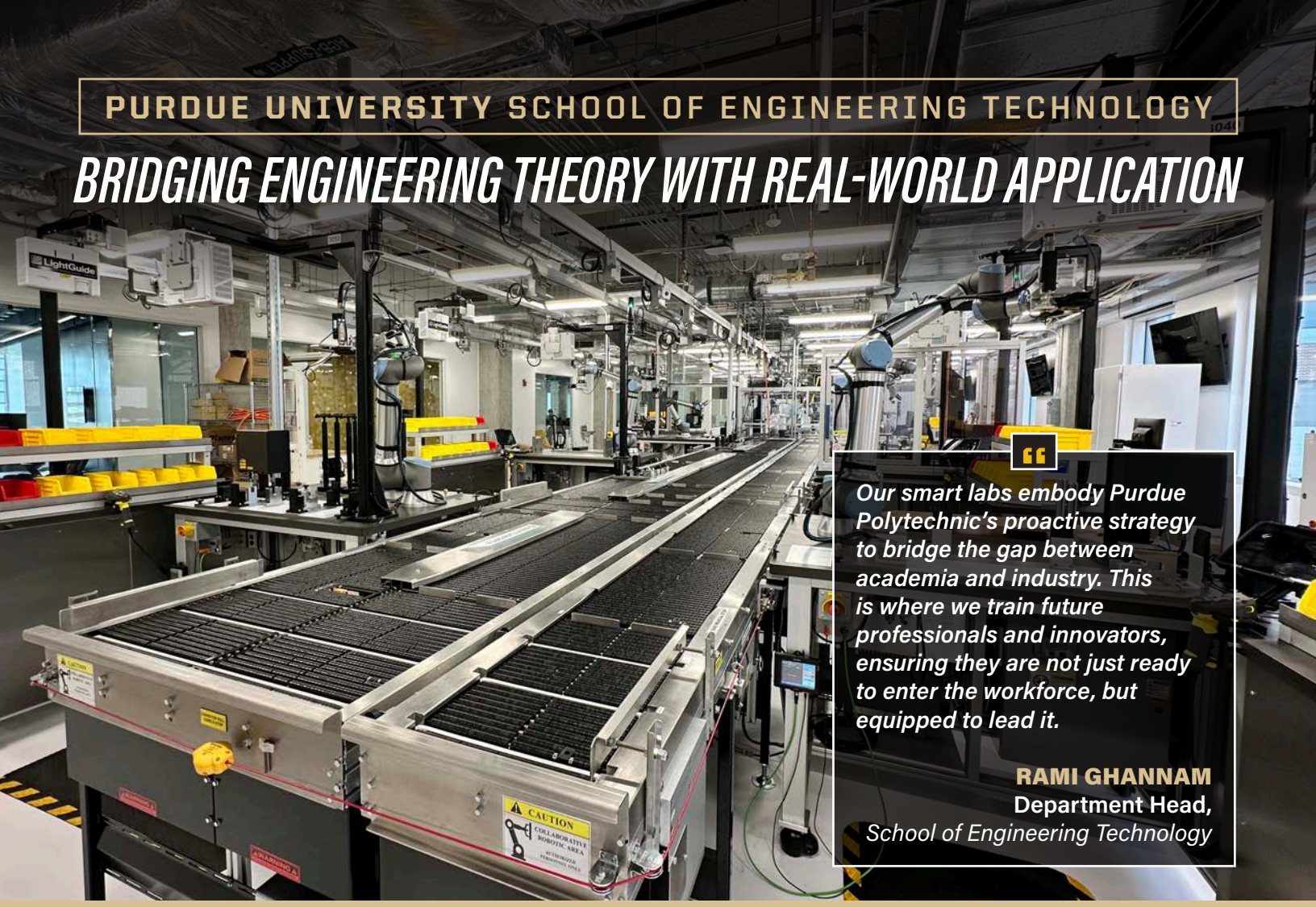






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From the EDITOR

Dear Colleagues:

It is a pleasure to reflect on recent developments within our community. We congratulate Marty Gordon on being elected ASEE President-Elect and look forward to his leadership. We also sincerely thank Ron Land for his dedicated service as Subscription and Financial Editor, as he has recently stepped down from this role. We welcome Ankit Gupta of California State University, Los Angeles, and wish him great success in strengthening the Journal's financial sustainability.

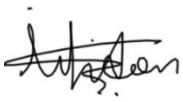
Through my recent involvement in the Grand Challenges Scholars Program in Brazil and Italy, I observed that Engineering Technology remains underrecognized globally. This reinforces the importance of continued advocacy for our field:

"The degree is Engineering Technology; the career is Engineering."

This issue of the ***Journal of Engineering Technology*** features five contributions: a roadmap for doctoral education in technology; strategies to increase high school student interest; the use of digital twins in lean manufacturing education; the impact of low-cost learning modules on student performance; and a practical guide to prompt engineering for ChatGPT. We are particularly interested in receiving more submissions related to AI practices in Engineering Technology. Please feel free to connect with our editorial team if you have AI-related best practices to share.

We appreciate the contributions of our authors and reviewers and invite your continued support and submissions. I look forward to seeing many of you at ASEE 2026.

Regards,



Ismail Fidan, PhD
Editor-in-Chief
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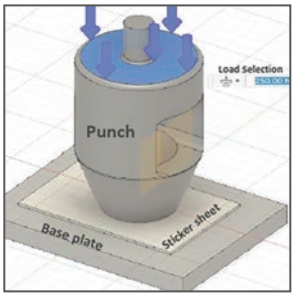
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ETD BEST PRESENTATION 2025 CIEC CONFERENCE

Evolutional Roadmap from BS Degree to Doctoral Degree in Technology

Ge Jin and Mohammad A. Zahraee

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Abstract

In 2008, the School of Technology, now College of Technology (COT), launched a Master of Science (MS) in Technology degree program. The MS in Technology degree program was designed to equip students with advanced technical skills as well as leadership capabilities necessary for thriving in various technological sectors. Since 2008, the program has successfully graduated over 700 students, making significant contributions to industry and academia. The MS in Technology program offers a flexible and comprehensive curriculum that blends theoretical knowledge with practical application. The program is structured to provide a robust foundation in core technological principles along with some Leadership/Management skills, while allowing students to specialize in areas aligned with their career goals. The MS in Technology degree program started with seven (7) Primary Areas, which were later changed to four (4) concentrations based on the industry and market needs. To further address the needs of Industry, the College of Technology Graduate Studies also developed three graduate-level professional certificate programs: Six Sigma for Business and Industry, Organizational Leadership and Supervision, and Cybersecurity Post Baccalaureate Certificates.

Since 2016, Purdue University Northwest (PNW)'s strategic mission has shifted from an undergraduate teaching institution to a metropolitan doctoral-granting institution. Having over 700 MS graduates, and to contribute to the strategic goals of the institution, the COT at PNW initiated a Doctor of Technology (DTech) degree program, which was approved by the Indiana Commission for Higher Education (ICHE) on June 9, 2022. Since its inception, the DTech program has been instrumental in fostering high-level research and expertise in various technological fields. The DTech program emphasizes best practice techniques for implementation in business, industry, government, and non-governmental organizations. This doctoral program is designed for both traditional students and industry professionals seeking an advanced degree to provide innovative solutions in their fields. The Doctor of Technology program currently enrolls 6 full-time doctoral students. This paper will share the best practices and lessons learned from the evolutional roadmap from a BS degree to a doctoral degree in Technology graduate education.

1. Introduction

Purdue University Northwest (PNW) is a vibrant regional university that is part of the Purdue University system. PNW serves a diverse student population by offering over 70 undergraduate and graduate degree programs across various disciplines. PNW has earned official designation as a Hispanic-Serving Institution (HSI) by the US Department of Education (DOE) in May 2024. The College of Technology at Purdue University Northwest offers 8 undergraduate, and 3 graduate degree programs focused on preparing students for careers in various technology-driven industries. The college emphasizes hands-on learning, providing students with practical experience in addition to theoretical knowledge.

The PNW College of Technology graduate program started with a Master of Science (MS) in Technology degree program in 2008. The MS in Technology program consists of four concentration areas: Computer Information Technology, Engineering Technology, Industrial Engineering Technology, and Technology Leadership and Management. Since 2008, the program has successfully graduated over 700 students. The College of Technology also developed three Post Baccalaureate professional certificate programs: Six Sigma for Business and Industry, Organizational Leadership and Supervision, and Cybersecurity Post Baccalaureate Certificates.

The rapid advancements in artificial intelligence (AI) technologies have catapulted them into the forefront of global innovation and economic competitiveness. As the US strives to harness the potential of AI for societal, economic, and strategic advantages, the importance of cultivating a skilled and diverse AI workforce has become a critical national imperative. To meet the national need for an AI workforce, the PNW College of Technology developed a new Master of Science in Applied AI program in Fall 2023. The PNW Master of Science in Applied AI (MS in Applied AI) program was designed to equip students with the knowledge and skills to tackle a broad spectrum of challenges across diverse industries by harnessing the potential of artificial intelligence and

machine learning. The program empowers graduates to apply AI techniques creatively and responsibly to make a positive impact in their chosen fields. Purdue University Board of Trustees approved the MS in Applied AI degree for PNW on June 7, 2024. The MS in Applied AI was approved by the Indiana Commission for Higher Education on July 24, 2024, and will admit students from Spring 2025.

The mission and strategic goals of PNW are to transform students' lives and its metropolitan region through a diverse campus committed to innovative education, applied research, and community engagement. The offering of the Doctor of Technology degree will contribute to meeting the mission and strategic goals of PNW by providing innovative, affordable education and applied research opportunities for advanced-level professionals. The COT at PNW initiated a Doctor of Technology degree program and it was approved by the Indiana Commission for Higher Education on June 9, 2022. Since its inception, the DTech program has been instrumental in fostering high-level research and expertise in various technological fields. The Doctor of Technology program currently enrolls 6 full-time doctoral students.

This paper will share the best practices and lessons learned from the evolutional roadmap from a BS degree to a doctoral degree in Technology graduate education.

2. History

Purdue University Northwest was established in 2016 through the merger of two existing Purdue University system campuses: Purdue University Calumet (Hammond campus) and Purdue University North Central (Westville campus). In 1946, both Purdue Calumet and Purdue North Central became degree-granting institutions. Over the next 70 years, these campuses grew and developed independently, serving the educational needs of Northwest Indiana. The unification of two campuses brought together the strengths of both institutions, allowing Purdue University Northwest to offer more than 70 undergraduate and graduate degree programs, balancing urban and rural settings across its two campuses and offering innovative education to students in the region and beyond.

Purdue University Calumet was established in 1946 as an extension campus of Purdue University. In 1962, it was redefined as a regional campus and renamed Purdue University Calumet Campus. In 1967, Purdue Calumet graduated its first class of baccalaureate degree students. The College of Technology is offering 8 undergraduate degree programs, and most of them are accredited by ABET. The Construction Engineering and Management Technology (CMET), Mechanical Engineering Technology (MET), and Electrical Engineering Technology (EET) programs at Purdue University Calumet (PUC) began in 1968, with CMET and MET receiving ABET accreditation in 1972 and EET in 1976. The Bachelor of Science in Computer Information Technology (BS CIT) program started in 1974 and was accredited by ABET in 2011. The BS in Organizational Leadership and Supervision (OLS) launched in 1994 and was also accredited by ABET in 2011. The Bachelor of Science in Computer Graphics Technology (CGT) program began in 2002 and was accredited by ATMAE in 2011. The Mechatronics Engineering Technology (MTB) program started in 2008 and was ABET-accredited in 2013.

Thanks to the strong alumni base from the Engineering Technology and Information Technology programs dating back to the 1970s, the College of Technology launched a Master of Science in Technology graduate program in 2008 without adding any additional faculty or administrative resources. Initially, the M.S. in Technology program did not have any specific concentration, and the curriculum consisted of 33 credit hours (11 courses) including a 3-credit-hour required directed project course. The M.S. in Technology program had peak enrollment in 2015 with 159 registered students, which brought in both opportunities and some challenges. To overcome the limited faculty resources, the M.S. in Technology program introduced a 30-credits coursework-only option and 6 concentration areas (Zahraee and Latif 2017). This gave faculty the opportunity to define the requirement for the concentration which was printed on the student's transcript. Currently, the M.S. in Technology program has four concentrations in various disciplines in engineering technology and information technology. In addition, a fixed plan of study with Technology Leadership and Management Concentration is offered fully online.

By 2020, the College of Technology at Purdue University Northwest had graduated over 500 individuals in the Master of Science in Technology program since its inception in 2008. Many of these alumni were working in the Chicagoland and Northwest Indiana region. Purdue University Northwest is committed to innovative education, applied research, and community engagement as stated in its mission and strategic goals. The PNW strategic plan states "increase the quality and scope of collaborative, interdisciplinary research focused on real-world challenges in the surrounding community, incorporating this research into the student experience." This commitment means offering an advanced degree that includes an understanding of complex areas of mod-

ern technology. A Doctor of Technology program enables industry professionals to learn and understand extremely sophisticated concepts and problem-solving skills to optimize systems and processes, as well as prepare students to provide innovative solutions.

The College of Technology proposed a professional Doctor of Technology program, offering students the opportunity to expand and apply knowledge and research to solve practice-based problems in several technology-related fields. Graduate education in technology involves a theoretical foundation followed by practical applications through research activities, underscoring the importance of hands-on learning and real-world problem-solving (Hartman et al. 2009, 15). The Doctor of Technology program requires 90 credit hours of coursework, including 30 credits of master's level study applied toward the degree. The DTech curriculum systematically develops enhanced skills and understandings that enable professionals, already holding a master's degree or equivalent, to apply their heightened technical and conceptual understandings of technology, research, and development. The Doctor of Technology degree has two concentration areas: Engineering Technology and Computer Information Technology. Although there are several online Doctor of Technology programs in the United States, PNW on-campus doctoral program in the technology field is the only one of its kind, fostering innovation through applied research. This program will provide the opportunity for traditional students, as well as industry professionals, to pursue an advanced degree that will provide innovative solutions in their field of interest. Purdue University Board of Trustees approved the Doctor of Technology degree for PNW on Dec 3, 2021. The Doctor of Technology degree was approved by the Indiana Commission for Higher Education on June 9, 2022. Currently, there are 6 full-time Doctor of Technology students in the College of Technology.

3. Needs and Justification of the Doctor of Technology Program

The justification and rationale for the Doctor of Technology program is described in terms of institutional mission and goals, regional benefit, workforce need, faculty expertise, and program availability in the field.

4. Institutional Mission and Goals

The mission and strategic goals of Purdue University Northwest are to transform students' lives and its metropolitan region through a diverse campus committed to innovative education, applied research, and community engagement. Through a broad range of quality undergraduate, graduate, and continuing education programs that meet regional needs, PNW seeks to advance and share knowledge through research and creative endeavor, and to work with the community to develop intellectual, cultural, economic, and human resources. The PNW strategic plan incorporates the University's mission to provide graduate study to meet the growing needs of profit and non-profit organizations in the Chicagoland and northwest Indiana region, which aligns with the Indiana Commission for Higher Education's Policy on Regional Campus Roles and Missions (Indiana Commission for Higher Education 2020). Purdue Northwest is committed to contributing to the economic wellbeing of the Region, and to preparing students to be active and responsible members of a global society and workplace. This commitment increasingly means offering post- baccalaureate study that includes an understanding of complex areas of modern technology. A Doctor of Technology program enables industry professionals to learn and understand extremely sophisticated concepts and problem-solving skills to optimize systems and processes, as well as prepare students to provide innovative solutions. The graduates of the program will be able to incorporate advanced technologies and apply them in their respective industries. This comports with the roles and missions of regional campuses designed to meet state and regional workforce needs.

The PNW strategic plan, in its mission, calls for experiential learning, faculty scholarship, and community partnerships. Goal 3 of the strategic plan states, "increase the quality and scope of collaborative, interdisciplinary research focused on real-world challenges in the surrounding community, incorporating this research into the student experience." Two of the strategies to achieve this goal are to "encourage research projects and contract opportunities which support initiatives with regional impact" and "target support with enhanced processes for increasing student-faculty research and creative collaboration." The DTech program, by serving professionals in industry, helps PNW to achieve these goals. Not only does this program address a regional need, but it also helps the regional industry with innovation, and therefore, boosts the economic development of the Region.

The program builds upon the particular strengths of Purdue University Northwest and its College of Technology, by leveraging the well-established capabilities from existing units, including Computer and Information Technology, Computer Graphics Technology, Construction Management Technology, Engineering Technology, and Technology Leadership and Management. Furthermore, other units across the PNW campus provide a rich environment for the proposed professional doctoral program. These units

include, but are not limited to, the College of Business, the College of Engineering and Sciences, and the College of Education.

Moreover, with Purdue Northwest's mission calling for responsiveness to the needs of Chicagoland and Northwest Indiana business and industry, the College of Technology is launching this practice doctorate program to aid in providing regional support to business and innovators surrounding our metropolitan university.

5. Regional Benefit

The professional doctoral degree enables students to build on the existing MS Technology degree offerings at PNW, allowing students to attain a more advanced degree and continue the path to being life-long learners. The affordability and accessibility of PNW will promote equity which is critical to our state's success. Citizens with advanced degrees earn higher salaries, enjoy accelerated career trajectories, and contribute more to local and regional economic development and prosperity. This program will help develop and unleash the potential of individuals to drive the state workforce and economy. By utilizing existing space and faculty across much of the College and University, offering the DTech at PNW will also contribute to a fuller utilization of existing resources. The Doctor of Technology is designed to encompass best practice techniques that can be implemented in business, industry, government, and NGOs, as well as by entrepreneurs, to solve complex technology-related problems. The proposed curriculum systematically develops enhanced skills and understandings that enable individuals who already hold a Master's degree or equivalent, to apply their heightened technical and conceptual understandings of technology, research, and development as they work to develop strategies to advance/enhance a PNW regional enterprise. Consequently, the Doctor of Technology will accelerate and further the careers of individuals who are already employed as they contribute to enterprise performance, efficiencies, and sustainability through contemporary applied research-based techniques. It will also increase the employability of those who are not already part of an enterprise - all students will be required to complete a dissertation focusing on applied/use-inspired research of direct relevance to professional practice.

6. Workforce Need

The need for professional doctorate degrees has been documented by Archbald who points to the fact that in addition to traditional students seeking such a degree, a professional degree such as this will also serve mid-career professionals in specific areas like healthcare, education, information technology, and business (Archbald 2011). Because technology is rapidly changing, growth in these industries/arenas demands a higher baseline of knowledge in order to adapt to the changing environment and to stay competitive for both the individual and the business unit. Kot & Hendel concluded that "professional doctorates constitute a noticeably strong trend in the USA, UK, and Australia, and similar patterns of expansion have occurred in these three countries" (Kot and Hendel 2012). They also summarized forces contributing to the emergence of professional doctorates with a detailed analysis that can be captured in three categories: (1) Employability, (2) Growth of the knowledge economy, and (3) Government involvement and public policy. Industry has recognized the importance of the human capital and resource supply chain, particularly at the high talent/highly innovative end of the spectrum. Sperling, then director of the National Economic Council, pointed to the strengthening of skills, i.e., "investing in a skilled workforce" as one of the five pillars of a proposed National Manufacturing Strategy (Sperling 2013). Industry needs technologically capable people at the high-capability end of the human resource spectrum (Wellington and Sikes 2006). The rationale is further supported by evidence collected through three surveys of PNW College of Technology Master of Science alumni who have shown an interest in continuing their studies once this degree is offered at Purdue Northwest. Over 92% of those surveyed in November 2017, 2018, and 2019 expressed an interest in pursuing a Doctorate in Technology. Furthermore, a 2019 survey focusing on the need for and interest in a Doctor of Technology degree was sent to all MS in Technology alumni and students. This survey showed that 92.5% of respondents believe the degree is beneficial to them professionally. 76% (62) will enroll in the degree program, if offered, within the next two years.

7. Job Market Analysis and Surveys of Alumni

The following shows the data supporting the need and sustainability of the Doctor of Technology degree program at PNW. Based on data received through EMSI (Labor Market Analytics) economic modeling 2019, Q4, there were 1053 unique (5,269 total) job postings within a 150-mile radius of Hammond, IN, using doctoral or Ph.D. as a requirement or preferred requirement within the listing for the following engineering-based CIPs: 11.0103.

- Based on data received through EMSI, economic modeling 2019, Q4, there were 6,504 unique (32,800 total) job postings14 within

a 150-mile radius of Hammond, IN, using doctoral or Ph.D. as a requirement or preferred requirement within the listing for the following computer/information technology-based CIPs: 15.0303, 15.0403, 15.0612, 15.0613, 15.0702, 15.0805.

- The results of surveys gathered from attendees of the 2017, 2018, and 2019 annual Technology Graduate Program alumni receptions have shown alumni interest in and overwhelming support for a terminal degree in Technology.
- A 2019 survey focusing on the need for and interest in a Doctor of Technology degree was sent to all MS in Technology alumni and students. This survey showed that 92.5% of respondents believe the degree is beneficial to them professionally. 76% (62) will enroll in the degree program, if offered.

The College of Technology Graduate Studies at Purdue University Northwest has a Graduate Studies Advisory Council (GSAC) composed of 15 representatives, each holding a graduate degree, from regional industry as well as surrounding educational institutions. These members, based on the needs of the industries they represent, and as part of the strategic plan of the College of Technology graduate program, incorporated the offering of a Doctor of Technology as one of the goals for the graduate studies program in the College of Technology.

In summary, not only is there a regional and national need for graduates of such a degree program, but it is also clear from the survey data and the market analysis findings, that there is enough interest from our alumni and sufficient market need in the region to begin offering the Doctor of Technology degree with a large pool of qualified candidates. Sustainability will occur through those who complete the current MS in Technology at PNW, in addition to other MS programs at other regional and national institutions.

8. Faculty Expertise

The MS in Technology graduate courses are taught by the COT graduate faculty members, who are sufficient to start the Doctor of Technology program. The initial number of DTech students is not expected to be large for the current faculty to manage. However, if graduate enrollment and specifically DTech enrollment grows, appropriate part-time and/or full-time faculty will be recruited as needed. Also, to start this program, an initial commitment of funding in the sum of $50,000 was allocated for new course development. In Addition, the Provost committed to covering tuition remission of 5 DTech students for three years. See Table 1 for faculty expertise.

9. Program Objectives, Curriculum, Courses, and the Semester Plan

The DTech from Purdue University Northwest is designed to prepare professionals to meet the needs of industry with leadership competence and advanced technology research and development skills. This doctoral program will develop leaders who are in high demand by start-ups, emerging industries, and established corporations operating in the advanced technology arena.

The core learning outcomes of the DTech program are:

1. Knowledge and Scholarship: To build the capacity to identify and conduct original research, scholarship, or creative endeavors.
2. Communication: To be able to effectively communicate their field of study
3. Critical Thinking: To think critically, creatively, and to solve problems in their field of study
4. Ethical and Responsible Research: To demonstrate the ability to conduct research in an ethical and responsible manner
5. Professional Development: To demonstrate attributes of professional development consistent with expectation within their field of study

The DTech degree program requires a total of 90 credit hours (thirty 3-credit-hour courses) to be completed, with 30 credit hours of master's level credits applicable toward the degree. For the 60-credits doctoral study, 18 credit hours are required core courses, with an additional 24 credit hours of electives and 18 credit hours of DTech dissertation research. The sample DTech plan of study for CIT and ET concentrations is shown in Tables 2 and 3.

10. Program Availability at National and Regional Levels

Nationally and regionally, there are few universities that offer Doctor of Technology degree programs. Currently, there are two similar programs within the state of Indiana: Purdue Polytechnic Institute's Doctor of Technology degree program and Indiana State University's Ph.D. in Technology Management. Both degree programs are offered as an online degree. At the national level, similar programs are offered either distance or on-campus, including:

- University of Northern Iowa, Department of

Table 1. Graduate faculty expertise in the College of Technology.

Faculty	Degree
Professor of Computer Information Technology	Ph.D., Engineering Science
Professor of Civil Engineering	Ph.D., Civil Engineering
Professor of Computer Graphics Technology	Ph.D., Technology
Professor of Organizational Leadership and Supervision	Juris Doctor
Professor of Electrical Engineering Technology	Ph.D., Electrical Engineering
Professor of Computer Information Technology	Ph.D., Biomedical Engineering
Professor of Computer Information Technology and Graphics	D.Sc., Computer Science
Associate Professor of Electrical and Computer Engineering Technology	Ph.D., Electrical Engineering
Professor of Computer Information Technology	Ph.D., Telecommunications and Networking
Professor of Electrical Engineering Technology	Ph.D., Industrial Technology
Associate Professor of Computer Information Technology	Ph.D., Computer and Electrical Engineering
Professor of Mechanical Engineering Technology	Ph.D., Chemical Engineering/Corrosion Science
Associate Professor of Mechatronics Engineering Technology	Ph.D. Computer Information System Engineering
Associate Professor of Computer Information Technology	Ph.D., Electrical Engineering
Professor of Computer Information Technology	Ph.D., Computer Science
Associate Professor of Industrial Engineering Technology	Ph.D., Technology Management
Assistant Professor of Construction Engineering and Management Technology	Ph.D., Civil/Structural Engineering
Assistant Professor of Construction Engineering and Management Technology	Ph.D., Civil, Environmental and Sustainable Engineering
Assistant Professor of Mechatronics Engineering Technology	Ph.D., Sustainable Energy Systems Engineering
Assistant Professor of Cybersecurity	Ph.D. in Engineering and Applied Science
Professor of Mechanical Engineering Technology	Ph.D., Engineering Mechanics

Technology, offering a Doctor of Industrial Technology.

- Texas A&M University (TAMU) has a D. Engineering program in its College of Engineering with a different focus.
- Capella University and Walden University both offer a Doctor of Information Technology, a fully online program, as opposed to this program, which is on-campus.

11. Sustaining the College of Technology Graduate Programs

To sustain the quality of the program, a continuous feedback mechanism and assessment are in place. A survey of program alumni from 2020 to 2024 shows that the outcomes and goals of the program were met (Figure 1). Detailed assessments of this program are described in two papers by Zahraee, Latif, and Colwell (Latif, N., Zahraee, M.A., Colwell, J. 2013) (Latif, Zahraee, and Colwell 2013; Latif and Colwell 2014). A similar data collection of alumni in 2016 showed that many of them were hired by regional companies, resulting in the program having a positive impact on the economic development of the region.

To sustain the growth of the program and have a stronger alumni base, an annual alumni event was introduced in 2015 and continued until 2019. The alumni event was paused due to COVID-19, and we are planning to resume the alumni event. Alumni from the MS in Technology program were invited from all over the country and were updated on the progress of the program. This program is a fun homecoming event to introduce some of our existing graduating students to our alumni and create an atmosphere of camaraderie among our graduates. Alumni were also surveyed at these events to measure the support for the creation of a new Doctor of Technology program (Table 4).

12. Assessment and Quality Assurance

Due to the large number of students who enroll and graduate every year (Figure 2), to maintain the enrollment numbers, a large pool of applicants is needed. Having a robust and comprehensive marketing plan is the most critical challenge posed to a successful, growing degree. It requires both effort and financial resources. The program decided to run the fully online master's program through the office of Academic Outreach and Contract Training (AOCT).

While marketing the program to attract a large number of applicants is a major task, the needs of constituents and keeping the program up to date should never be forgotten. Each academic year, the COT graduate coordinator and the associate dean will collect required graduate course assessment data from the faculty member who taught graduate courses in that academic year. The threshold level for each Performance Indicator (PI) is indicated on the associated tab. Generally, if the percentage of students' score is less than 80% on a PI, attention is needed. Each of the five COT graduate learning outcomes is tabulated

Table 2. PNW Doctor of Technology Plan of Study for CIT Concentration.

	Course Number	Course Title	Semester Offered	Credits
From Master's Degree				**30**
Core Courses 18 - Cr.	IT 57100	Project Management in Industry and Technology	F	3
	OLS 58900	Leadership and Ethics	F	3
	MET 52700	Technology from a Global Perspective	F	3
	ITS 53100	High Performance Computing and Big Data	Sp	3
	TECH 62110	Enterprise System Design	Sp	3
	TECH 64600	Analysis of Research in Industry & Technology	F, Sp	3
Electives 24 - Cr.	TECH 6XXXX	Industry 4.0	F, Sp	3
	ITS 66600	Advanced Visualization Techniques	F, Sp	3
	ITS 6XXXX	Advanced Topics in Cybersecurity	F, Sp	3
	ITS 62000	Cybersecurity and Machine Learning	F, Sp	3
		Free 50000/60000 level Technology Electives	F, Sp	3
		Free 50000/60000 level Technology Electives	F, Sp	3
	TECH 58100	Workshop in Technology	F, Sp	3
	TECH 62110	Seminar in Technology/CIT	F, Sp	3
Dissertation 18 - Cr.	TECH 64010	Research DTech Thesis	F, Sp, Su*	**
	TECH 64010	Research DTech Thesis	F, Sp, Su*	**
	TECH 64010	Research DTech Thesis	F, Sp, Su*	**
	TECH 64010	Research DTech Thesis	F, Sp, Su*	**
	TECH 64010	Research DTech Thesis	F, Sp, Su*	**
	TECH 64010	Research DTech Thesis	F, Sp, Su*	**
			Total Credits	**90**

* Summer session available only if Major Professor has another course on the summer schedule.
** TECH 64010 is a variable credit course usually scheduled for 3 credit hours; however, it may be taken for more or less than 3 credit hours. Major Advisor approval required.

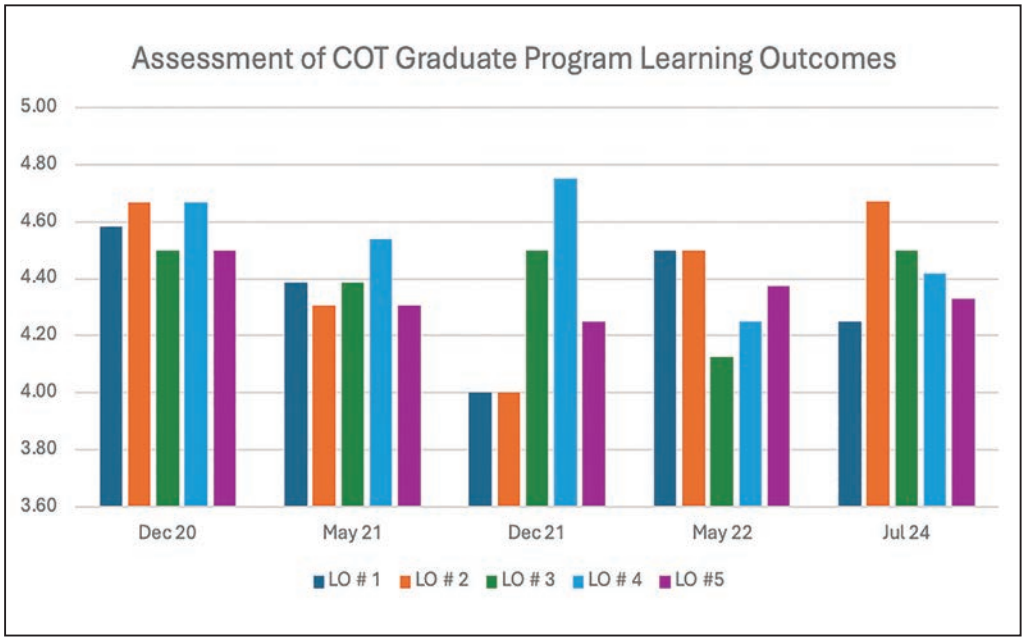


Figure 1. 2020-2024 College of Technology graduate student exit survey. July 2024 survey includes alumni from 2023 and 2024.

Table 3. PNW Doctor of Technology Plan of Study for ET Concentration.

	Course Number	Course Title	Semester Offered	Credits
From Master's Degree				**30**
Core Courses 18 - Cr.	IT 57100	Project Management in Industry and Technology	F	3
	OLS 58900	Leadership and Ethics	F	3
	MET 52700	Technology from a Global Perspective	F	3
	ITS 53100	High Performance Computing and Big Data	Sp	3
	TECH 62110	Enterprise System Design	Sp	3
	TECH 64600	Analysis of Research in Industry & Technology	F, Sp	3
Electives 24 - Cr.	TECH 6XXXX	Industry 4.0	F, Sp	3
	TECH 62510	Risk Analysis and Management	F, Sp	3
	TECH 6XXXX	Enterprise Planning	F, Sp	3
	STAT 6XXXX	Advanced Statistics	F, Sp	3
		Free 50000/60000 level Technology Electives	F, Sp	3
		Free 50000/60000 level Technology Electives	F, Sp	3
	TECH 58100	Workshop in Technology	F, Sp	3
	TECH 62110	Seminar in Technology/ET	F, Sp	3
Dissertation 18 - Cr.	TECH 64010	Research DTech Thesis	F, Sp, Su*	**
	TECH 64010	Research DTech Thesis	F, Sp, Su*	**
	TECH 64010	Research DTech Thesis	F, Sp, Su*	**
	TECH 64010	Research DTech Thesis	F, Sp, Su*	**
	TECH 64010	Research DTech Thesis	F, Sp, Su*	**
	TECH 64010	Research DTech Thesis	F, Sp, Su*	**
			Total Credits	**90**

Table 4. Alumni Support by Major to Survey Question: Doctor of Technology.

Program	2017	2018	2019
Computer Information Technology	4	1	1
Electrical Engineering Technology	2	0	0
Industrial Engineering Technology	4	3	2
Mechanical Engineering Technology	1	1	1
Mechatronics Engineering Technology	0	1	1
Technology Leadership Management	5	4	2
Total	**16**	**10**	**7**

with associated courses, performance indicators, specific assessment methods, performance indicator targets, and actual assessment data. Table 5 shows the IT50700 course assessment outcome. Based on the assessment results, the course instructor will provide a continuous improvement plan for each academic year (Table 6).

13. Conclusion

The College of Technology at Purdue University Northwest started to offer B.S. degrees in Mechanical, Electrical and Construction Engineering Technologies in 1968. Most of the B.S. degree programs in the College of Technology are accredited by the ABET. With the strong alumni base, the College of Technology launched a Master of Science in Technology graduate program in 2008 without adding any additional faculty or administrative resources. Currently, the M.S. in Technology program has four concentrations in various disciplines in engineering technology and information technology. The Master of Science in Technology program has graduated more than 700 students since its inception in 2008. Many of these alumni were working in Chicago, South Chicago, and Northwest Indiana.

With the success of the Master of Science in Technology graduate program, the College of Technology proposed a professional Doctor of Technology program, offering students the opportunity to expand and apply knowledge and research to solve practice-based problems in several technology-related fields. The DTech curriculum systematically develops enhanced skills and understandings that enable professionals, already holding a master's degree or equivalent, to apply their heightened technical and conceptual understandings of technology, research, and development. This program provides the opportunity for traditional students, as well as industry professionals, to pursue an advanced degree that will provide innovative solutions in their field of interest. Currently, there are 6 full-time Doctor of Technology students in the College of Technology.

This paper focused on the development of the Doctor of Technology program with regards to institutional mission and goals, regional benefit, workforce need, faculty expertise, and program availability in the field. In addition, the paper describes the approaches taken to sustain the COT graduate

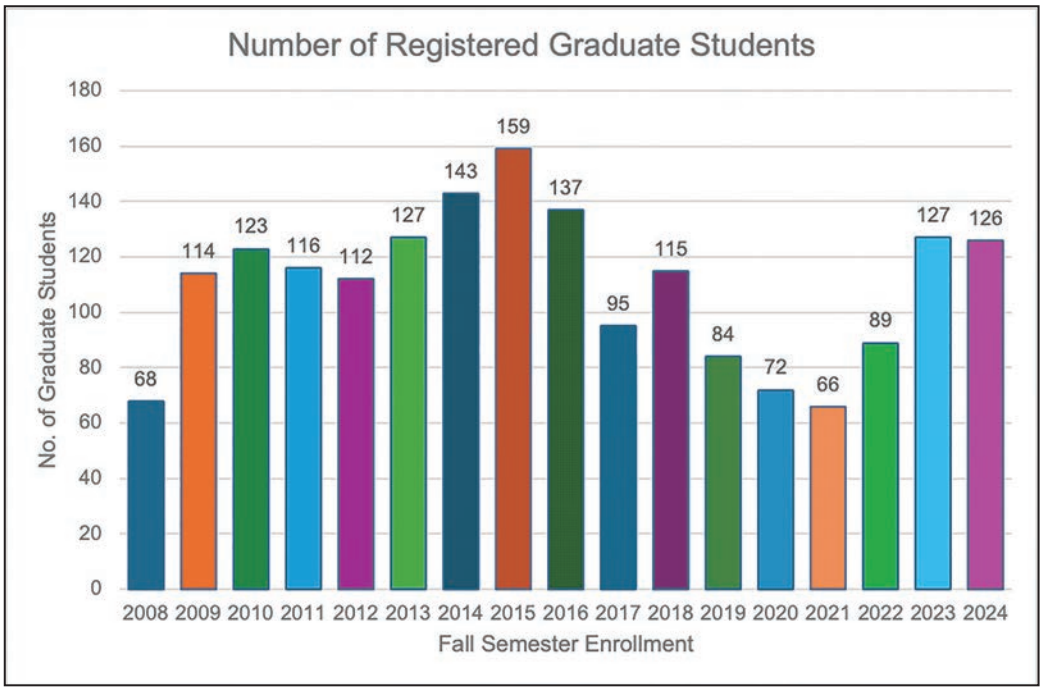


Figure 2. Number of College of Technology graduate students from 2008 to 2024.

Table 5. Spring 2024 IT50700 course assessment outcomes.

Course Objective	Supported Purdue Student Outcomes	Assessment Tool 1	Score (%)	Assessment Tool 2	Score (%)	Assessment Tool 3	Score (%)	Assessment Tool 4	Score (%)	Excellent	Good	Average	Poor	Very poor	Composite
1. Describe and display data appropriately.	1, 2, 3, 5	A 1	98%	Midterm exam	79%					12	3				4.80
2. Apply rules of probability.	1, 2, 3	A 2	89%	A 3	95%	A 4	90%	Midterm exam	84%	12	3				4.80
3. Explain random variable and sampling distributions.	1, 2, 3	A 5	94%	Midterm exam	84%					11	3	1			4.67
4. Apply hypothesis testing and regression analysis.	1, 2, 3, 5	A 7	81%	A 8	81%	A 9	67%	A 10	75%	11	4				4.73
5. Compare populations' parameters. 1, 2, 3 Assignment 8 81% 9.00 5.00 1.00 4.53	1, 2, 3	A 8	81%							9	5	1			4.53
6. Communicate statistical concepts and applications.	1, 2, 3, 5	Term paper	94%	Midterm exam	84%					10	5				4.67

Table 6. Spring 2024 IT50700 course assessment outcomes.

IT 50700 - Measurement and Evaluation in Industry and Technology			
Date Implemented	**Impetus for change**	**Action & Impact**	**By whom**
Spring 2024	Updating group project	Student groups given databases such as the government's Open Data to formulate a research question for their term papers.	Instructor
Fall 2023	Updating group project	Student groups prepared a recorded lecture on an assigned topic.	Instructor
Spring 2022	Clarification	To promote conceptual understanding, more hand calculation examples were used.	Instructor
Spring 2021	Statistical concepts	Prepare a lecture on P-value and Chi-square.	Instructor

programs, and the assessment and quality assurance methods adopted by the COT graduate programs.

Few lessons have been learned throughout the evolution of the COT graduate programs. A step-by-step approach in growth, by slowly expanding the program, will help the program flourish as the offering becomes broader and therefore addresses the needs of a broader constituency. The College of Technology at Purdue University Northwest understood that enrollment would increase as students find employment or see advancement in their current position. It took advantage of the faculty's industrial contacts to provide internships to its students to increase their employability. This helped the reputation of the program as more and more students applied for the program. Some innovative approaches are needed to provide a sound financial strength for the graduate programs. This helps with marketing the program and having a large pool of applicants. The graduate program decided to run its online program through the office of AOCT, which allows revenue generation for the program. This enabled the program to provide assistantships, as well as have financial resources for further marketing the program. As the growth occurs, the program should continuously assess the needs of its constituencies to ensure an up-to-date curriculum, addressing those needs.

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Dr. Mohammad A. Zahraee

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Using Product Archeology to Increase High School Student Interest in Engineering Technology Majors

Matthew Turner, Joseph F. Dues, Jr., Thomas Lucas, Damon Sisk and Andy Schaffer

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Abstract

This paper reports the results of a novel Engineering Technology (ET) education recruiting activity where teams of high school students dissected consumer products and matched the discrete parts and assemblies to engineering functions printed on a card. The theory of the event is to introduce students to engineering design via product archeology; the combination of product dissection with functional analysis. Product dissection is the disassembly of products in order to understand technical aspects of their design, e.g. "how are products constructed?". Functional analysis is the study of the intended behavior of a component in a system, e.g. "what was the purpose of that part?". The goal of the activity is that students could connect the "what" and the "how" of engineering design in a compact and engaging event to positively influence their perceptions of ET as a college major. The impact of the recruitment event was assessed via surveys of students' perceptions using Likert style and open response questions. Results indicate that the event was viewed overwhelmingly positively in the areas of engagement and understanding, but less successful in recruitment effect to the specific college.

1. Introduction

Purdue University New Albany (PUNA) is part of Purdue Polytechnic statewide system, serving students the Southern Indiana/Greater Louisville KY metropolitan region. PUNA is a small commuter school, offering Bachelor of Science degrees in Engineering Technology (ET) disciplines and producing graduates that frequently stay in the region when joining the workforce. Like many small schools and commuter programs, PUNA relies heavily on local recruiting activities with area high schools to meet enrollment goals. A major recruitment strategy has been for ET faculty to develop and host hands-on workshops for high-school students. Typically, these events focus on the applied nature of ET by using a learn-by-doing approach.

Prior faculty-developed recruiting events at PUNA were successful in developing positive perceptions of ET in potential students. However, they required significant time commitments from both faculty and the student attendees which limited the number of events that could be offered. A strategy was developed to increase the effectiveness of the recruiting events, consisting of three tiers (Figure 1) arranged in a funnel. The first tier is *Awareness* of PUNA and ET majors, followed by *Interest* in ET majors/careers, and finally *Recruitment* of interested students into PUNA ET majors.

Tier 1 consists of a Boiler Visit, which is a "chalk-and-talk" style presentation that explains ET and PUNA to student groups. While not hands-on, Boiler Visits focus on introducing students to ET and differentiating the program from engineering by emphasizing the project and laboratory-based curriculum. They require one or two faculty to deliver, need less than 15 minutes of advanced preparation, and are less than one hour in length. Additionally, these programs can be delivered to large groups of students and have little to no operational costs. On the other end of the spectrum, Tier 3 is Purdue Mission to Mars (PM2M) (Turner et al. 2016), a design-project event where students build, program, and test robots. PM2M typically involves five or more faculty, more than a full day of preparation, and is seven hours in length (or more). It can be delivered to a group of up to 50 and has high operation costs due to the need for robot kits and consumables.

The subject of this paper is the development, initial implementation, and assessment of the Tier 2 event, BoilerUp! Bingo. Serving as a "2nd-touch" opportunity with potential applicants, the event was designed with the following criteria:

- Focus on engineering technology design via a hands-on lab style activity.
- Related to both electrical and mechanical engineering technology.
- Sub 1 hour and 45 minutes operational time to align with student and faculty schedules.

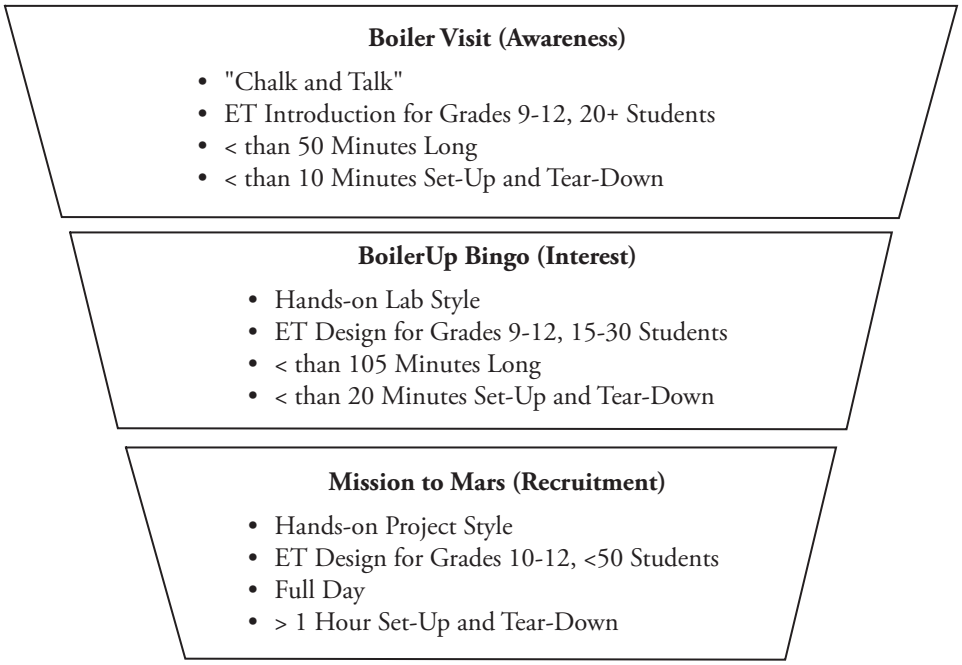


Figure 1. Recruiting event "funnel" strategy.

- Scalable to a typical high school class size of less than 50 students.
- Easily repeatable for multiple student groups:
  - o Less than 20 minutes of setup.
  - o Less than 20 minutes of clean up.
  - o Less than 1 hour of advanced prep required to train new faculty facilitators.
- Cost effective at less than $5 dollars per student in materials.
- Effective at generating interest in ET programs:
  - o Perceived as fun and interesting.
  - o Perceived as improving understanding of engineering technology.
  - o Improved interest in attending specific college programs.

Section 2 of the paper describes the theoretical design frameworks of Product Dissection and Functional Analysis and how they were operationalized as a recruiting event. Section 3 provides an event description. Section 4 presents the quantitative and qualitative results of the event data. Conclusions and future work are outlined in Section 5.

2. Theoretical Frameworks of Engineering Design

BoilerUp! Bingo was conceived as a fun way to introduce students to engineering design thinking. Many common design education activities are approached from a problem-solving perspective, i.e. students are asked to solve problems. Examples include egg-drop challenges or building bridges from pasta noodles. In contrast, BoilerUp! Bingo is based in the frameworks of Product Dissection and Functional Analysis which have their roots in product and mechanical design.

2.1 Product Dissection

Product Dissection is the deconstruction or disassembling of consumer products to infer design thinking from artifacts. It is a technique used in engineering design courses to answer the question "How did past engineers solve a problem?". It is premised on the idea that a hands-on deconstruction of a consumer product can help students develop a vocabulary of engineering, understand mechanical artifacts, and be aware of the engineering design processes (Sheppard 1992). The roots of product dissection in engineering education are from Stanford University, where mechanical engineering students dissected products including bicycles. These activities were followed by relevant lectures, such as discussions on loads on brake systems, (free-body diagrams), material selection for calipers, and material characterization/tests (Sheppard 1992). One of the primary motivations for the development of dissection-based courses is to bridge the gap between theoretical textbook learning and the hands-on practical experience often required to understand how products are designed, how they function and how they are made (Eggert 1996), (La-

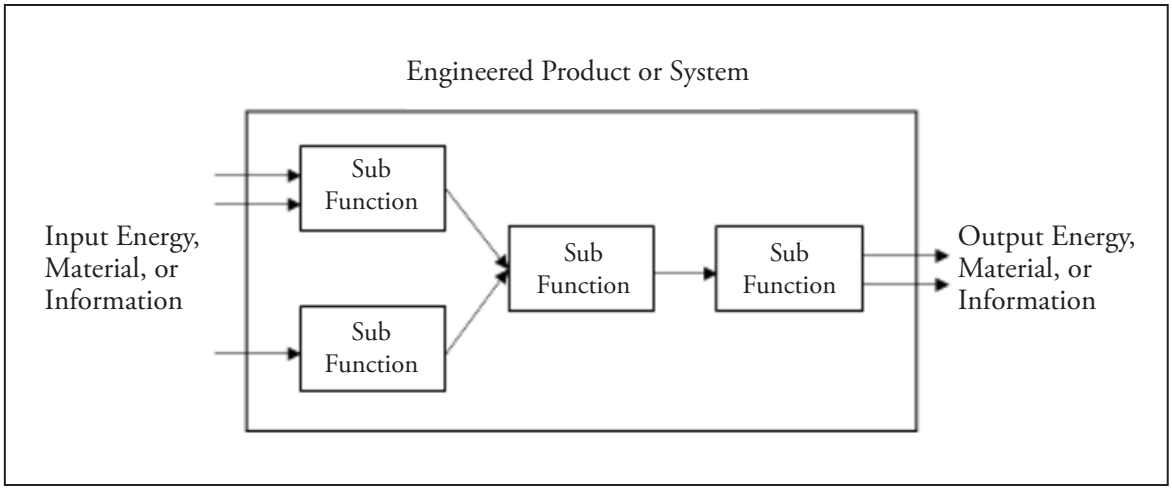


Figure 2. Example functional decomposition subfunction structure.

mancusa, Jorgensen, and Fridley 1996). Extensions of this technique have included investigations into how product design is influenced by global, environmental, and economic considerations (Lewis et al. 2011), (Lewis et al. 2013).

2.2 Functional Analysis

Originally developed to improve the creation of new engineered systems (Beitz, Pahl, and Grote 1996), functional analysis is frequently used in the engineering design process to describe an engineering product in terms of abstracted functions that are independent of specific technologies (Otto and Wood 2001), (Ulrich, Eppinger, and Yang 2008). Often this is described as setting "what a system must achieve or do" as opposed to engineering form, or "how a system will achieve or do". Typically, this is performed by considering a system as a "black box" that converts a specific set of inputs ("flows" of energy, material, information) into outputs using one or more subfunctions (Figure 2). For example, a blow dryer is an engineered system that receives inputs of air (material), electricity (energy) and on/off (information) and converts them to an output of heated air. This is achieved via a variety of sub functions and flows, such as converting electrical energy to heat or motion. Identification of the abstracted sub-functions required by an engineered system to perform its primary function is a design step often called "functional decomposition".

Design abstraction in the form of functional analysis is often taught in engineering design courses (Booth, Reid, and Ramani 2013) and has been previously used as a framework to explain engineering and technology to both introductory engineering students and non-majors through application to products such as a hair dryer, vacuum cleaner, and coffee maker (Krupczak 2010).

2.3 BoilerUp Bingo to Explain Engineering Design

Based on their prior use in engineering education, the previously described techniques of product dissection and functional analysis were operationalized into the BoilerUp Bingo event. The goal is to expose participants in the event to engineering design thinking and methods, specifically how engineers solve previous problems and how physical components are used to achieve abstracted functions, i.e. learn what it means to think like an engineer to solve problems and to understand how designed products and systems work.

For product dissection, three consumer products were chosen; a video game controller, blow dryer, and radio controlled (RC) car with remote (Figure 3). Factors considered in product selection included the likelihood of familiarity by high-school students, general appeal to high-school students, inclusion of both electrical and mechanical systems, ease of dissection using common tools, sufficient complexity as to contain interesting functions, and not overly complex as to be too difficult to analyze by novices.

For functional analysis, decomposition techniques were adapted from (Little, Wood, and McAdams 1997) and (Stone and Wood 1999) in which the requirements of engineered systems are described as in Figure 2 using functions (a description of an items task in verb-object form) and flows (changes in material, energy, or information between an item's subfunctions). Prior work has identified that approximately twenty functions can be used to accurately and completely describe all major operations of engineered systems (Little, Wood, and McAdams 1997), which are commonly used via verb-noun pairings



Figure 3. Original and dissected consumer products for BoilerUp Bingo. From the left, a game controller, a hair dryer and a remote-controlled car.

with the flows they operate on (e.g. separate material, transmit force). To organize the functions, a bingo card (Figure 4) was developed with the squares containing the adapted engineering functions. A definition and example(s) were included for each function.

	A	B	C	D	E
1	Stop	Measure	Absorb	Slide	Indicate
2	Stick	Separate	Align	Translate	Seal
3	Switch	Convert		Supply	Couple
4	Store	Push	Stabilize	Distribute	Cover
5	Sense	Transmit	Rotate	Brace	Secure

A. Stop
   i. To cease, or prevent something from occurring.
   ii. Example: A reflective coating on a window *stops* the transmission of UV radiation through a window. A switch *stops* electricity from flowing in an electric circuit.

Figure 4. Bingo card with simplified engineering functions and example definition for "Stop" function.

The functions used on the card were adapted from those developed by Little and Stone such that they could be utilized by novice designers (i.e. high school students). There are cases in the referenced work where proposed functions have similar definitions, for example indicate vs. display. Although originally defined in (Stone and Wood 1999) as two different functions, they were not considered unique enough concepts to be clearly distinguished by students. For example, does a red LED indicate (to make something known to the user) that power is on or display (to show a visual effect)? This confusion was further complicated by the examples from (Stone and Wood 1999) which were "A small window in the water container of a coffee maker indicates the level of water in the machine." and "The face and needle of an air pressure gage display the status of the pressure vessel." for indicate and display, respectively. Additionally, multiple new functions were added to simplify the exercise. For example, one function of a tire is to provide traction between a tire and a surface, and a rubber coating on a button provides a similar function between the finger and button. Although these could be viewed as applications of the function secure (to firmly fix a material or energy path), this level of connection was considered too difficult. Instead, a related function of "stick: to cause a resistance to a change in motion or direction" was created. A second example is the function of a protective case, which can be seen as a support function (to firmly fix a material into a defined location). This was changed to "cover: to put something in place in order to protect or conceal something".

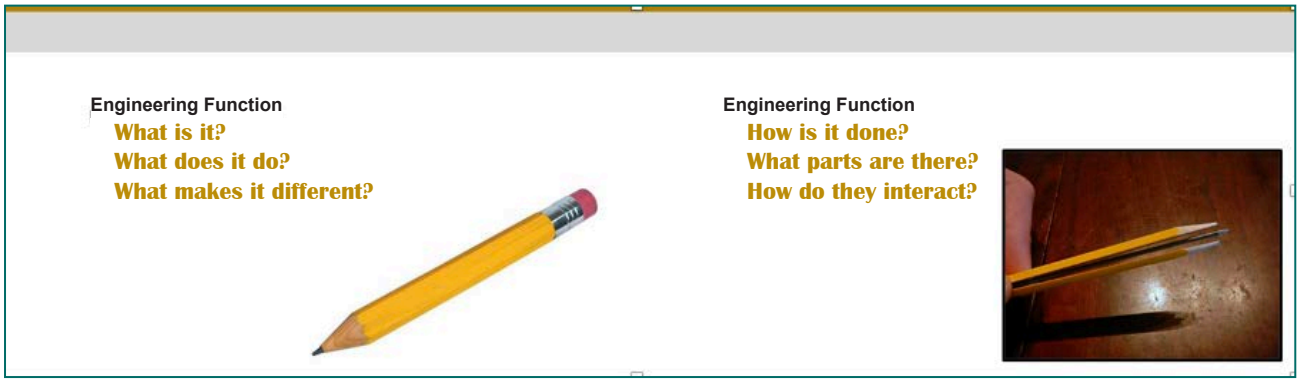


Figure 5. Guided discussion slides for functional analysis and product dissection.

3. Event Description

3.1 Introduction to Design Thinking

The first stage of the event is to introduce students to engineering design thinking by analyzing a #2 pencil via the techniques of functional analysis and product dissection separately (Figure 5) using a guided discussion. The students are first asked to describe the function of the pencil, which most quickly identify as "writing". The faculty facilitator then uses the Socratic method to engage the students. Pencils write, but so do pens, markers, crayons, etc. They are all different products with different applications. What functions differentiate the pencil? Students quickly identify that pencils erase and can be used for drawing, or general marking purposes. The facilitator uses this process to guide the students to a functional definition of a pencil: a handheld implement used to make removable marks, drawings, or writing, on a variety of surfaces. Students were then asked to link the identified functions to the form of the pencil. Again, guided discussion is used to help students connect how the different parts of the pencil achieve the previously identified functions. In this case, the handheld function of a pencil is typically served by a wood casing, but other forms exist such as plastic and paper. Similarly, the marking core of the pencil can be graphite, charcoal, grease, etc. Through this process, students are introduced to the idea of engineering design: to first define what the system must do (functions), and then brainstorm different mechanisms by which the functions can be achieved (form).

3.2 Product Archeology

In the second stage of the event, the larger student group is divided into three to five-person teams. Each team is given a self-selected consumer product, a small kit of tools, a 36"x36" bingo card, an engineering function definition and example sheet, and QR codes linking to disassembly videos for each product. The teams are given 40 minutes to dissect the product and to place the dissected components onto the bingo card with the goal of placing the component on a square that correctly identifies its function (Figure 6). While the process is mainly peer-to-peer, faculty facilitators check in with the teams to gauge progress, answer questions, and provide general guidance. For example, students ask questions about mechanical and electrical components which they are not familiar with or for clarification on engineering functions. Once a team has placed five components forming a straight line on the card (i.e. bingo), a faculty facilitator evaluates the card, discussing their evaluation with the team. Teams that are not successful are given feedback by the facilitator and continue to work to score a bingo. Teams that are successful are given a



Figure 6. Single line bingo for row 1 and diagonal using a game controller.

reward and are then challenged to score a cover-all bingo card (all function squares on the card are covered with a correct component/device/sub-system). Early runs of the event indicate that 40 minutes is sufficient time for all teams to score a bingo, and for most teams to score a cover-all.

3.3 Explanation

The third stage of the event returns to large group guided discussion where the teams are asked how the components identified contribute to the overall function of the product. This challenges the students to think about how the individual components of each product work together to achieve a major function, the reverse of the process that was used to analyze the #2 pencil. This discussion is guided so that the following functional definitions of the products are identified:

- Game Controller: to communicate with a game system by collecting input from a human's hands and to provide user feedback via light, vibration, and tactile response.
- Blow Dryer: to provide a flow of hot hair to increase the evaporation of water from a surface or material and to assist in hair styling.
- RC Car: to control the speed and direction of a model vehicle from a distance by collecting and transmitting inputs from a human's hands.

3.4 Real World Connection

In the fourth and final stage of the event, faculty facilitators discuss the role of engineering technology in product design and manufacture via presenting on their own real-word engineering design experiences.

4. Results and Discussions

4.1 Demographics and Selection

The BoilerUp Bingo event has been offered twice to a total of 42 high school students. Students were part of Indiana Gear Up (Johnson et al. 2023), a program that helps prepare Indiana students from lower income communities to start college successfully. Students at high schools participating in Indiana Gear Up voluntarily signed up for the event. 24 of the program participants identified as female, and 16 as underrepresented minorities. On day one, 32 students were separated into eight groups, and on day two, ten students were separated into four groups.

4.2 BoilerUp Bingo Results

In order to build self-perception of STEM efficacy, the bingo activity was designed such that a single-line bingo could be achieved with any of the given products. Of the 12 groups in this sample, all were able to complete a single-line bingo. The fastest team reached the goal in 15 minutes using the RC car, and the longest achieved 'bingo' in 45 minutes using the hair dryer. The approximate mean time to completion of a single-line bingo across all groups was 25 minutes. It was observed that the time to completion depended upon the faculty facilitator evaluating the component and function pairings, with some facilitators interpreting the engineering functions more narrowly than others, resulting in longer completion times. All teams that finished before the allotted time were given the chance at a cover-all bingo. On the first day, teams were allowed to disassemble an additional product to achieve this. Of the eight groups, four achieved a cover all. On the 2nd day, teams were restricted to one product for the entire activity. All four groups were able to achieve a coverall. Figure 7 illustrates the high level of student interaction during the event.



Figure 7. Student participation in BoilerUp bingo.

4.3 Survey Results

Student perception was evaluated using a post-event survey. Questions one through five had students rate their agreement with a provided statement on a scale from *1. Do Not Agree at All to 4. Agree a Lot.* Descriptive statistics for the student responses are given in Table 1. The overall high scores for Q1 to Q4 indicate that the overall student perception of the event was as intended: a fun activity that engaged their thinking in a way that improved their self-perceived understanding of engineering technology and engineering product design. The lower score of 2.6 for Q5 should be viewed in the context that Purdue New Albany only offers engineering technology degrees, which many students will not be intrinsically interested in.

Table 1. Post event survey data. Sample Size = 42.

Statement	Mean	SD
Q1. The activity was fun.	3.88	0.25
Q2 The activity made me think.	3.69	0.45
Q3. The activity improved my understanding of engineering technology.	3.55	0.49
Q4. The activity improved my understanding of how products are designed.	3.55	0.61
Q5. The activity increased my interest in attending college at Purdue New Albany.	2.60	0.89

Questions six and seven of the survey were open-ended response questions asking the students to provide comments on what aspects of the event appealed to them the most and what they would like to see improved. Table 2 summarizes the overall themes found in the responses (multiple themes can be contained in a single student's response). Results show that the majority of students enjoyed the hands- on nature of the event and had no suggestions for changes.

Table 2. Summary of themes found in open response questions.

Theme	Number of Comments Containing Theme
Something I really liked about today's activity was:	
Hands On	27
Real World Application	6
Fun Game	6
Increased Knowledge	8
Instructor Interaction	5
Teamwork	1
Something that I think could be improved about today's activity was:	
No Suggestions	21
Not Enough Interaction with College Students	2
Disassembly Too Easy	2
Not Enough Variety in Product Selection	2
Disassembly Too Small	1
Engineering Functions Unclear	1
Event Too Long	1
Event Too Short	1

4.4 Facilitator Observations

At the end of each day the faculty facilitators were asked to provide a one paragraph observation of the event. Overall, faculty facilitators shared two major observations. First, they believed that the students were engaged with the activity and enjoyed taking things apart. This agrees with the student reported survey data and supports the overall conclusion that the event was successful in appealing to student interests. The second observation is related to the students' understanding of engineering design and functional analysis. Generally, the faculty reported that students required some assistance with identification of engineering function and overall understanding of engineering design thinking. The following responses illustrate these points:

> "All of the student groups were engaged with the activity. They started taking apart the game controller without any hesitancy, including breaking pieces apart. They were mostly successful with function identification given the reading and their background knowledge, but they did require assistance on a few terms… Most of the mechanical element were more familiar to them, but there were multiple teams asking about electrical components they had heard of (LED and capacitor) and what they looked like on the board."
>
> "Students seemed to gain some understanding of the engineering design mindset from the activity. Since every team in my group chose the game controller, we were able to have a class-wide discussion of the hair dryer and RC car functions without anyone having seen the

inside of them. … Students were asked about the function of the hair dryer, which they initially replied "to dry hair". Once prompted with "how?", the group was able to deconstruct "blow hot air" into a smaller and smaller set sub-functions that contribute to the overall function. Similarly, they seemed to have a realization that the RC car contained many of the same components and engineering functions as the game controller and blow dryer, but that the placement interaction of the elements is what determined the overall operation."

5. Conclusions and Future Work

BoilerUp Bingo is a sub 2-hour engineering technology outreach program designed to be entertaining, low-cost, and easily repeatable with little setup or teardown time. Program participants learned about engineering design thinking by tearing apart a consumer product (product dissection) and identifying engineering functions for the dissected components (functional analysis). Initial offerings of the activity were promising, with students reporting that the event was entertaining and improved their understanding of both ET and product design. These results are highly encouraging given the large percentage of female and URM participants in the pilot. However, no data has been collected to evaluate efficacy of the program in recruiting students into ET majors. In the future, the authors plan to collect longitudinal data of incoming freshman to better understand the impact of the recruiting strategy outlined in Figure 1.

In addition to recruiting, BoilerUp Bingo could be utilized as part of an engineering design course or course sequence such as "design thinking" or "design spine". Functional analysis is widely viewed as a difficult concept, especially when employed as a design activity in capstones and similar courses. BoilerUp Bingo introduces the concept in a way that is engaging and understandable to students at an earlier stage of their education and may provide a foundation for deeper and more critical discussion in advanced courses.

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In Teaching Lean Manufacturing with Digital Twin: A Modern Approach to Engineering Education

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Abstract

Engineering education must evolve beyond conventional classroom techniques as technology advances rapidly and Industry 4.0 practices become increasingly prevalent. This study explores integrating digital twin technology into engineering education as an innovative and effective approach to teaching lean manufacturing principles. The central research question guiding this work is: Can digital twin–based learning improve students' understanding and application of lean manufacturing concepts compared to traditional teaching methods? A total of 40 senior-year students were surveyed, revealing an overall 63% improvement in course evaluation following the adoption of digital twin–based learning. Focusing on sensor stamping in renewable energy applications, the digital twin was developed using CAD tools such as Fusion 360 and NVIDIA Omniverse to create interactive virtual manufacturing systems. Students conducted time-motion studies, defect analyses, and production cycle optimizations through iterative simulations involving three manufacturing methods: traditional hammering, manual pressing, and automated stamping. Results demonstrated the value of design optimization and force-controlled stamping, validating the digital twin's effectiveness in enhancing process understanding and decision-making. Overall, this study highlights the transformative potential of digital twin technology to foster experiential, data-driven learning and align engineering education with Industry 4.0 competencies.

1. Introduction

The manufacturing sector is undergoing a significant transformation, driven by the convergence of automation, data-driven systems, and lean philosophies—collectively encapsulated within the paradigm of Industry 4.0. As a result, engineering education must also evolve to prepare future professionals for this dynamic landscape (Irwin et al. 2024). While theoretical instruction remains a cornerstone of engineering curricula, a considerable gap persists between classroom learning and practical industrial application. Bridging this gap is essential for developing engineers who are not only technically proficient but also capable of fostering continuous improvement in complex manufacturing environments (Adrian et al. 2020).

A Digital Twin (DT) is a virtual replica of a physical asset, process, or system that is continuously updated with real-time data to mirror current operational conditions. Initially adopted for predictive maintenance and performance monitoring in advanced manufacturing, DTs have matured into powerful tools for simulation (Phanden, Sharma, and Dubey 2021) , optimization (Anis Fatima, Muhammad Wasif, and Irwin 2025), and decision support (Grieves and Vickers 2016). In manufacturing contexts, DTs facilitate experimentation without disrupting actual operations, allowing engineers to explore "what-if" scenarios, test process improvements, and visualize system-wide impacts.

Lean manufacturing—originating from the Toyota Production System—emphasizes maximizing value while minimizing waste (Womack and Jones 1996). Traditionally, lean principles are taught through lectures, case studies, and physical simulations such as the "LEGO factory" model. These methods introduce foundational concepts like muda (waste), kaizen (continuous improvement), and takt time, but often fall short in capturing dynamic process interactions, real-time data usage, and system-level thinking (Dombrowski and Mielke 2013). A major limitation in conventional lean education is the inability to simulate the cascading effects of localized inefficiencies across the broader production system. This restricts students' understanding of lean manufacturing as a cohesive, integrated methodology rather than a set of isolated tools.

The literature suggests that digital twin technology can offer students an interactive, immersive experience with virtual models of real-world systems, thereby enhancing the effectiveness of engineering education. However, most of the research around digital twins (DTs) continues to centre on factory-level or

industrial implementations, such as process optimization (Roquini et al. 2026), value-stream mapping (Nwamekwe et al. 2025; Reslan et al. 2025), and predictive maintenance (van Dinter, Tekinerdogan, and Catal 2022). Meanwhile, a parallel body of literature on computer simulation - typically static or fixed-scenario models rather than dynamic twin-based systems- has been used in lean manufacturing education, offering a useful but less immersive alternative. Also, to maintain relevance, this review focuses exclusively on simulation studies published within recent years, highlighting the latest advancements in virtual/computer simulations. Cudney et al (Cudney, Corns, and Gadre 2014) developed a virtual simulation platform using the VE-Suite virtual engineering framework, which allows students to experience multiple applications of lean in a real-world setting. Talbi et al (Talbi et al. 2025) propose a framework for a virtual laboratory in mechanical and industrial engineering that leverages virtual reality (VR) to simulate laboratory environments while integrating lean manufacturing principles to optimize flow shop processes. Similarly, Salleh et al (Salleh et al. 2024) employ FlexSim software to visualize a production line system and develop a virtual game platform, enabling students to apply basic assessments of lean principles and identify challenges within lean manufacturing systems. Terkaj et al (Terkaj et al. 2024) present a framework for developing virtual learning applications that address multidisciplinary requirements through an open-source solution, utilizing VR to support innovative higher-education learning activities in industrial engineering.

Recent developments in the digital twin (DT) field further highlight the potential of new frameworks to support real-time monitoring and dynamic reconfiguration of production lines in response to disturbances. However, studies examining the use of DTs specifically to bridge the gap between theory and practice in lean manufacturing education remain limited. Barbieri et al (Barbieri et al. 2023) highlight how visualization technology enhances student comprehension beyond theoretical or numerical representation. In their work, a digital twin of a factory layout was developed, enabling control and optimization through the interaction of various DT components. Similarly, Hazrat et al (Hazrat et al. 2023) demonstrate the advantages of DTs in teaching lifecycle management, including predictive maintenance, remote diagnostics, and remote operations. Nwamekwe et al (Nwamekwe et al. 2025) integrate digital twins (DTs) with a lean manufacturing framework to optimize value stream flow, minimize waste, and enhance real-time decision-making capabilities. The study examines layered DT architecture encompassing physical, virtual, and communication interfaces, while incorporating Lean tools such as Kaizen, Kanban, and Just-in-Time (JIT) to facilitate continuous process improvement. Ortiz et al (Ortiz et al. 2025) demonstrates that integrating Digital Twin technology into engineering education can enhance active learning by linking physical teaching modules with a virtualized industrial process. Using an S7-1200 PLC and WinCC HMI interface, students could monitor and control the cocoa production process in real time, resulting in a 38% reduction in task execution time compared to conventional methods. The findings suggest that Digital Twins improve student performance through immersive, interactive simulations and also offer practical benefits for optimizing industrial processes in line with Industry 4.0. Guo and Mantravadi (Guo and Mantravadi 2024), in a systematic literature review of 33 studies on supply chains and digital twins using the SCOR framework, found that digital twins primarily support planning, production, and delivery processes, enhancing information flow, logistics optimization, and just-in-time practices. The study also highlights their contributions to supply chain coordination and resilience, proposes a framework for smart lean supply chain management, and emphasizes the need for further research on digital twin mapping, interaction, cognition, services, and education.

These advances suggest untapped opportunities for DTs to more effectively support lean manufacturing education by providing richer immersive experiences, live data feedback, and scenario-based learning that go beyond static simulations. Despite the growing emphasis on Industry 4.0 and lean manufacturing, traditional engineering education remains largely theoretical, relying on static classroom simulation exercises that limit students' exposure to real-world manufacturing challenges. For example, in sensor production for the energy sector, customized stickers are applied to clean and tested sensors before final packaging, a process critical for both quality and efficiency. Conventional training typically emphasizes manual hammering techniques or press stamping, offering little opportunity for students to analyze process efficiency, identify sources of waste, or evaluate quality outcomes. To address this gap, this study develops a digital twin of the stamping die and the entire sensor manufacturing line using Fusion 360 and Siemens Tecnomatix software. The digital twin enables students to simulate and optimize the stamping process, providing hands-on experience with lean manufacturing principles, system-level interactions, and data-driven decision-making, practical skills that remain underrepresented in traditional engineering curricula.

2. Methodology

This study employed an experimental mixed-methods approach to evaluate the effectiveness of digital twin–based learning in teaching lean manufacturing principles to engineering students. The methodology consisted of three main phases: module design, development of the digital twin model, and performance evaluation and analysis of the course.

3. Module Design and Participants:

The study was conducted within a senior-level undergraduate course on Lean Manufacturing and Quality Techniques, involving 40 senior engineering students. A dedicated laboratory module was developed to facilitate hands-on learning. The learning objectives for students included:

1. Identifying sources of muda (waste) within the system.
2. Calculating cycle time and balancing workloads across the production line.
3. Perform DPMO (Defects Per Million Opportunities) analysis and identify root causes.
4. Performing a comparative analysis of stamping methods.

The study executed as follows:

Phase I (Traditional Learning): Evaluation data were collected from student surveys after they were introduced to lean manufacturing principles through conventional lectures and manual lab exercises. Students were provided with two scenarios:

1. **Hammering** – Stickers were stamped using a wooden die and a manual hammering technique. This method relied heavily on human operation, resulting in variable stroke force and inconsistent motion.
2. **Manual Press** – A steel die was mounted on a mechanical press and operated manually. This setup reduced unnecessary operator movement and improved control over the stamping action.

These activities provided a baseline for comparison with the digital twin–based learning approach implemented in Phase II.

Phase II (Digital Twin–Based Learning): The same lean manufacturing concepts were reinforced using a digital twin model used in laboratory sessions. By building a full-featured digital twin within NVIDIA Omniverse, students moved beyond static diagrams and theoretical concepts. Near real-time data visualizations demonstrated how process variations directly impacted key performance indicators (KPIs), such as cycle time, production velocity, yield, and product quality. In addition to the previous two scenarios (Hammering and Manual Press), a third scenario was introduced:

- Automated Stamping Process – Using the digital twin platform, students analyzed the effects of different loads and punch speeds. This setup eliminated manual delays, resulting in a high-throughput, standardized system with predictable and stable performance.

To ensure high-fidelity simulations and practical relevance, the materials selected closely replicated industrial stamping operations:

- Servo Stamping Press: A servo-driven stamping press was employed to conduct stamping of stickers. The servo press allows precise control of ram position, speed, and force. Its programmable motion characteristics were particularly advantageous for analyzing cutting forces and material deformation behavior.
- Die Material: The die was made of mild steel due to its cost, machinability, and because it resists deformation under repetitive loading
- Sticker Material: The sticker was a composite structure with three layers: a 1 mm sticker label (paper), a 1.5 mm acrylic adhesive core, and a 0.5 mm bottom release layer. This was critical in measuring the cutting force required.
- Base Surface: A nylon board served as the pressing surface during manual testing, offering stability, shock absorption, and die protection.

4. Development of digital twin model

The design and analysis of the stamping die were performed entirely within Fusion 360, a widely adopted CAD/CAM platform used in both industrial and academic settings. The process began with reverse engineering the original die, followed by the redesign and optimization of a mild steel die to enhance performance (Figure 1).

The redesign focused on improving structural integrity, ensuring consistent stamping performance, and enabling seamless integration with subsequent simulation and testing stages. The stamping setup was implemented using Fusion 360's CAM-integrated force control, with a force application range of 10–250 N and a punch speed (stamping velocity) adjustable across 25 incremental steps. Precise part positioning was also defined within the simulation to enhance accuracy and repeatability. Outputs from the automated stamping method included time-

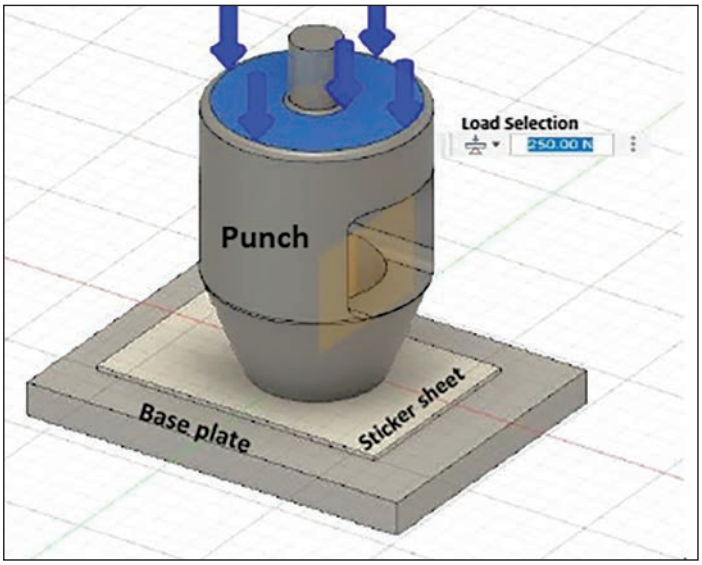


Figure 1. CAD model for the stamping process.

based deformation data and visualizations of stress distribution, providing insight into material behavior under varying process conditions.

Fusion 360 supports Universal Scene Description (USD) files, a universal format for 3D data that facilitates the integration of CAD models, simulation results, and real-time information within a single environment (Tran et al. 2023). In this workflow, CAD models designed in Fusion 360 were exported as USD files and imported into the NVIDIA Omniverse platform, which uses USD as its core format to enable real-time collaboration and photorealistic visualization. Simulation data was also integrated into Omniverse via the Omniverse ParaView Connector, bridging simulation outputs with the USD ecosystem and merging CAD models and simulation data into a cohesive digital representation. Real-time press data, including force, incremental velocity, and position, was streamed into Omniverse using the Omniverse Kit and connectors. The result is a fully integrated digital twin environment that combines engineering accuracy with real-time visualization, allowing interactive analysis, validation, and optimization of designs.

A virtual model of the sensor production line was developed using Siemens Tecnomatix software and subsequently linked into the NVIDIA Omniverse platform (Figure 2). Key performance indicators (KPIs) were tracked, which included cycle time, yield, defects per million opportunities (DPMO), and overall system efficiency. These metrics enabled a comprehensive evaluation of how

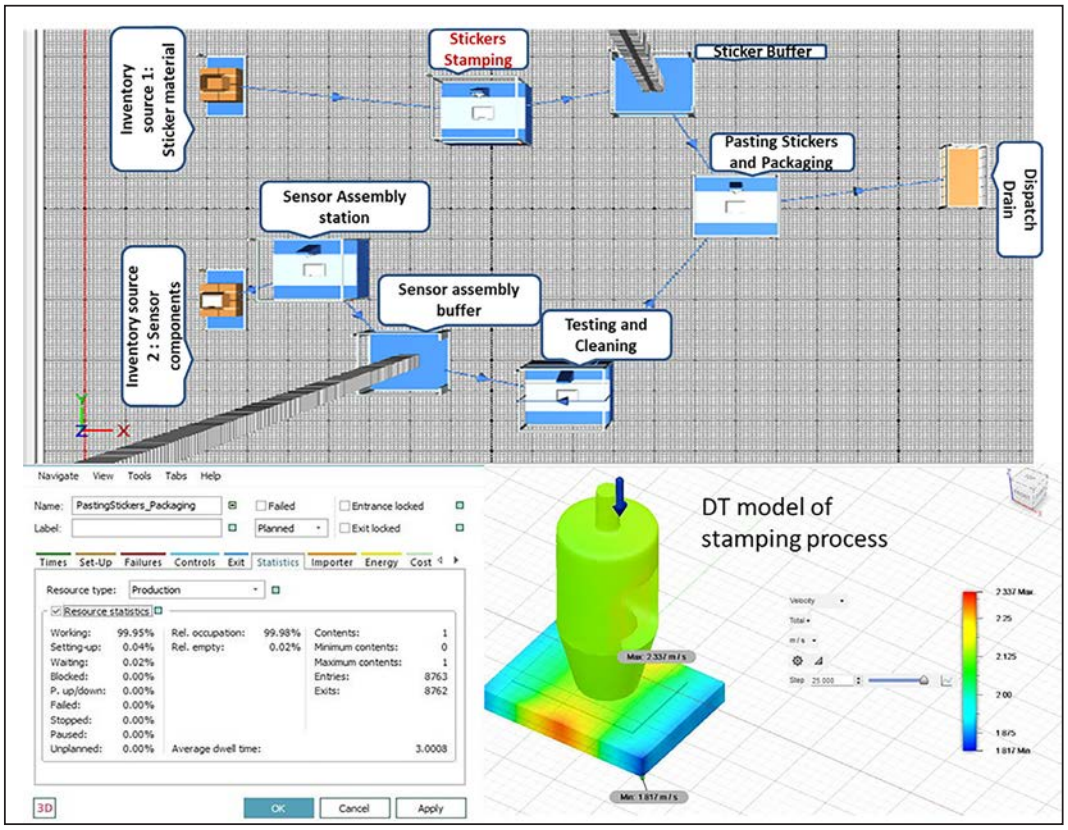


Figure 2. Digital twin for sensor manufacturing.

changes at the stamping station affected overall system output, highlighting the cumulative impact of localized process improvements on total manufacturing performance. This Production line model incorporates the following stations:

1. Inventory Source 1 & 2: Feeding raw material to the line
2. Assembly station: sensors are assembled
3. Buffer Zone: Temporarily held semi-finished items for synchronization
4. Testing and Cleaning Station: Ensured quality control before sticker application
5. **Stamping Station: The optimized stamping method was deployed here**
6. Sticker application and packaging Station: Applied stamped stickers to tested products and is identified as the pacemaker controlling takt time
7. Dispatch Drain: Completed products exited the system

4.2. Results and Discussion: Insights from the Digital Twin–Based Learning Activities

4.2.1 Reduction in Cycle Time

One of the primary goals of this study was to reduce the cycle time associated with the stamping operation. Figure 3 shows that the manual press decreased cycle time by nearly 18%, while the automated method provided an additional improvement, reducing total stamping time by 22% compared to hammering. This reduction in cycle time is brought by optimized stamping velocity and load selection.

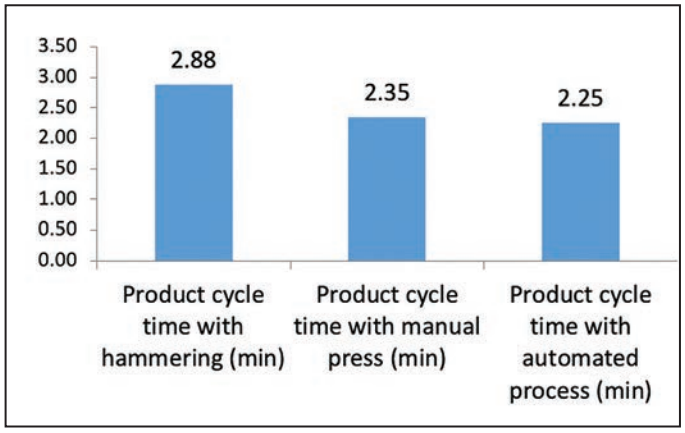


Figure 3. Decrease in cycle time of stamping process.

4.2.2 Quality Improvement Through DPMO Reduction

The transition from a traditional hammering process to a digitally optimized stamping approach resulted in a substantial improvement in quality, as measured by defects per million opportunities (DPMO). Manual operation generally produces fewer defects compared to hammering, primarily due to improved control over loading during the stamping process. While automated stamping methods achieved a DPMO of zero, demonstrating that the controlled force and part positioning application effectively eliminated inconsistencies in the stamping process (Figure 4). In contrast, the hammering method consistently produced defects due to its variability and lack of precision, further reinforcing the necessity for process redesign and controlled operational parameters.

4.2.3 Yield Increase at Six Sigma Levels

Yield is a fundamental performance metric in both Lean Production and Six Sigma methodologies. In this study, a significant increase in yield was observed—from 81% in the conventional hammering process to 100% under Six Sigma-compliant methods (Figure 5). This improvement is both statistically meaningful and economically impactful. Achieving a perfect yield not only enhances customer satisfaction but also leads to substantial reductions in material waste, rework, and labor costs—all of which are critical to driving a successful lean transformation.

While individual improvements in stamping processes are valuable, the true impact of lean manufacturing emerges when these localized enhancements lead to system-wide benefits (Garcia, Bregon, and Martínez-Prieto 2022). To evaluate this, a discrete digital twin model of the entire production line for a sensor product was developed. This model was used to analyze how optimization of the stamping process influenced overall production efficiency. Within the simulation, the packaging station was identified as the pacemaker, setting the system's takt time and governing the flow rate. As a result, improvements at upstream stations—particularly at stamping—needed to be carefully aligned to prevent issues such as underutilization or overproduction.

When the hammering method was used for stamping, its inconsistent output and frequent delays led to severe downstream bottlenecks. This was reflected in the system's total efficiency, which was limited to just 10%, accompanied by buffer over-accumulation, as well as idle time at packaging stations. Following the implementation of the manual press method, improvements in cycle time and yield significantly reduced idle times and rework in subsequent stages. The system-wide efficiency improved to 75%, with significant reductions in work-in-progress (WIP) inventory and pro-

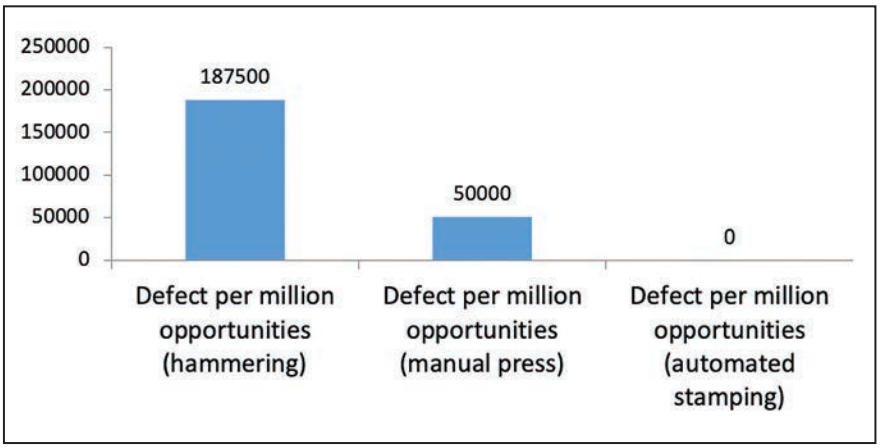


Figure 4. Decrease in DPMO.

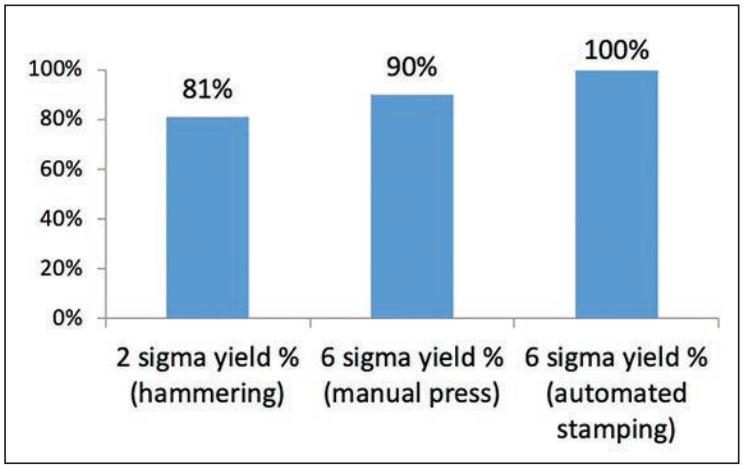


Figure 5. Increase in yield after achieving Six Sigma.

duction stoppages. Importantly, the buffer zone was better synchronized, maintaining a smooth material flow and reducing over-processing. The final transformation came with the adoption of the automated stamping process through digital twin. The speed, loading and positioning of the punch over base surface was controlled though DT model of stamping process. With the highest stamping velocity and a DPMO of zero, the system efficiency reached a staggering 99%. It was noted that the stamping station becomes capable of copying the rhythm of the pacemaker station and has developed the capabilities to abolish both upstream accumulations and downstream shortages. Through this study it was shown that even small and limited technical developments could trigger holistic excellence in operations.

5. Evaluation Metrics of the course

The results, based on a survey (Appendix A) of 40 senior-year engineering students and analyzed at a confidence level of 95% ($\alpha = 0.05$), indicate a substantial improvement in students' perceptions of the lean manufacturing course following the integration of digital twin–based learning (Table 1). Interest stimulation showed the highest increase, with the overall criterion improving by 93%, and individual items such as "The course content captured my interest and kept me engaged" and "The use of technology made the course more interactive and exciting" showing 100% improvement, reflecting the strong engagement and motivation generated by the interactive simulations. Content relevance increased by 34%, suggesting that students found the topics and exercises more closely aligned with real-world applications after using the digital twin, with consistent improvements across all items in this category. Support from course materials improved by 69%, highlighting that resources, independent usability, and instructor guidance were perceived as significantly more effective in aiding learning. Finally, overall satisfaction increased by 63%, with students reporting greater confidence in applying course concepts and acknowledging the positive contribution of the course to their learning. Collectively, these results demonstrate that the digital twin–based approach significantly enhanced student engagement, understanding, and perceived learning outcomes, with the improvements being statistically significant at the 5% level, validating its effectiveness as a teaching tool in lean manufacturing education.

Open-ended feedback emphasized that the digital twin approach was highly effective in making complex manufacturing concepts more tangible, interactive, and easier to understand. Learners particularly valued the hands-on experience and real-time visualization, which helped bridge the gap between theoretical knowledge and practical application. However, several participants suggested providing more in-depth tutorials and structured guidance on using software tools such as Fusion 360 and NVIDIA Omniverse to strengthen technical proficiency and confidence in applying digital twin concepts. Additionally, the module's pace was considered somewhat fast, with extensive coverage of traditional lean tools but limited time dedicated to exploring and learning from the digital platform.

Table 1. Lean Manufacturing course evaluation (average).

Evaluation Criteria	Lean manufacturing		Improvement
	Semester 1: Before	Semester 2: After	
Interest stimulation	**5.00**	**9.67**	**93%**
The course content captured my interest and kept me engaged	5.00	10.00	100%
The activities and exercises encouraged me to explore concepts further	5.00	9.00	80%
The use of technology made the course more interactive and exciting	5.00	10.00	100%
Content relevance	**6.00**	**8.03**	**34%**
The topics covered were relevant to current industry practices	6.00	8.00	33%
The course helped me understand practical applications of the course	6.00	8.00	33%
The exercises enhanced my understanding of real-world processes	6.00	8.10	35%
Support from course materials	**5.10**	**8.60**	**69%**
Resources (slides, readings, and tutorials) were helpful for learning	5.00	8.50	70%
I was able to use the course materials independently to complete tasks	5.00	8.70	74%
The instructor provided adequate support and clarification during the exercise	5.30	8.60	62%
Overall satisfaction	**5.39**	**8.76**	**63%**
The course met my expectations regarding learning outcomes	5.40	8.80	63%
I feel more confident applying course concepts after this course	5.30	8.70	64%
This course contributed positively to my learning	5.46	8.77	61%

The box plot analysis of the 40-student course evaluation data clearly illustrates the substantial impact of integrating digital twin-based learning into the lean manufacturing course (Figure 6). For all four evaluation criteria - Interest Stimulation, Content Relevance, Support from Course Materials, and Overall Satisfaction - the "After" box plots are positioned significantly higher than the "Before" plots, showing a strong upward shift in student responses. The median scores increased from approximately 5–6 in Semester 1 (before implementation) to around 8.5–9.5 in Semester 2 (after implementation), indicating a marked improvement in perceived engagement, relevance, and learning effectiveness. Moreover, the boxes in the "After" plots are narrower, suggesting reduced variability and more consistent positive feedback across the class. The whiskers for the after scores extend toward the upper end of the scale (8–10), with few or no low outliers, emphasizing that nearly all students benefited from the new teaching approach. This visual distribution supports the statistical findings of a 63% overall improvement, confirming that digital twin-based instruction significantly enhanced students' learning experience.

6. Discussion

This study explores the implementation of digital twin technology for lean manufacturing and its impact on student learning. It investigates how integrating digital twins into educational settings can enhance students' practical understanding of industrial processes, develop critical problem-solving and decision-making skills, and provide hands-on learning experiences aligned with Industry 4.0 advancements.

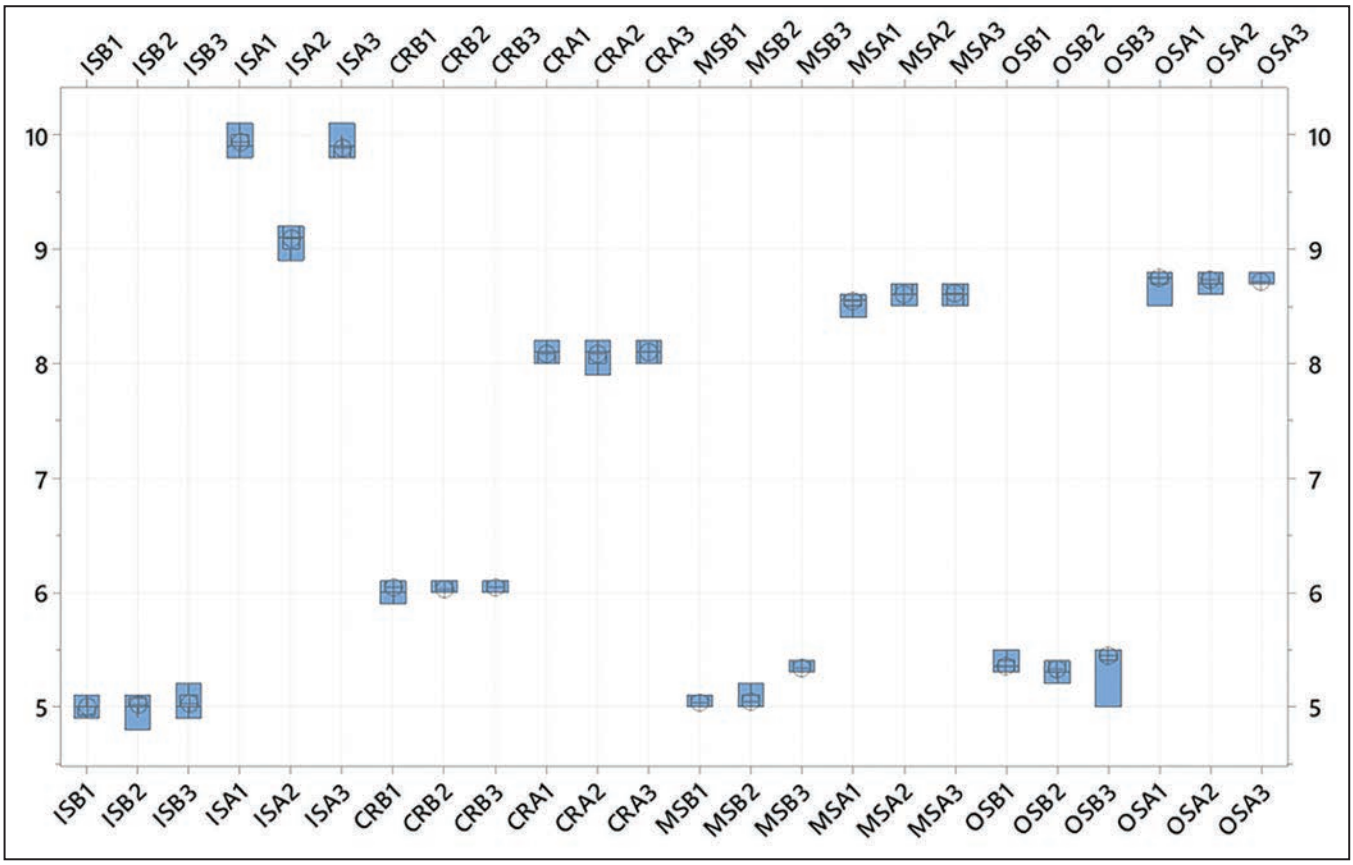


Figure 6. Box plot illustrating student evaluation scores before (B) and after (A) the implementation of digital twin–based learning across four criteria: IS1–IS3 (Interest Stimulation), CR1–CR3 (Content Relevance), SM1–SM3 (Support from Course Materials), and OS1–OS3 (Overall Satisfaction).

Within the digital twin environment, students engaged with real-time simulations of a manufacturing system, making decisions such as selecting stamping force levels or stamping velocity, and observing the downstream effects on system performance. This interactive, data-driven approach enabled students to witness the immediate consequences of their decisions, bridging the gap between theoretical knowledge and practical application. A key advantage of digital twin-based learning lies in its ability to make traditionally "invisible" forms of waste—such as waiting time, excess inventory, over-processing, and unnecessary motion—tangible. Through DT, students could observe how inefficiencies manifest dynamically within a production system. This visualization allowed learners to better diagnose problems, discuss solutions, and propose targeted improvements, which are often difficult in conventional textbook-based curricula that rely on theoretical instruction, Gemba walks, or visual boards for tracking metrics.

From a pedagogical perspective, the module aligns with several established learning theories. According to Kolb's experiential learning theory (Kolb 2014), learning is most effective when learners engage in concrete experiences, reflect on their observations, conceptualize insights, and actively experiment. The digital twin environment supports this cycle by enabling iterative experimentation and immediate feedback. The module also fosters situated learning (Lave and Wenger 1991), as students engage in tasks closely resembling authentic industrial scenarios, thereby promoting the transfer of knowledge to real-world applications. Furthermore, it supports cognitive apprenticeship (Collins, Brown, and Newman 2018), allowing learners to acquire expertise through guided interaction with complex systems. This experiential, data-driven approach enhances analytical and critical thinking skills, as students interpret simulation outputs, identify inefficiencies, and propose process optimizations. By integrating digital twins, students interact with complex, data-rich environments, strengthening computational thinking, digital literacy, and systems thinking, key competencies for Industry 4.0, thereby fostering technology-enhanced learning (Redecker and Punie 2017). Moreover, the module incorporates gamification and motivational learning (Deterding et al. 2011), as simulation-based tasks with real-time feedback and observable out-

comes increase engagement, motivation, and intrinsic learning drive. Together, these pedagogical foundations create a highly immersive, interactive, and reflective learning experience that bridges theory and practice, equipping students with both the technical skills and cognitive abilities required for modern engineering and manufacturing environments.

This study has several limitations. First, the digital twin was implemented in a controlled setting, which may not fully capture the complexities and variability of real-world manufacturing environments. Broader adoption of digital twin technology is further challenged by factors such as a shortage of skilled personnel, limited funding, a lack of a formal implementation strategy, and insufficient training to develop and operate digital twins effectively. Second, the sample size for feedback and evaluation was relatively small, limiting the generalizability of the findings. Third, the study primarily focused on integrating digital twins with lean manufacturing concepts and relied on specific software platforms, so the results may not be directly applicable to other tools or ecosystems. Future work can address these limitations by implementing digital twins in diverse industrial settings, including quality control, supply chains and/or predictive analytics, providing a more comprehensive understanding of DT benefits in engineering education. Exploring alternative software platforms and interoperability standards would enhance the scalability and adaptability of the approach. Additionally, ensuring that adequate funding is available and providing targeted training for personnel would facilitate broader adoption and effective utilization of Industry 4.0/5.0 technologies. Finally, longitudinal studies tracking skill development and process improvements over time would offer deeper insights into the long-term educational value of digital twin integration.

7. Conclusion

This paper presents a novel educational framework that integrates digital twin technology with lean manufacturing principles to enhance engineering education. Focusing on the stamping process of sensor manufacturing, the study demonstrates how digital modeling and real-time simulations can enhance student engagement and learning outcomes. Beyond these quantitative results, the work emphasizes the pedagogical value of teaching lean manufacturing through interactive, real-time simulation environments. Rather than being passive recipients of lean concepts, students actively identified inefficiencies, implemented corrective actions, simulated outcomes, and validated improvements using digital twin models. This approach effectively bridges the gap between classroom theory and real-world application, transforming lean manufacturing from an abstract concept into a practical capability.

As engineering education evolves to meet the demands of Industry 4.0, integrating digital twins and data-driven simulations into the curriculum becomes increasingly essential. This study presents a replicable model where process optimization, lean manufacturing education, and smart manufacturing technologies converge, equipping students to become future-ready engineers. the key contributions of this study to engineering education are:

1. This study demonstrates how digital twin technology can be effectively combined with lean manufacturing principles to create immersive, interactive learning experiences that bridge the gap between theory and practical application.
2. The approach fosters critical problem-solving, decision-making, and analytical thinking by allowing students to experiment with real-time simulations, observe immediate consequences, and identify inefficiencies in a manufacturing process.
3. By making traditionally intangible forms of waste, such as waiting time, over-processing, and unnecessary motion, visible within a simulated environment, students can better diagnose problems and propose targeted improvements.
4. The framework supports experiential, situated, and cognitive apprenticeship learning, promoting iterative experimentation, reflection, and knowledge transfer, and provides a foundation for broader implementation of digital twins in educational settings, including scalability, interoperability, and longitudinal skill assessment.

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Appendix

Course Evaluation Survey
Course Title:
Semester/Term:
Instructor Name:
Please rate the following statements about the course on a scale of 1 to 10, where 1 = Strongly Disagree and 10 = Strongly Agree.

Interest stimulation	
The course content captured my interest and kept me engaged.	
The activities and exercises encouraged me to explore concepts further.	
The use of technology made the course more interactive and exciting.	
Content Relevance	
The topics covered were relevant to current industry practices.	
The course helped me understand practical applications.	
The exercises enhanced my understanding of real-world processes.	
Support from Course Materials	
Resources (slides, readings, and tutorials) were helpful for learning.	
I was able to use the course materials independently to complete tasks.	
The instructor provided adequate support and clarification during exercises.	
Overall Satisfaction	
The course met my expectations regarding learning outcomes	
I feel more confident applying course concepts after this course.	
This course contributed positively to my learning.	

Open-ended feedback:

What did you like most about this course?
What improvements would you suggest?

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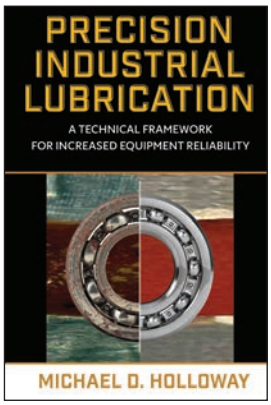
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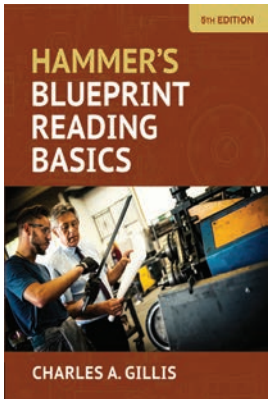


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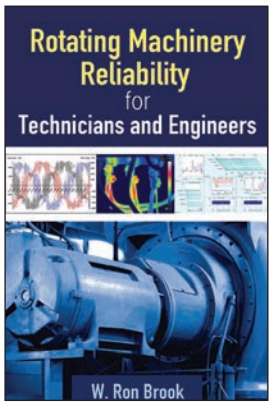
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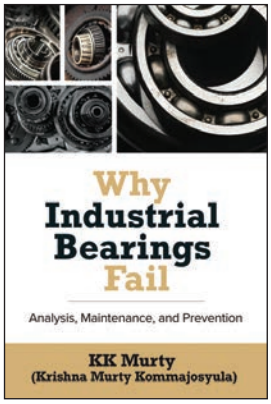
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Low-Cost Desktop Learning Modules: Effect of Implementation Types on Student's Learning Performance

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Abstract

Low-Cost Desktop Learning Modules (LCDLMs) are affordable, interactive instructional tools designed to enhance conceptual understanding in engineering education. With the appreciation that engagement of learners in interactive, constructive, active and passive frameworks produces different levels of learning, these modules promote deeper learning by engaging students through hands-on, constructive, or interactive activities. This study investigated the effects of three implementation types—virtual, hands-on, and traditional lecture—on undergraduate engineering students' learning outcomes across three specific LCDLMs: the Hydraulic Loss module, Venturi meter, and Double Pipe heat exchanger. A total of 918 students from fluid mechanics and thermodynamics courses participated. Results from the study revealed that students in the virtual implementation group significantly outperformed those in the hands-on and control groups. Among the module types, the Hydraulic Loss module led to the highest posttest performance. These findings underscore the potential of LCDLMs to optimize active learning strategies and suggest that virtual implementations may offer scalable and effective solutions for integrating technology-enhanced, hands-on learning experiences in engineering curricula.

1. Introduction

In the evolving field of engineering education, enhancing student engagement and learning outcomes through innovative instructional methods is a critical objective (Kaiphanliam et al. 2021). One significant innovation is the use of Low-Cost Desktop Learning Modules (LCDLMs), designed to provide hands-on, practical learning experiences at an affordable cost. These modules bridge the gap between theoretical concepts and real-world applications, allowing students to directly engage with engineering principles (Kaiphanliam et al. 2021). Research highlights that LCDLMs, with their interactive and transparent components, make abstract concepts more tangible and comprehensible, thereby fostering a deeper understanding and retention of the material (Reynolds et al. 2022). Research describe DLMs as low-cost tools designed to aid student comprehension, with a target cost comparable to a textbook (Khan et al. 2022).

LCDLMs offer pedagogical advantage by facilitating the management of intrinsic cognitive load, which refers to the mental effort required to comprehend complex or unfamiliar information (Sweller, 1988; Paas et al 2003). A hands-on, interactive design such as LCDLM can enhance learning of essential information more effectively. This is particularly beneficial in domains characterized by high content complexity, such as fluid dynamics and heat transfer. Consequently, LCDLMs apply principles that reduce extraneous cognitive load and promote interactive/constructive engagement, addressing limits of lecture-only instruction (Reynolds et al. 2022; Khan et al. 2022; Freeman et al. 2014; Chi and Wylie 2014; Menekse et al., 2013).

Research has argued that low socioeconomic status is the biggest barrier to STEM participation (Taylor & Francis Group 2020). Therefore, an affordable teaching tool like LCDLM would be beneficial for promoting inclusivity and access in engineering. LCDLMs were specifically designed to help engineering students explore fundamental principles in fluid mechanics and heat transfer (Durak 2023; Wong et al. 2024). One of the benefits of LCDLMs is their ability to visually demonstrate complex engineering phenomena, making them easier to understand (Reynolds et al. 2022). These visual tools are particularly effective in clarifying critical engineering concepts, such as delineating system boundaries for calculating heat transfer rates in heat exchangers and assessing fluid velocity in pipes. The broad-reaching potential of LCDLMs greatly enhances educational practices in engineering. LCDLM significantly enhances engineering education by aligning with core principles of constructivist learning theory, which emphasizes the importance of active engagement,

hands-on manipulation, and observation in the construction of knowledge. Berlyne , Piaget and Malcolm (2003) argued that learners build cognitive structures through direct interaction with their environment, especially during problem-solving and experimentation. Similarly, Vygotsky (1978) emphasized the sociocultural context of learning, highlighting how guided participation in hands-on tasks within the learner's zone of proximal development fosters deeper understanding. Therefore, high level students' engagement with selected academic content through visual learning experiences will be associated with positive learning outcome (Watson et al. 2022).

LCDLMs reflect these principles by enabling students to physically manipulate components, observe system responses, and engage in exploratory learning activities that promote conceptual change and mental model development. LCDLMs models are further supported by the ICAP framework, which highlights how LCDLMs facilitate student engagement and deeper understanding (Taylor & Francis Group 2020; Durak 2023; Wong et al. 2024).

The ICAP framework categorizes learning activities into four distinct types: Interactive (I), Constructive (C), Active (A), and Passive (P). Accordingly, Durak (2023) noted that learning activities that necessitate more intensive engagement, such as interactive and constructive activities, are more effective for learning compared to those that involve lesser degrees of engagement, such as active and passive activities. Specifically, the framework posits that interactive engagement facilitates superior cognitive involvement compared to constructive engagement, which in turn is more beneficial than active engagement. Active engagement, while more involved than passive engagement, still ranks lower in promoting cognitive engagement than either interactive or constructive engagement. Recognizing the importance of hands-on learning, educators created small-scale, cost-effective versions of industrial equipment to offer practical learning experiences (Kaiphanliam et al. 2021; Berlyne , Piaget and Malcolm. 2003; Menekse et al., 2013).

Spatial reasoning ability plays a critical role in engineering education, enabling students to visualize, manipulate, and interpret complex systems and structures (Zhou et al. 2024). Research has demonstrated that spatial abilities are strong predictors of success in STEM fields—often above and beyond other cognitive skills—particularly in relation to engagement in STEM activities and the pursuit of advanced education in these domains (Wai, Lubinski and Benbow 2009; Zhou et al. 2024). In engineering specifically, students with higher spatial visualization skills tend to perform better in tasks involving three-dimensional comprehension, mental rotation, and the application of abstract principles to physical systems. LCDLMs are well-positioned to support the development of spatial skills by offering students direct, hands-on experiences with physical models that reflect core engineering concepts. These modules encourage learners to observe real-time system responses, manipulate components, and mentally translate between theoretical representations and mechanical behaviors. Such active engagement fosters the refinement of spatial reasoning abilities through iterative visual, tactile, and cognitive interaction (Khan et al. 2022). In this way, LCDLMs not only enhance conceptual understanding but also nurture a set of cognitive skills that are foundational for long-term success in engineering and STEM pathways.

Active learning literature shows that interactive methods generally outperform traditional lectures (Freeman et al. 2014; Watson et al. 2022), though effectiveness depends on contextual factors such as instructor proficiency and student prior knowledge. Simple module design like hydraulic loss often yields larger gains, while more complex designs, such as the Venturi meter, tend to produce smaller effects. Structured implementation and instructor preparation can further enhance outcomes (Deslauriers, Schelew and Wieman 2011), and LCDLMs may particularly benefit students with lower prior knowledge (Watson et al. 2022).

Research on the effectiveness of LCDLMs in engineering education has produced mixed results. In prior work, the hands-on hydraulic loss module significantly outperformed its virtual counterpart, whereas the double pipe module showed minimal differences between formats (Reynolds et al. 2022), likely due to the more visual nature of the hydraulic loss phenomena and stronger alignment of its assessments with observable concepts. For the Venturi meter LCDLM, measured values closely matched theoretical predictions, confirming its accuracy for instructional use. Comparisons of hands-on and virtual implementations revealed no significant differences in learning gains, indicating that virtual delivery can be as effective as in-person instruction (Van Wie et al. 2022). While previous studies have compared individual LCDLMs—such as hydraulic loss, double pipe, and old versus new versions of the shell-and-tube and Venturi—most have done so in isolation or in combinations of only two modules (Hunsu, Adesope and Van Wie 2017, Reynolds et al. 2022). Few have directly compared three or all four modules on learning performance within the same study. Such comprehensive comparisons are valuable not only for identifying relative effectiveness across modules but also for generating consistent datasets

that can inform future systematic reviews or meta-analyses on LCDLM implementation in engineering education.

2. Implementation Types

Research indicates that hands-on learning significantly enhances student engagement, comprehension, and conceptual understanding. Particularly through LCDLMs, hands-on approaches reinforce theoretical knowledge by allowing students to directly interact with learning materials and experiment in meaningful ways (Kaiphanliam et al. 2021; Reynolds et al. 2022). These methods also increase student motivation. However, they can be resource-intensive and less scalable due to the need for physical presence and specialized materials, which may be limited in certain instructional contexts (Reynolds et al. 2022).

In contrast, virtual tools—such as videos and simulations—offer scalable, flexible learning opportunities, especially useful when in-person instruction is not feasible, as during the COVID-19 pandemic (Merchant et al. 2014; Van Wie et al. 2022). Studies on virtual learning environments more broadly have found that students using video-based or simulation-based demonstrations can achieve learning gains comparable to those using physical setups (Van Wie et al. 2022 ; Hunsu, Adesope and Van Wie 2017). Well-designed virtual settings can, in some contexts, match or even exceed the learning outcomes of physical formats by providing structured, distraction-free spaces where learners can proceed at their own pace, revisit content, and concentrate on essential concepts without the logistical constraints of physical setups (Sweeney et al. 2022). Broader research on virtual instruction also highlights its capacity to expand access to complex or abstract phenomena that are difficult to replicate in physical settings (Li and Liang 2024) and can boost motivation for learners with limited hands-on experience (Mahendra and Killis 2025).

Traditional lecture-based methods remain widely used, offering a consistent structure and serving as a useful baseline for comparing the effectiveness of innovative strategies. However, recent studies comparing hands-on and virtual methods suggest that transitioning to virtual formats does not compromise learning outcomes. Comparable improvements in student performance have been observed in both delivery modes (Hunsu, Adesope and Van Wie 2017), underscoring the need for continued research to determine the optimal conditions for each type of implementation.

The purpose of this study is to examine the effectiveness of three Low-Cost Desktop Learning Module (LCDLM) implementation types—virtual, hands-on, and traditional lecture—on undergraduate engineering students' academic outcomes. Although prior research has demonstrated the pedagogical value of LCDLMs in fostering engagement and conceptual understanding (Kaiphanliam et al. 2021; Reynolds et al. 2022), limited evidence exists on how different implementation types influence their effectiveness in engineering contexts. This study extends the literature by validating the conditions under which these approaches can be optimally employed to enhance student learning. Data were collected from participants across Fall and Spring 2022, increasing the generalizability of findings within a single academic year. While the study does not assess long-term retention or transfer, it addresses a critical gap by providing empirical insights into the immediate effects of different implementation types. Specifically, it investigates how both implementation type and LCDLM design affect student learning, guided by the following research questions:

RQ1: What is the effect of LCDLM implementation types on undergraduate engineering students' learning performance?

RQ2: To what extent do different LCDLMs influence undergraduate engineering students' learning performance?

3. Methodology

3.1. Participants

Participants consisted of 918 (Female 31.4%; Male; 62.0%; Non-binary 1.5%; Prefer not to answer 1.3%) postsecondary undergraduate engineering students enrolled in heat transfer and fluid mechanics courses across 8 different schools in the United States. The majority of students reported being of white ethnicity (Native American 0.6%; Asian 9.8%; Black/African American 7.7%; Hispanic 4.4%; International 1.7%; White 73.6%; Mixed 1.1%; Prefer not to answer 1.1%) and in their junior year of college (Freshman 0.2%; Sophomore 13.9%; Junior 64.8%; Senior 20%; Graduate (Masters) 0.3%; Graduate (PhDs) 0.6%; Prefer not to answer 0.1%). Participants were primarily undergraduates (96%) enrolled in engineering courses related to fluid mechanics and thermodynamics between the semesters of Fall 2021 and Spring 2022. Student recruitment was conducted in-class by instructors, who, along with their teaching assistants, received specific training prior to the study's implementation. Student participation in the study was voluntary. Assignment to instructional mode (LCDLM or control) was not randomized but was determined by whether their instructor opted to implement the LCDLMs or continue with standard instruction. This study was approved by Washington State University's Institutional Review

Board. Instructors received standardized training, with materials—including video demonstrations, PowerPoint slides, and detailed instructions—shared via OneDrive. To protect participant confidentiality, all identifying information was removed, and pseudonymous codes were assigned to each student. This study was approved by Washington State University's Institutional Review Board.

3.2. LCDLM Implementation Descriptions

To help teach and demonstrate abstract engineering concepts, learning modules and materials for four LCDLMs were created and used: double pipe, hydraulic loss, shell & tube, and Venturi meter. The hydraulic loss, double pipe, and Venturi LCDLMs are low-cost, small-scale devices fabricated using injection molding, robotically assisted adhesive application, and 3D printing. The hydraulic loss module features a constant-diameter pipe with four standpipe manometers for observing head loss. The double pipe heat exchanger has a transparent annular shell for visualizing fluid flow patterns. The Venturi meter, made from ABS and PETG, enables observation of velocity and pressure changes. Battery-operated pumps circulate colored water, and students collect measurements to calculate each module's key engineering parameters.

However, only three modules were included in this study - double pipe, hydraulic loss, and Venturi meter. The Shell & Tube Module for Virtual and Control groups were unavailable for virtual and traditional conditions; therefore, Shell & Tube Module was removed from this study. Professors and teaching assistants at the participating universities were provided training videos and materials on the LCDLMs by the research team. Three modes of instruction for the LCDLMs were available to the participants throughout the academic session. Students engaged with LCDLM content through one of three modes: (1) traditional lecture (control), (2) hands-on use of a physical LCDLM, or (3) virtual instruction using videos and simulations. Instructors selected the implementation mode for their course, and integration into the curriculum was aligned with relevant topics such as fluid mechanics or heat transfer. While the core content was consistent, the depth and timing of implementation varied slightly across instructors and institutions based on instructional preferences and logistical factors (see Figures 1.1 to 1.3).

3.3. Measures

3.3.1 Learning Performance

The pre- and posttests were developed by the research team in collaboration with experienced engineering faculty and aligned with the specific learning objectives of each LCDLM module. The number of pre and posttest items ranges from six to nine questions. The test items have been refined and used across multiple course offerings over the past three years, supporting their content validity and practical utility in assessing key engineering concepts such as fluid mechanics and heat transfer. Expert instructors with over a decade of teaching and research experience reviewed the items to ensure relevance and alignment with instructional content. While formal construct validation was not conducted, internal consistency reliability was acceptable (Cronbach's alpha = 0.74). The tests included conceptual multiple-choice, true/false, and open-ended questions.

3.4. Procedure

During two academic semesters, faculty at participating universities implemented LCDLMs as instructional tools to facilitate student learning in fluid mechanics and heat transfer. All participants received a minimum of 50 minutes of weekly instruction, delivered through one of three modes: traditional lecture, hands-on, or virtual instruction. Instructors in



Figure 1.1. Example of double pipe.

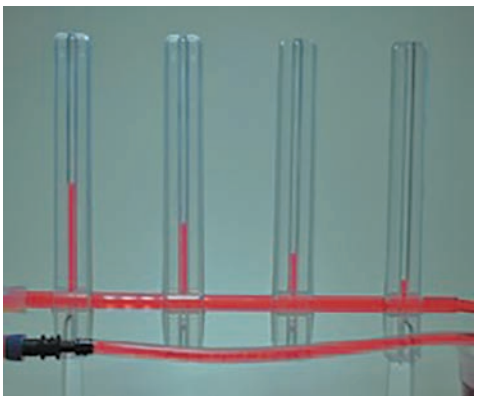


Figure 1.2. Example of hydraulic loss.

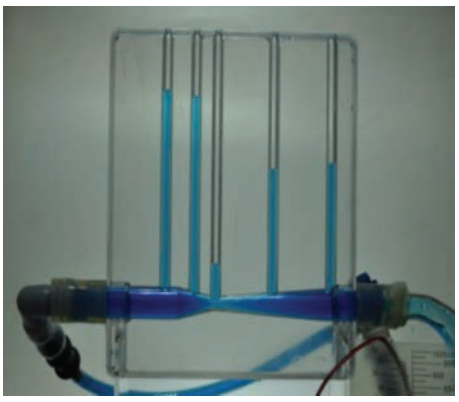


Figure 1.3. Example of Venturi meter.

the virtual condition used a combination of Zoom and YouTube for synchronous instruction, conducting live sessions and sharing pre-recorded demonstrations to enhance flexibility and accessibility. As modules were implemented, students were informed of the opportunity to participate in our study and were provided consent forms if they decided to participate. Students who consented were also given a demographic survey via Qualtrics. Before engaging in a LCDLM activity, students completed a pretest related to the topic. After the LCDLM activity, they were given the corresponding posttest. Data were collected from both in-person and online settings. The pre-test and post-test were both administered via Qualtrics. The pre-test was administered before students started working on the LCDLMs and the post-test was administered after completion of LCDLM learning activities.

3.5. Data Analysis

A one-way Analysis of Covariance was conducted to examine the effect of LCDLM implementation type (virtual, hands-on, or traditional lecture) on students' posttest performance, controlling for pretest scores. All ANCOVA assumptions—normality, homogeneity of variances, linearity, and homogeneity of regression slopes—were tested and met. Instructional mode was not randomized but determined by whether instructors adopted LCDLMs or continued with standard instruction. To minimize bias, student module use was guided and monitored. The Shell & Tube module was implemented exclusively within the hands-on LCDLM condition; therefore, it was excluded from the analysis due to concerns about threats to internal validity and lack of comparability across implementation types. Additionally, missing data associated with Shell & Tube module, which was only implemented in the hands-on condition, were handled in accordance with best practices for addressing structurally missing data (Allison 2009).

4. Results

4.1. Preliminary Analysis

Prior to data analysis, the accuracy of data entry, missing values, outliers, and distribution normality were assessed. Skewness values ranged from -1.03 to 0.76 and kurtosis from -1.05 to 0.12 for implementation type, LCDLMs, pretest, and posttest scores—indicating acceptable univariate normality [25]. To determine whether students began the study with comparable levels of prior knowledge, a one-way analysis of variance (ANOVA) was conducted. The independent variable was LCDLM implementation type, and the dependent variable was the pretest score. Results revealed a significant difference in pretest performance across groups, F (2, 850) = 24.74, p < .001. Students in the Venturi group (M = 0.55, SD = 0.02) outperformed those in the Double Pipe group (M = 0.51, SD = 0.01) and the Hydraulic Loss group (M = 0.43, SD = 0.01). Because these differences indicate unequal starting points, pretest score was included as a covariate in subsequent analyses to statistically control for prior knowledge and strengthening the internal validity (See Table 1.1 and Figure 1.4 for descriptive statistics).

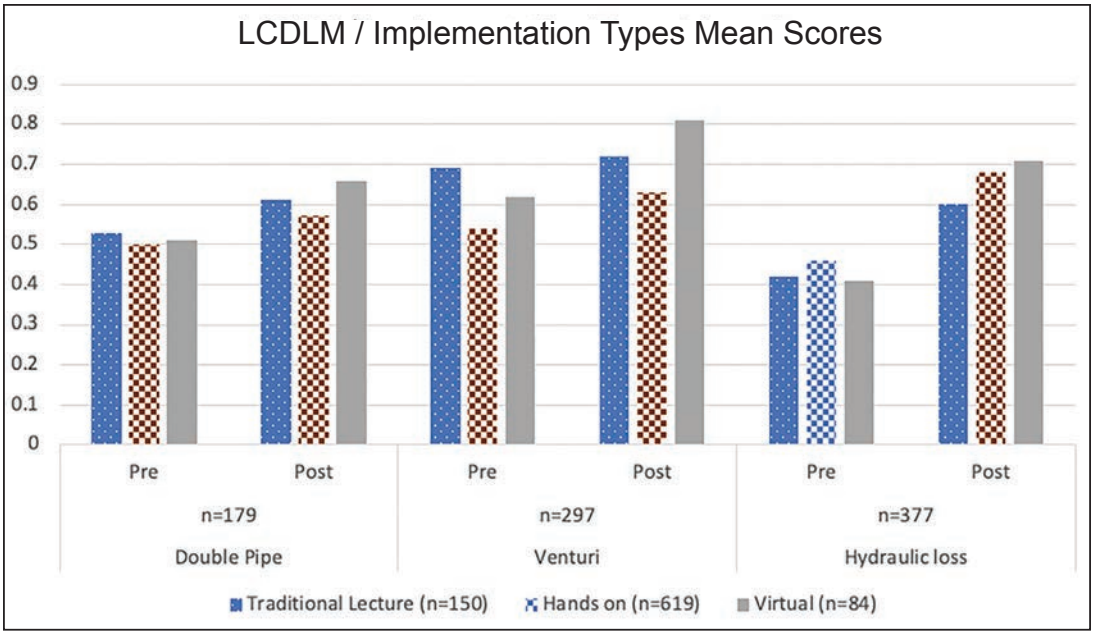


Figure 1.4. LCDLM Implementation Types Descriptive Statistics Bar Chart.

Table 1.1 LCDLM implementation types descriptive statistics

LCDLM	Double Pipe (n = 179)		Venturi (n = 297)		Hydraulic Loss (n = 377)	
Implementation	**Pre**	**Post**	**Pre**	**Post**	**Pre**	**Post**
Traditional Lecture (Control) (n = 150)	M = 0.53 SD=0.16	M= 0.61 SD= 0.24	M= 0.69 SD=0.13	M= 0.72 SD= 0.14	M= 0.42 SD=0.28	M= 0.60 SD= 0.33
Hands-On (n = 619)	M= 0.50 SD=0.18	M= 0.57 SD= 0.21	M= 0.54 SD=0.18	M= 0.63 SD= 0.20	M= 0.46 SD=0.32	M= 0.68 SD= 0.29
Virtual (n = 84)	M= 0.51 SD=0.36	M= 0.66 SD= 0.19	M= 0.62 SD=0.16	M= 0.81 SD= 0.14	M= 0.41 SD=0.28	M= 0.71 SD= 0.30

4.2. LCDLM implementation types and learning performance.

To address the first research question regarding the effect of LCDLM implementation types on learning performance, a one-way analysis of covariance (ANCOVA) was conducted. The analysis examined differences in learning performance across implementation types—Virtual, Hands-on, and Control—while statistically controlling for prior knowledge (pretest scores). Results revealed a significant effect of implementation type on learning performance (posttest scores), F (2, 914) = 6.33, p < .002, partial eta squared = .014. Post-hoc comparisons using the Tukey HSD test indicated mean scores for the Virtual group (M = 0.72, SD = 0.28), Hands-On (M = 0.64, SD = 0.25), and Control (Traditional lecture) (M = 0.61, SD = 0.24). See Table 1. 2 below:

4.3. LCDLM and Learning Performance

To address the second research question, a one-way ANCOVA was conducted to compare the effect of LCDLM types on posttest scores controlling for prior knowledge (pretest). There was a statistically significant effect of LCDLM types on posttest scores, F (2, 849) = 11.81, p < .001, partial eta squared = .032. Results showed that the mean score for the Hydraulic Loss group (M = 0.67, SD = 0.02) outperformed both the Venturi group (M = 0.65, SD = 0.19) and the Double Pipe group (M = 0.58, SD = 0.20). No significant difference was found between the Venturi and Double Pipe conditions. Although the differences were statistically significant, the small effect sizes (partial η^2 = .014 and .032) indicate that Implementation accounted for only a small portion of the variance in learning performance (posttest scores). This suggest that other factors may have contributed to the student learning performance. See Table 1.3 below:

Table 1.2 LCDLM Implementation Types ANCOVA.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.	Partial Eta Squared
Pretest	2.23	1.00	2.23	37.43	0.00	0.039
Implementation	0.75	2.00	0.38	6.33	0.00	0.014
Error	54.36	914	0.06			
Total	441.66	918				

Table 1.3 LCDLM ANCOVA.

Source	Type III Sum of Squares	Df	Mean Square	F	Sig.	Partial Eta Squared
Pretest	2.25	1.00	2.25	37.15	0.00	0.042
LCDLM	1.43	2.00	0.71	11.81	0.00	0.032
Error	51.34	849	0.06			
Total	414.93	853				

5. Discussion

Present research examined the effect of LCDLM Implementation types on undergraduate student engineering learning. Contrary to previous research, we found that the virtual LCDLM implementation had outperformed both hands-on and lecture-based methods, which is particularly notable. This contrasts with prior research reporting that hands-on LCDLM activities yielded greater learning gains than virtual implementations (Reynolds et al. 2022). and with studies suggesting no significant difference in effectiveness between physical and digital implementations (Van Wie et al. 2022). The findings indicate that, in this context, well-designed virtual environments can simulate hands-on experiences effectively and, in some cases, surpass them in promoting learning outcomes.

This result suggests that well-designed virtual environments can effectively simulate—and in some contexts surpass—hands-on learning. A plausible explanation is that virtual LCDLMs offer a structured, distraction-free environment where students can work at their own pace, revisit demonstrations, and focus on key concepts without the logistical demands of physical setups (Sweeney et al. 2022). They also expand access to complex or abstract phenomena difficult to replicate physically (Li and Liang 2024) and can enhance motivation and engagement, particularly for students with limited prior hands-on experience (Mahendra and Killis 2025). Imperatively, deep students' engagement with academic contents through virtual learning experiences is linked to high positive learning outcome (Yanik et al. 2021). These benefits align with research on the scalability and accessibility of virtual methods during periods of limited physical interaction, such as the COVID-19 pandemic (Van Wie et al. 2022; Merchant et al 2014), and with evidence that consistent, repeatable experiences support learning without the constraints of physical resources or time (Winn 1993). The findings also suggest that hands-on instruction, without additional scaffolding, may be no more effective than traditional lectures—a conclusion consistent with evidence that minimally guided, discovery-based activities often yield limited gains without sufficient instructional support (Sweller, Kirschner and Clark 2007). Future research should investigate the conditions under which virtual methods are most effective.

Consistent with past research, we found hydraulic loss module outperformed other types of LCDLMs (Double pipe & Venturi meter) in learning performance (Durak, 2023; Watson et al. 2022). Students with higher engagement—especially those interacting with modules like hydraulic loss—demonstrated significantly greater posttest gains (Reynolds et al. 2022). This suggests that modules with high concept specificity allows students to grasp key concepts more effectively, leading to improved learning performance (Khan et al. 2022, Van Wie et al. 2022). These finding highlights how different LCDLMs contribute uniquely to student learning and cognitive processing. While LCDLMs have generally been shown to enhance engagement (Khan et al. 2022; Watson at el. 2022), our study extends this understanding by demonstrating that certain module types—such as the hydraulic loss module—may yield greater learning gains. One possible explanation is that the hydraulic loss module addresses foundational concepts with clear, observable cause-and-effect relationships, making it more accessible to students. Its relatively straightforward design may also reduce extraneous cognitive load, allowing learners to focus on core principles and applications. This suggests that the cognitive complexity and instructional clarity of individual modules play a critical role in their effectiveness.

Although LCDLMs have been shown to improve learning performance, this study examines whether these improvements are consistent across different implementation types (Kaiphanliam et al. 2021). This research contributes to the field by addressing the limited empirical evidence regarding the replication and validation of the impact of LCDLMs on learning performance, as noted by (Watson et al. 2022). This research enhances our understanding of certain boundary conditions under which different LCDLM types might be optimally employed. These results have significant implications for educational practice, particularly in STEM fields where both hands-on and virtual learning are commonly employed. The demonstrated effectiveness of virtual simulations suggests that engineering programs and instructors should consider integrating more virtual elements into their curricula to complement and potentially enhance traditional instructional methods when using LCDLMs. The virtual element may enhance engineering education by enabling accessible, interactive simulations and remote labs that integrate seamlessly with curricula to potentially improve student engagement and learning outcomes. Furthermore, the finding that virtual LCDLM implementations outperformed both hands-on and traditional lecture approaches in learning performance supports the broader conclusion that the method of content delivery can substantially influence student outcomes. This underscores the importance of deliberately selecting instructional strategies that align with the intended learning goals and the characteristics of the subject matter (Freeman et al. 2014). These results align with the ICAP framework, supporting

the effectiveness of interactive, constructive, and active features in learning tools (Chi and Wylie 2014). Future research should explore the specific features of virtual simulations that contribute most to their effectiveness, as well as how they can be best integrated with other instructional materials to maximize educational outcomes.

6. Limitation and Future Direction

While this study found that virtual implementation types outperformed hands-on and traditional lecture approaches in learning performance, these results are limited to the three LCDLMs analyzed—hydraulic loss, double pipe, and Venturi meter. The Shell & Tube module was excluded because neither the control nor virtual implementation groups participated. Future research should incorporate the Shell & Tube module across all three implementation modes to assess whether the observed advantage of virtual delivery is sustained under expanded conditions. The analysis did not include data on professors and schools involved in the LCDLM implementation, as not all schools participated in each of the LCDLM modules. This omission may limit the depth of understanding regarding how different educational contexts influence the effectiveness of each LCDLM. Future research should aim to collect and incorporate data on the different types of LCDLMs for all schools participating in LCDLM implementations. This comprehensive data set would allow for a more detailed analysis of how varying educational environments and instructional methods impact student learning outcomes across different LCDLM modules and semesters. Although variability between implementations represents a limitation, it also enhances ecological validity by reflecting the diversity of instructional practices likely to occur in real classrooms.

While the present study discussed student engagement, cognitive load, and ICAP framework, it did not incorporate or measure the Community of Inquiry (Akyol and Garrison 2011) or the MVEE model (Putwain et al. 2018) in its design. Future studies may build upon this work by explicitly measuring and analyzing distinct types of engagement (e.g., motivational, volitional, emotional) within a defined theoretical framework to better understand engagement dynamics in diverse learning environments.

The current study drew on a relatively large sample of 918 undergraduate engineering students across eight institutions in the United States, several limitations should be noted. The sample was predominantly composed of white students (73.6%) and juniors (64.8%), which may limit the generalizability of the findings to more racially diverse student populations or to students at other stages of their academic careers. Additionally, most participants were enrolled in fluid mechanics and thermodynamics courses, which may constrain the applicability of the results to other engineering subdisciplines or non-engineering fields. These demographic concentrations suggest that further research is needed to explore whether the observed effects of LCDLM implementation types hold across more varied educational and demographic contexts. Another limitation of the study is the non-random sampling based on course enrollment and institutional collaboration, which may introduce selection bias. However, instructor training was provided to support consistent implementation across sites. While the use of a control group strengthens internal validity. While the pre- and posttest instruments had been refined and used across multiple semesters, no formal item difficulty analysis was conducted for this study. As such, we did not examine whether specific items were consistently answered correctly or incorrectly. Future research should include item-level analyses to identify patterns in student responses and improve test sensitivity.

The potential of hybrid instructional methods that combine both virtual and physical learning experiences was not explored in the present study. While virtual and hands-on learning approaches each offer unique benefits, hybrid models could capitalize on the strengths of both. Future studies should compare the effectiveness of hybrid versus traditional methods, particularly in improving student engagement and learning performance. Additionally, exploring best practices for implementing LCDLMs in diverse classroom settings will help educators optimize these tools for varied learning environments.

7. Conclusion

In this paper, we examined the effects of different LCDLM implementation modes on undergraduate engineering learning. Students engaged with virtual, hands-on, and lecture-based modules across multiple institutions. The findings point to two main conclusions. First, virtual LCDLMs outperformed both hands-on and lecture-based approaches, highlighting the potential of well-designed virtual environments to achieve similar—and in some cases greater—gains than in-person, hands-on or lecture-based learning environments. This finding suggests the practical value of virtual implementations in expanding access and flexibility, particularly in under-resourced settings.

Second, significant differences were observed among LCDLM types. The Hydraulic Loss module yielded higher posttest scores than both the Venturi

and Double Pipe modules, suggesting that the effectiveness of LCDLMs depends on how well module design aligns with learning objectives and concept complexity. However, the relatively small effect sizes indicate that module type explains only a portion of the variance, pointing to the influence of other factors such as instructional support, student engagement, or prior experience.

Taken together, these findings should guide educators to align module choice with instructional purpose, encourage institutions to invest in virtual modules and faculty training, and signal to policymakers the value of broadening access to scalable, cost-effective tools. Future research should extend LCDLMs to non-engineering disciplines, employ qualitative studies to capture student experiences, develop AI-driven adaptive simulations, and investigate hybrid models that combine virtual and hands-on approaches. Such efforts will strengthen the flexibility, inclusivity, and resilience of higher education.

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Prompt Engineering for ChatGPT: A Quick Guide to Techniques, Tips, and Best Practices

Sabit Ekin

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In the rapidly evolving landscape of artificial intelligence (AI), generative language models such as ChatGPT (Generative Pre-trained Transformer) are increasingly being adopted across engineering and technology-focused disciplines. To effectively leverage these tools, users must understand prompt engineering—the practice of designing and refining inputs to guide AI systems toward useful and reliable outputs. This article provides a comprehensive guide to prompt engineering techniques and best practices, with an emphasis on applied use cases relevant to achieving effective outcomes with ChatGPT. The discussion introduces foundational prompt design principles, explores techniques such as explicit constraints, iterative refinement, and prompt chaining, and examines strategies for balancing user intent, system behavior, and ethical considerations. The article also discusses the integration of external resources and APIs (Application Programming Interface), along with practical considerations for responsible and ethical use of generative AI systems. Advanced strategies, such as temperature and token control, domain-specific adaptation, and handling ambiguous or incomplete inputs, are also addressed. Real-world case studies demonstrate the practical applications of prompt engineering in technical support, content generation, domain-specific knowledge retrieval, and engineering technology education. The article concludes by highlighting prompt engineering as an emerging technical skill that can enhance engineering technology instruction, support workforce readiness, and promote responsible use of generative AI tools.

1. Introduction

1.1 Brief overview of ChatGPT

ChatGPT (OpenAI 2023a) is an advanced language model developed by OpenAI, based on the GPT-4 architecture. It has been trained on a large corpus of text and has the ability to generate human-like responses in various contexts (including generating images using Deep Learning methods). ChatGPT's primary strength lies in its ability to understand and generate text in a wide range of domains, making it suitable for applications such as customer support, content generation, and interactive storytelling. This capability builds on foundational work in large language models (LLMs), notably the few-shot learning abilities demonstrated by GPT-3 (Brown et al. 2020), the instruction-tuning innovations via human feedback (Ouyang et al. 2022), and the expanded capabilities of GPT-4 (OpenAI 2023b).

The rapid integration of generative AI tools into professional workflows has also intensified discussions surrounding workforce readiness, digital literacy, and the need for AI-augmented skill development in engineering and technology disciplines (Di Battista et al. 2023; Sciences et al. 2018; Bommasani et al. 2021; Kasneci et al. 2023).

Recent studies have begun examining the integration of generative AI tools within engineering and STEM classrooms, highlighting both instructional opportunities and challenges related to skill development, academic integrity, and workforce preparedness (Cotton, Cotton, and Shipway 2024; Kshetri et al. 2023; Kasneci et al. 2023).

1.2 Importance of prompt engineering in maximizing the effectiveness of ChatGPT

Prompt engineering is the art of crafting effective prompts that guide ChatGPT to generate desired responses. It plays a crucial role in maximizing the effectiveness of the language model by bridging the gap between user intent and model understanding. A well-engineered prompt can significantly improve the quality and relevance of ChatGPT's output, while a poorly crafted one may lead to unsatisfactory or erroneous responses.

For example, consider the following prompts and their corresponding ChatGPT responses:

Prompt 1: "Tell me about AI."

Response 1: "Artificial intelligence (AI) is a branch of computer science that deals with the creation and development of machines that can perform tasks requiring human-like intelligence. This includes learning, reasoning, problem-solving, and understanding natural language."

Prompt 2: "Provide a concise summary of artificial intelligence, its subfields, and current applications."

Response 2: "Artificial intelligence (AI) is the study of creating intelligent agents capable of performing tasks autonomously. Key subfields include machine learning, natural language processing, and robotics. Current applications range from virtual assistants and recommendation systems to autonomous vehicles and medical diagnosis."

The second prompt yields a more informative and focused response due to its clarity and specificity. Prompt engineering can also be situated within broader theoretical domains such as Human-Computer Interaction (HCI), user-centered design, and cognitive load theory. From an HCI standpoint, the prompt serves as the interface through which human intent is translated into machine-readable commands, requiring iterative design and feedback loops. User-centered design principles emphasize crafting prompts that align with user goals and minimize ambiguity. Cognitive load theory further explains how well-structured prompts can reduce extraneous mental processing and guide both the model and user toward efficient, comprehensible outcomes. These perspectives reinforce the view of prompt engineering as a dynamic cognitive and communicative process.

1.3 Objective and structure of the article

The objective of this article is to provide an in-depth guide on prompt engineering for ChatGPT, covering various techniques, tips, and best practices to achieve optimal results. The article is structured as follows:

1. Introduction
2. Fundamentals of Prompt Engineering
3. Techniques for Effective Prompt Engineering
4. Best Practices for Prompt Engineering
5. Advanced Prompt Engineering Strategies
6. Case Studies: Real-World Applications of Prompt Engineering
7. Prompt Engineering for Engineering Technology Education
8. Conclusion

By the end of this article, readers will have a comprehensive understanding of prompt engineering and will be better equipped to harness the full potential of ChatGPT in their respective applications.[1]

To support this practical guide with deeper academic grounding, we have drawn upon recent peer-reviewed studies in prompt tuning, instruction-following, and LLM evaluation. For example, (Gu et al. 2022) introduce the Pre-trained Prompt Tuning (PPT) framework, demonstrating that soft-prompt initialization via pre-training can approach or surpass full-model fine-tuning in few-shot scenarios. (Perez, Kiela, and Cho 2021) explore limitations of few-shot learning in large language models, while (Son et al. 2024) introduce the MTI Bench, a multi-task inference benchmark that evaluates whether models can follow multiple instructions simultaneously—a demanding test of real-world instruction-following capabilities. Conceptually, the idea of cognitive offloading via prompts connects with the extended mind framework (Clark and Chalmers 1998). Additionally, (Si et al. 2022) address prompt reliability, and foundational surveys such as (Bender et al. 2021) and (Bommasani et al. 2021) opportunities in foundation model development. These sources provide both practical and theoretical perspectives that complement the hands-on techniques outlined in this work.

The recommendations presented throughout this article are grounded in author-led experimentation using ChatGPT with GPT-4 under default settings through OpenAI's web interface. Strategies were tested and refined using A/B-style prompt comparisons to assess output clarity, factuality, and coherence. These insights were synthesized from OpenAI documentation, user-facing guidance, and widely shared commu-nity practices. Although this article does not report formal experimental results, it reflects a structured observational approach supported by practical testing and iterative refinement.

We also reference prompt evaluation metrics such as BLEU (Bilingual Evaluation Understudy) and ROUGE (Recall-Oriented Understudy for Gisting Evaluation), and factual faithfulness, which are widely used in language model evaluation. While these are valuable for systematic benchmarking, applying them empirically is beyond the scope of this article and is suggested as a direction for future studies.

2. Fundamentals of Prompt Engineering

2.1 What is prompt engineering?

Prompt engineering is the process of designing, refining, and optimizing input prompts to effectively com-municate the user's intent to a language model like ChatGPT. This practice is essential for obtaining accurate, relevant, and coherent responses from the model. As language models continue to advance, proper prompt engineering has become a critical skill for users looking to harness the full potential of

1 Prompt behavior and output quality may vary between model versions.

ChatGPT and achieve optimal results in a wide variety of applications.

2.2 The role of prompts in interacting with ChatGPT

Prompts serve as the primary means of communication between the user and ChatGPT. They guide the model to generate responses that align with the user's intent. Since the quality of the prompts directly affects the quality of the generated responses, understanding the nuances of prompt engineering is vital for creating effective and meaningful interactions with ChatGPT.

An essential aspect of crafting prompts is anticipating how the model will interpret and respond to the given input. This involves considering factors such as the model's training data, biases, and other limitations that may influence its understanding and generation capabilities.

For instance, consider these two prompts and their respective ChatGPT responses:

Prompt 1: "Write a poem."

Response 1:

"In the quiet of the night,

A solitary moon takes flight,

Its silver beams caress the land,

A gentle touch from a celestial hand."

Prompt 2: "Write a haiku about the changing seasons."

Response 2:

"Autumn leaves fall slow,

Winter's breath chills,

spring buds grow,

Summer sun aglow."

The second prompt results in a more specific and relevant response by specifying the type of poem and the subject matter. This example demonstrates the importance of clarity and specificity in prompt engineering.

2.3 Factors influencing prompt selection

Selecting the right prompt depends on several factors, including:

- User intent: Understand the user's goal and desired output. This helps in crafting a prompt that aligns with the user's expectations. Consider the purpose of the interaction, whether it's for information retrieval, content generation, or problem-solving.
- Model understanding: Familiarize yourself with the strengths and limitations of ChatGPT. This knowledge assists in designing prompts that exploit the model's capabilities while mitigating its weaknesses. Keep in mind that even state-of-the-art models like ChatGPT may struggle with certain tasks or produce incorrect information.
- Domain specificity: When dealing with a specialized domain, consider using domain-specific vo-cabulary or context to guide the model towards the desired response. Providing additional context or examples can help the model generate more accurate and relevant outputs.
- Clarity and specificity: Ensure the prompt is clear and specific to avoid ambiguity or confusion, which can result in suboptimal responses. Ambiguity can arise from unclear instructions, vague questions, or insufficient context.
- Constraints: Determine if any constraints (e.g., response length or format) are necessary to achieve the desired output. Explicitly specifying constraints can help guide the model towards generating responses that meet specific requirements, such as character limits or structured formats.

By considering these factors, you can craft prompts that effectively communicate your intent to ChatGPT and elicit high-quality responses. Additionally, prompt engineering is an iterative process. Experimenting with different prompt variations, testing their effectiveness, and refining your approach based on the model's performance can lead to significant improvements in the quality of the generated output.

2.4 Prompt engineering as an iterative feedback System

Prompt engineering can be modeled as an iterative feedback system. The process begins with user intent, followed by prompt design, model response generation, evaluation of output quality, and refinement of the prompt. This loop continues until the output meets desired performance criteria. This framework aligns prompt engineering with control-system optimization principles, emphasizing iterative improvement.

3. Techniques for Effective Prompt Engineering

3.1 Clear and specific instructions

Providing clear and specific instructions within the prompt helps guide ChatGPT towards generating the desired output. Ambiguity in the prompt can lead to responses that may not fulfill the user's expectations.

Example:

Prompt 1: "Tell me about the solar system."

Response 1: "The solar system is a collection of celestial bodies, including the Sun, eight planets, their moons, and various other objects like asteroids and comets. It is located in the Milky Way galaxy."

Prompt 2: "Describe the order of the planets in the solar system from the closest to the farthest from the Sun."

Response 2: "The order of the planets in the solar system, from closest to farthest from the Sun, is Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune."

The second prompt's specific instructions result in a more targeted and useful response.

3.2 Using explicit constraints

In some cases, it is beneficial to specify explicit constraints in your prompt, such as format, length, or scope. This helps ChatGPT generate responses that adhere to the desired limitations.

Example:

Prompt: "Summarize the main points of photosynthesis in three sentences."

Response: "Photosynthesis is a process where plants, algae, and some bacteria convert sunlight, water, and carbon dioxide into oxygen and glucose. This process occurs in the chlorophyll-containing chloroplasts found in these organisms. The two main stages of photosynthesis are the light-dependent reactions and the Calvin cycle, where the former generates energy and the latter synthesizes glucose."

The constraint on the number of sentences ensures a concise response.

3.3 Experimenting with context and examples

Incorporating context or examples in your prompt can guide ChatGPT to generate more accurate and relevant responses. This is especially helpful when dealing with abstract concepts or specialized domains. Recent prompt-programming frameworks formalize this process for broader task adaptation (Reynolds and McDonell 2021).

Example:

Prompt 1: "What is the difference between conduction and convection?"

Response 1: "Conduction is the transfer of heat through a material without the movement of the material itself, while convection is the transfer of heat through the movement of fluids, such as air or water."

Prompt 2: "Explain the difference between conduction and convection using a frying pan and boiling water as examples."

Response 2: "Conduction occurs in a frying pan when heat is transferred from the heat source through the pan to the food being cooked, without the pan material itself moving. Convection occurs in boiling water when heat is transferred through the movement of the water molecules, causing the hot water to rise and the cooler water to sink, creating a continuous circulation pattern."

The second prompt, with context and examples, results in a more illustrative and informative response.

3.4 Leveraging System 1 and System 2 questions

Understanding the difference between System 1 and System 2 questions can improve the quality of ChatGPT's responses. System 1 questions typically require quick, intuitive, or pattern-recognition-based answers, while System 2 questions involve more deliberate, analytical, or complex problem-solving. By crafting prompts that cater to these two types of questions, you can effectively guide ChatGPT to generate the desired output. Advanced reasoning techniques such as chain-of-thought prompting (Wei et al. 2022), least-to-most prompting (Zhou et al. 2022), and self-consistency (Wang 2022) further enable large models to perform more complex, multi-step reasoning tasks. Chain-of-thought prompting decomposes reasoning into intermediate steps. Least-to-most prompting orders sub-tasks by difficulty, while ReAct (Yao 2022) blends tool usage with inference. These works collectively advance the capabilities of large language models and serve as a foundation for this guide (Table 1).

Prompt (System 1): "What is the capital of France?"

Response: "The capital of France is Paris."

In this example, a simple and direct question is posed, requiring a straightforward answer. ChatGPT can easily provide the correct information, as it is a fact-based question that does not require complex reasoning.

Prompt (System 2): "Imagine a scenario where two companies, Company A and Company B, are considering a merger. Company A specializes in renewable energy, while Company B focuses on fossil fuels. Discuss the potential advantages and disadvantages of this merger."

Response: "Advantages of the merger could include the diversification of energy sources, shared expertise and resources, and increased market presence. Disadvantages might involve

Table 1. Comparative overview of prompt techniques.

Technique	Description	Use Case	Complexity	Reasoning Depth
Zero-shot	Prompt with no examples	Fact retrieval	Low	Shallow
Few-shot	Prompt with few examples	Classification	Medium	Moderate
Chain-of-thought	Step-by-step reasoning	Math, logic	High	Deep
Least-to-most	Ordered subtasks	Planning	High	Deep
ReAct	Combine reasoning and acting	Tool-augmented tasks	High	Variable

conflicting company values, challenges in integrating the two businesses, and potential public backlash against Company A for partnering with a fossil fuel-focused company."

This example demonstrates a System 2 question, which requires more in-depth analysis and the ability to weigh pros and cons. By crafting a prompt that encourages this type of thinking, you can guide ChatGPT to provide a more thoughtful and detailed response.

In conclusion, leveraging System 1 and System 2 questions in your prompt engineering can help you obtain more accurate and contextually relevant responses from ChatGPT. Tailoring your prompts to the type of question being asked will allow you to optimize the interaction and maximize the usefulness of the generated output.

We propose a basic typology of prompt types organized by communicative intent and function. Table 2 outlines four common categories—informative, instructive, evaluative, and narrative—along with a brief purpose description and recommended strategy. This categorization is designed to help practitioners select the most effective prompt design for their desired outcome (Table 2).

3.5 Controlling output verbosity

Adjusting the verbosity of ChatGPT's responses can be beneficial for obtaining information at the desired level of detail. You can control verbosity by explicitly requesting responses of a specific length or by asking the model to provide more or less information.

Example:

Prompt 1: "Briefly explain the water cycle."

Response 1: "The water cycle is the continuous movement of water on Earth through evaporation, condensation, and precipitation, driven by the Sun's energy."

Prompt 2: "Provide a detailed explanation of the water cycle, including its various stages and processes."

Response 2: "The water cycle, also known as the hydrologic cycle, is the continuous movement of water on, above, and below the Earth's surface. It involves several key stages and processes:

- Evaporation: Solar energy heats water in oceans, lakes, and rivers, turning it into water vapor that rises into the atmosphere.
- Transpiration: Plants release water vapor into the air through small openings in their leaves, called stomata.
- Condensation: As water vapor rises and cools, it condenses into tiny water droplets or ice crystals, forming clouds.
- Precipitation: When cloud particles grow large enough, they fall back to Earth as rain, snow, hail, or sleet.
- Runoff: Precipitation that reaches the ground flows into streams, rivers, and eventually back into oceans, where the cycle begins anew.
- Infiltration: Some of the precipitation seeps

Table 2. Typology of prompt types and strategies.

Prompt Type	Purpose	Example Strategy
Informative	To elicit factual or descriptive output	Ask for summaries, definitions, or explanations
Instructive	To direct the model to perform a task	Use imperative tone with clear constraints
Evaluative	To assess, critique, or compare information	Request pros/cons, rankings, or recommendations
Narrative	To generate creative or fictional output	Provide story elements or character-driven setup

into the ground, replenishing underground water reserves called aquifers.

The water cycle plays a critical role in maintaining Earth's climate, distributing fresh water, and supporting ecosystems."

By explicitly requesting a brief or detailed explanation, you can control the verbosity of ChatGPT's responses to suit your needs.

3.6 Tuning model behavior with parameters

In addition to specifying response length or verbosity, users can control the stochastic behavior of the model through the temperature parameter. Temperature influences the randomness of output generation: a low value (e.g., 0.2) leads to more deterministic and focused outputs, while a high value (e.g., 1.0) introduces diversity and creativity. Likewise, adjusting the max tokens parameter limits the length of the generated response, which is crucial for tasks requiring concise summaries or detailed narratives. Understanding and manipulating these parameters helps users tailor ChatGPT's output to meet specific needs, whether prioritizing precision, creativity, or completeness.

To summarize the structured approach to effective prompt development, Figure 1 presents the overall prompt design workflow. The figure illustrates how user intent is translated into structured prompts, evaluated, and iteratively refined to achieve optimal model performance.

4. Best Practices for Prompt Engineering

In this section, we discuss best practices for prompt engineering to ensure optimal performance and user experience when interacting with ChatGPT.

4.1 Iterative testing and refining

One of the most effective ways to improve prompt engineering is through an iterative process of testing and refining. Continuously refining your prompts based on the generated responses helps to identify areas that require improvement and fine-tune the model's behavior.

Example:

Initial Prompt: "Tell me about the solar system."

Initial Response: "The solar system is a collection of celestial bodies, including the Sun, planets, moons, asteroids, and comets, bound by gravity."

Refined Prompt: "Describe the planets in our solar system, their order from the Sun, and their main characteristics."

Refined Response: "The solar system has eight planets, ordered as follows: Mercury, Venus, Earth, Mars, Jupiter, Saturn, Uranus, and Neptune " (Detailed characteristics of each planet follow.)

4.2 Balancing user intent and model creativity

While ChatGPT is capable of generating creative responses, it is crucial to balance user intent with model creativity. Ensure that the prompt addresses the user's needs while allowing room for the model to showcase its capabilities.

Example:

Prompt: "Write a science fiction story about a robot uprising."

Response: "(A creative and engaging story that satisfies the user's request while demonstrating ChatGPT's storytelling abilities.)"

4.3 Harnessing external resources and APIs

In some cases, ChatGPT may not have sufficient knowledge or accuracy to respond to user queries effectively. To address this limitation, prompt engineering can be augmented with external resources and APIs (Application Programming Interface), enabling ChatGPT to access real-time or domain-specific information. Integrating APIs into your prompts can significantly improve the quality and relevance of ChatGPT's responses.

Consider an example where a user wants to know the current weather in a specific location. You can use an API like OpenWeatherMap to fetch the necessary

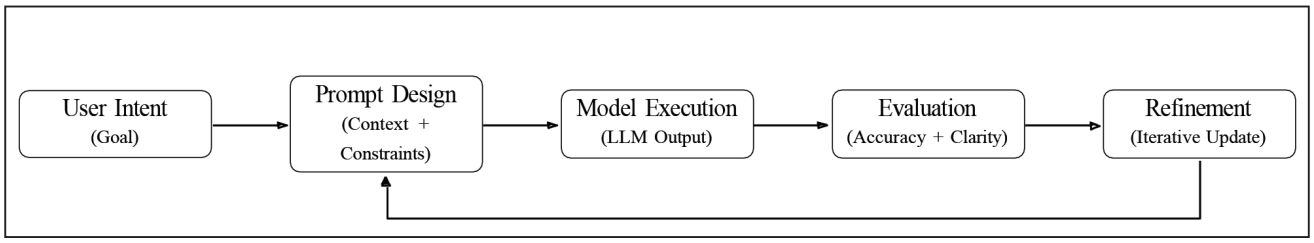


Figure 1. Prompt design workflowi illustrating structured prompt creation, execution, evaluation, and iterative refinement.

Example 1

```
import openai_secret_manager import
requests

api_key = openai_secret_manager.get_secret("OpenWeatherMap")["api_key"] location = "San
Francisco, US"
url = f"http://api.openweathermap.org/data/2.5/weather?q={location}&appid={ api_key}&
    units=metric"
response = requests.get(url) weather_data
= response.json()

temperature = weather_data["main"]["temp"]
weather_description = weather_data["weather"][0]["description"]

prompt = f"The current weather in {location} is: {weather_description}. The temperature is {
    temperature} degrees Celsius. Can you provide a brief summary of the weather?"
chatgpt_response = chatgpt.generate(prompt)
```

data and then craft a prompt for ChatGPT to generate a human-readable weather report (Example 1).

In this example, we fetch the weather information using the OpenWeatherMap API and create a prompt that includes the fetched data. ChatGPT then generates a brief summary of the weather based on the given information.

Another example is using the Wikipedia API to search for information on a specific topic, then crafting a prompt for ChatGPT to provide a summary of the topic (Example 2).

By using external resources and APIs, you can improve the performance of ChatGPT in tasks that require real-time or specialized data. When using APIs, remember to account for API limits, response time, and any other constraints that may affect the user experience.

Example 2

```
import wikipediaapi

wiki = wikipediaapi.Wikipedia("en") page_title = "
Natural language processing" page = wiki.page(
page_title)
summary = page.summary[0:500]

prompt = f"The Wikipedia summary of {page_title} is:\n{summary}\nCan you provide a concise
    explanation of natural language processing in your own words?"
chatgpt_response = chatgpt.generate(prompt)
```

Example 3.

```
import openai

openai.api_key = "your_openai_api_key_here"

def chat_with_gpt(prompt):

response = openai.Completion.create(

engine="text-davinci-002", prompt=prompt,

max_tokens=50,

n=1,

stop=None, temperature=0.8,
)

return response.choices[0].text.strip()


prompt = "Write a brief introduction to the history of computers." response_text =

chat_with_gpt(prompt)

print(response_text)
```

4.4 ChatGPT OpenAI API example

In this part, we present an example of using the OpenAI API with the ChatGPT model. The provided Python code (Example 3.) demonstrates how to interact with the API to generate a response for a given text prompt. This is a useful application for various tasks such as content generation, question-answering, and conversational AI.

The code begins by importing the necessary libraries and setting up the API key for authentication. A function called chat with gpt is defined, which takes the input prompt and makes an API call to the GPT model using the specified parameters. The generated response is then processed and printed to the console. This example demonstrates the ease of integrating OpenAI's ChatGPT API into your Python appli-

cations, enabling you to leverage the power of GPT models for a wide range of tasks.

- **Importing required libraries:**
  We start by importing the openai library, which is the official Python library for OpenAI's API.
- **Setting the API key:**
  We set the API key for OpenAI by assigning it to openai.api key. Replace "your openai api key here" with your actual API key.
- **Defining the chat with gpt function:**
  We define a function called chat with gpt that takes a single argument, prompt. This function will call the OpenAI API and return the generated response.
- **API call:**
  Inside the function, we use the openai. Completion.create() method to make an API call. This method takes several parameters:
  - engine: The ID of the GPT model. In our example, we use the "text-davinci-002" engine.
  - prompt: The text prompt that we want the model to respond to.
  - max tokens: The maximum number of tokens (words or word pieces) in the generated response.
  - n: The number of generated responses.
  - stop: An optional sequence that indicates the end of a response.
  - temperature: Controls the randomness of the output. A higher value makes the output more random, while a lower value makes it more deterministic.

- **Processing the response:**
  After making the API call, we extract the generated text from the response.choices[0].text attribute and remove any leading or trailing whitespace using the strip() method.
- **Using the function:**
  We define a variable prompt containing the text we want the model to respond to and then call the chat with gpt function with this prompt. The generated response is stored in the response text variable.
- **Printing the response:**
  Finally, we print the generated response to the console using the print() function.

4.5 Ensuring ethical usage and avoiding biases

As an AI language model, ChatGPT may inadvertently generate biased or inappropriate content. To ensure ethical usage, it is essential to set guidelines and constraints that help mitigate these issues and avoid reinforcing harmful stereotypes. These issues mirror broader concerns about model size, data biases, and downstream harms, as discussed in "Stochastic Parrots" ((Bender et al. 2021)) and the comprehensive survey on foundation model risks (Bommasani et al. 2021).

1. Being aware of potential biases: Large language models like ChatGPT pose several ethical challenges that go beyond simple factuality or moderation. One such issue is *model hallucination*, where the model generates plausible-sounding but inaccurate or fabricated responses. In practical settings, this can mislead users or propagate false information, especially when prompts seek authoritative answers. Familiarize yourself with the possible biases that may arise in ChatGPT's responses. This awareness will help you identify and address such biases when crafting prompts.
2. Using inclusive language: Another concern is *prompt-based bias amplification*. Even neutral-seeming prompts may elicit responses that reinforce stereotypes, marginalize certain identities, or reflect narrow cultural assumptions. For instance, prompts like "Who are the most successful CEOs?" may lead to over-representation of Western male figures if not framed inclusively. When designing prompts, use language that encourages diverse perspectives and avoids reinforcing stereotypes. This approach helps ensure that the generated content is inclusive and respectful.
3. Evaluating generated content: A third layer involves *representational harms*—the tendency of models to under-represent or omit certain groups, ideas, or geographies. These harms are subtle and often persistent across applications, including education, hiring, and content generation. Regularly assess the content generated by ChatGPT for potential biases or ethical concerns. If you discover issues, refine the prompts to mitigate them.
4. Implementing content filters: To mitigate these issues, prompt engineers should apply iterative testing, adversarial probing, and scenario-based audits. Content moderation tools and user feedback loops can further improve prompt alignment with ethical standards. Importantly, ethical prompt engineering is not one-size-fits-all; it must adapt to evolving use cases, social norms, and deployment settings. Utilize content filters or moderation tools to screen the generated responses for potentially harmful or biased content before presenting them to users.

Example:

- **Initial Prompt:** "List the most successful entrepreneurs of the 21st century."
- **Biased Response:** "A list that disproportionately features male entrepreneurs, such as Elon Musk, Jeff Bezos, and Mark Zuckerberg."
- **Improved Prompt:** "List some successful entrepreneurs of the 21st century, including a diverse range of individuals."
- **Unbiased Response:** "A list that features entrepreneurs from various backgrounds, genders, and industries, such as Elon Musk, Oprah Winfrey, Jeff Bezos, Arianna Huffington, Mark Zuckerberg, and Indra Nooyi."

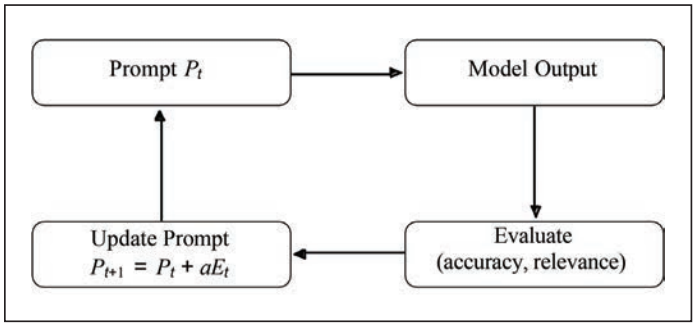


Figure 2. Iterative prompt refinement loop based on evaluation feedback.

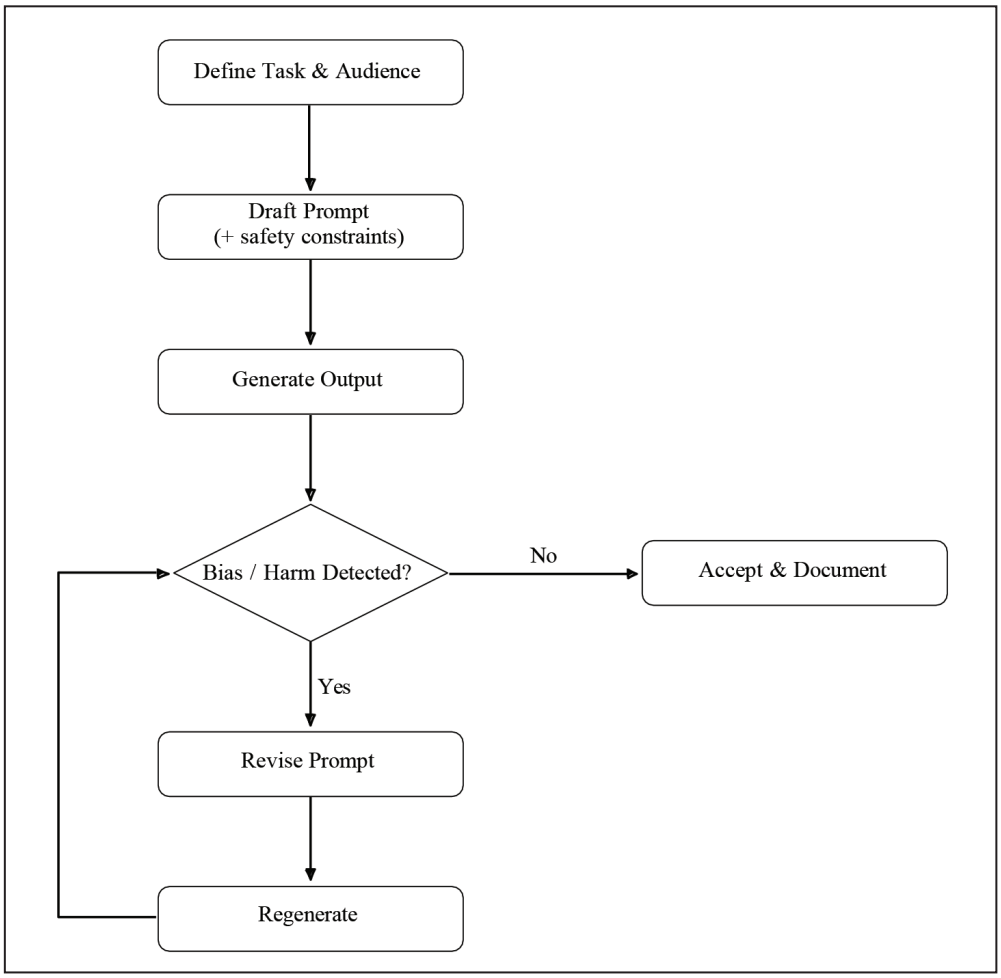


Figure 3. Bias mitigation workflow using iterative prompt refinement.

The iterative nature of prompt optimization is formalized in Figure 2, which models prompt engineering as a feedback-driven refinement cycle.

To systematically address bias and ethical concerns, Figure 3 presents a structured bias mitigation workflow incorporating prompt-level constraints and iterative review.

5. Advanced Prompt Engineering Strategies

This section delves into more advanced techniques that can further enhance the effectiveness of your prompts, helping you obtain better results from ChatGPT.

5.1 Temperature and token control

Adjusting the temperature and token count of ChatGPT's responses can have a significant impact on the generated content. Lower temperature values result in more focused and deterministic outputs, while higher values lead to more diverse and creative responses.

Example:

Low Temperature (0.2)

- **Prompt:** "Write a short poem about spring."
- **Response:**

"Spring has arrived with a gentle breeze,
Awakening flowers and rustling leaves.
The sun shines bright, the days grow long,
Birds sing their sweet and joyful song."

High Temperature (1.0)

- **Prompt:** "Write a short poem about spring."
- **Response:**

"Beneath the sun's glistening crown,
The once-silent world starts to resound.
Spring is a vibrant dancer on the stage,
Unfurling colors in a whimsical parade."

Table 3. Rule-of-thumb guidelines for temperature andt token Settings.

Task Type	Temperature	Max Tokens
Fact-based Q&A	0.1 – 0.3	Low to Moderate
Technical Explanation	0.2 – 0.5	Moderate
Creative Writing	0.7 – 1.0	Moderate to High
Brainstorming Ideas	0.8 – 1.2	High
Structured Formatting	0.1 – 0.4	Moderate

To provide practical guidance for parameter selection, Table 3 summarizes rule-of-thumb settings for common prompt types.

It is important to note that language models are updated periodically, which may lead to variations in output behavior ("prompt drift"). To ensure reproducibility, users should document the specific model version and parameter settings used during testing. Maintaining version-controlled prompt templates can help preserve consistency across deployments and future evaluations.

5.2 Prompt chaining and multi-turn conversations

By connecting multiple prompts together, you can create a more interactive and dynamic conversation with ChatGPT. This technique can be especially useful for multi-turn dialogues or when seeking more detailed responses.

Example:

Prompt 1: "What are the health benefits of drinking green tea?"

Response 1: "Green tea is rich in antioxidants, which can help reduce the risk of chronic diseases, improve brain function, and promote weight loss. It may also help lower the risk of certain cancers and improve dental health."

Prompt 2: "Tell me more about the antioxidants in green tea."

Response 2: "Green tea contains a high concentration of polyphenols, particularly a group of antioxidants known as catechins. The most abundant and well-studied catechin in green tea is epigallocatechin gallate (EGCG), which has been shown to have numerous health benefits, including anti-inflammatory and anticancer properties."

5.3 Adapting prompts for domain-specific applications

Tailoring prompts for specific domains or industries can help you obtain more accurate and relevant infor-mation from ChatGPT.

Example:

Domain: Web development

Prompt: "Explain the concept of responsive web design and its importance in modern web devel-opment."

Response: "Responsive web design is an approach to web development that ensures a website's layout and functionality adapt to different devices and screen sizes. This is achieved through the use of fluid grids, flexible images, and CSS media queries. Responsive design is crucial in modern web development because it provides a seamless user experience across various devices, improving accessibility and reducing the need for separate mobile websites or applications."

5.4 Handling ambiguous or contradictory user inputs

ChatGPT may occasionally receive ambiguous or contradictory inputs. In such cases, you can design prompts that encourage clarification or provide multiple interpretations.

Example:

Ambiguous Prompt: "How long does it take to charge?"

Clarifying Response: "Your question is ambiguous. Please specify the device or object you are referring to, and I will provide the charging time."

Contradictory Prompt: "What is the best way to lose weight: a high-fat diet or a high-carb diet?"

Multiple Interpretations Response: "There is no one-size-fits-all answer to this question, as the best diet for weight loss depends on an individual's specific needs, preferences, and goals. Some people may find success with a high-fat, low-carb diet like the ketogenic diet, while others may benefit from a high-carb, low-fat diet, such as a plant-based diet. It's important to consult a healthcare professional or nutritionist to determine the most suitable approach for your unique circumstances."

Figure 4 illustrates the multi-turn prompt chaining process, highlighting how context is retained and progressively refined across conversational turns.

5.5 Prompt failure modes and taxonomy

Despite following best practices, prompt design

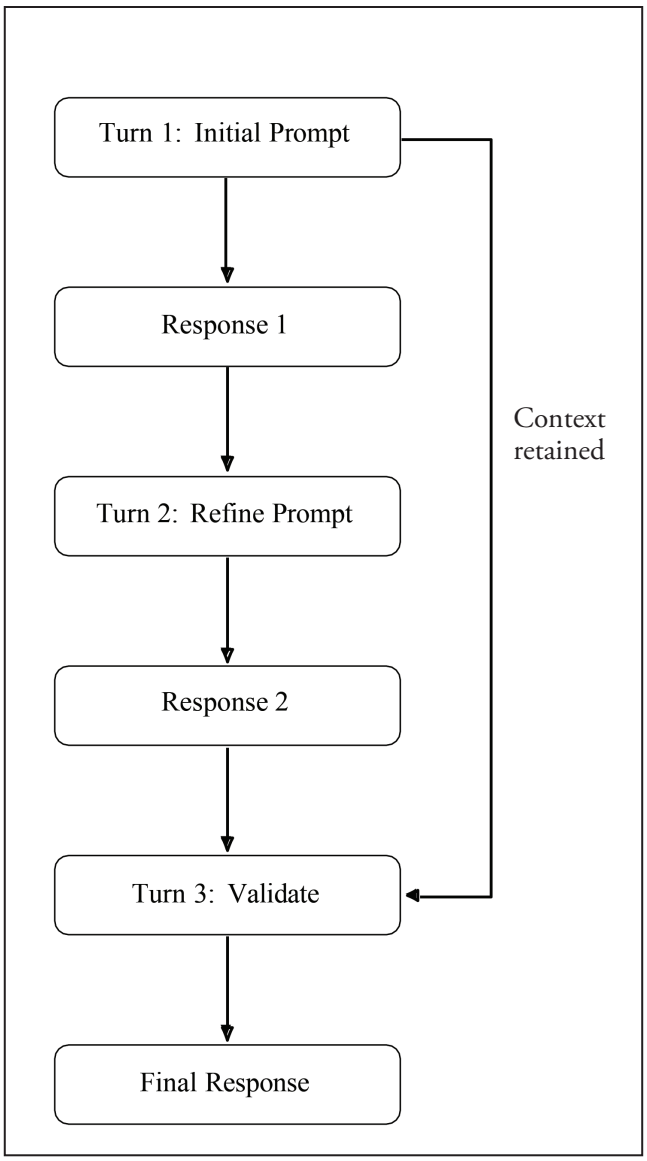


Figure 4. Multi-turn prompt chaining with iterative refinement and context retention.

often suffers from typical issues:

- **Under-specification:** Missing constraints lead to vague outputs.
- **Over-specification:** Excessive detail inhibits creativity.
- **Objective misalignment**: Prompt goals do not match desired outcomes.
- **Ambiguity:** Conflicting interpretations result in inconsistent behavior.

Identifying and categorizing these modes is essential for iterative refinement.

6. Case Studies: Real-World Applications of Prompt Engineering

In this section, we explore various real-world applications of prompt engineering to demonstrate how these techniques can enhance ChatGPT's performance across diverse domains.

6.1 Customer support chatbots

ChatGPT can be used to create customer support chatbots capable of addressing user queries effectively. By crafting precise prompts and leveraging context, you can ensure that the chatbot provides relevant and accurate responses.

Example:

Prompt: "As a customer support chatbot, explain how to reset a user's password."

Response: "To reset a user's password, please follow these steps:

1. Go to the account login page.
2. Click on the 'Forgot Password' link.
3. Enter the user's registered email address.
4. Click 'Submit' to send a password reset link to the user's email.
5. Ask the user to check their email and click on the link provided.
6. They will be redirected to a password reset page, where they can create a new password.
7. Once the new password is set, instruct the user to log in using their new credentials."

6.2 Content generation and editing

ChatGPT can generate and edit content for various purposes, such as blog posts, social media updates, or product descriptions. By providing clear instructions and desired outcomes, you can achieve higher-quality output.

Example:

Prompt: "Write a short and engaging introduction for a blog post about the benefits of meditation."

Response: "In today's fast-paced world, finding inner peace and tranquility can seem like an elusive goal. But what if there was a simple, time-tested practice to help you unlock the door to mental clarity and emotional balance? Enter the world of meditation – a powerful tool that can transform your life, one mindful breath at a time. Read on to discover the remarkable benefits of this ancient practice and

learn how it can help you cultivate a calmer, more focused mind."

6.3 Domain-specific knowledge retrieval

ChatGPT can be used to answer domain-specific questions or provide specialized advice by refining prompts for better context. In addition, recent studies have specifically examined ChatGPT's role in education, highlighting both its tutoring potential and the challenges it poses for learning integrity (Kasneci et al. 2023).

Example:

Prompt: "As a gardening expert, what are some easy-to-grow plants for beginners?"

Response: "For beginners looking to start gardening, I recommend the following easy-to-grow plants:

1. Marigolds: These vibrant flowers are low-maintenance and thrive in a variety of soil types.
2. Basil: This popular herb grows quickly and can be used in a wide range of dishes.
3. Tomatoes: Choose a hardy variety like cherry tomatoes for a bountiful harvest.
4. Zucchini: These fast-growing vegetables are perfect for garden beds or containers.
5. Sunflowers: With their cheerful appearance, sunflowers are easy to grow and require minimal care.
6. Remember to provide adequate sunlight, water, and well-draining soil for optimal growth."

6.4 Interactive storytelling and gaming

ChatGPT can be utilized for interactive storytelling and gaming experiences by creating engaging narratives and responding to user inputs.

Example:

Prompt: "You are an adventurer entering a mysterious cave. Describe the cave and mention a hidden treasure."

Response: "As you step into the mysterious cave, the cool, damp air envelops you. The faint glow of bioluminescent fungi illuminates the walls, revealing ancient symbols etched into the stone. The cave seems to stretch endlessly, with numerous twisting passageways branching out in every direction. Somewhere deep within this subterranean labyrinth lies a hidden treasure, a legendary artifact said to possess unimaginable power. As you venture further into the darkness, each step echoing through the silent passages, you prepare to face the unknown challenges that await you on your quest to uncover the lost secrets of the cave and claim the fabled treasure as your own."

6.5 Business case- Enterprise efficiency through prompt engineering

Example:

Prompt: "You are a corporate chatbot that summarizes customer email issues and suggests next-best actions. Given this email, extract the key issue, propose a response, and assign a priority level.."

Response: "Key Issue: Billing discrepancy for June invoice Suggested Response: "Thank you for contacting us. I see an overcharge on your June statement. I've issued a $150 credit and attached the corrected invoice. Please let me know if anything else comes up." Priority: High"

6.6 Business decision support through prompt chaining

Consider a retail manager using prompt chaining:

1. **Prompt 1:** Summarize sales data for product X.
2. **Prompt 2:** Predict next month's demand based on trends.
3. **Prompt 3:** Recommend reorder quantity and timing.

This approach demonstrates how multi-step prompts can support real-world decision-making.

6.7 Expanded business use case – email triage workflow

ChatGPT can prioritize and draft a customer service email reply using prompt chaining.

Step 1: Summarize the email.

Prompt: "Summarize the following customer email in 2–3 sentences, focusing on the problem and urgency."

Observation: GPT-4 correctly extracted the customer's request and dissatisfaction but sometimes omitted key timeline details.

Step 2: Identify the correct action.

Prompt: "Based on the summary, what is the appropriate next action our team should take?"

Observation: Suggested a clear and reasonable resolution, but required slight rewording to match tone.

Step 3: Draft the email.

Prompt: "Now write a polite and professional email replying to the customer, incorporating the action above."

Observation: GPT-4 produced coherent, actionable text aligned with customer expectations.

Multi-step prompting improved specificity and tone. A/B tests showed that breaking the task into smaller parts produced more consistent and accurate replies. Informal user feedback confirmed clarity and usefulness of model-generated content.

6.8 Educational use case – engineering technology instructional support

Generative AI tools such as ChatGPT can support engineering technology education when used as structured instructional aids rather than as answer-generation systems. This case study illustrates how prompt engi-neering can be applied to an engineering technology topic to enhance conceptual understanding, technical reasoning, and student engagement.

Example Topic: Three-Phase Induction Motor Operation

Step 1: Conceptual Explanation

Prompt: "Explain the operating principle of a three-phase induction motor in simple terms suitable for a junior-level engineering technology student."

Observation: The model produced a clear, accessible explanation describing rotating magnetic fields, induced rotor currents, and torque generation without excessive mathematical detail. This level of abstraction aligned well with ET instructional goals focused on system behavior rather than derivation-heavy theory.

Step 2: Applied Engineering Contex

Prompt: "Describe two common reasons why a three-phase induction motor might overheat in an industrial setting, assuming it is controlled by a variable frequency drive (VFD)."

Observation: The response identified issues such as improper VFD parameter settings and mechan-ical overloading. While generally accurate, minor omissions required instructor clarification, reinforcing the need for domain validation and guided discussion.

Step 3: Assessment and Reinforcement

Prompt: "Create three multiple-choice questions to assess student understanding of induction motor overheating causes and VFD-related issues."

Observation: The generated questions were technically appropriate and suitable for formative assessment. Minor edits were required to align terminology with course materials, but overall quality was sufficient for instructional use.

This structured prompting approach demonstrates how prompt engineering can support engineering technology instruction by reinforcing applied concepts, promoting diagnostic reasoning, and assisting with assessment development. Informal classroom observations indicated improved student engagement when AI-generated explanations were used as discussion starters rather than authoritative answers. Evaluation emphasized instructional clarity and engineering relevance rather than automated performance metrics.

7. Prompt Engineering for Engineering Technology Education

Engineering technology (ET) programs emphasize applied problem solving, system-level thinking, and hands-on interaction with modern tools and platforms. Within this context, prompt engineering can be viewed not as an abstract AI concept, but as a practical human–machine interface skill that enables students to effectively leverage generative AI systems in engineering workflows. Similar to configuring industrial controllers, developing simulation scripts, or interacting with advanced instrumentation, prompt engineering requires users to translate domain knowledge into structured, operational inputs that produce usable outputs.

From an instructional perspective, prompt engineering aligns naturally with core learning objectives in engineering technology education. Students must articulate constraints, define performance criteria, and iteratively refine their inputs based on system feedback—skills that closely mirror established ET practices in laboratory experimentation, troubleshooting, and process optimization. Rather than replacing hands-on activities, prompt engineering can augment traditional instruction by supporting conceptual understanding, technical communication, and pre-laboratory preparation.

In ET courses, generative AI tools can be used to assist with tasks such as explaining manufacturing processes, interpreting technical standards, generating troubleshooting hypotheses, and drafting structured laboratory documentation. For example,

students may use prompt engineering to request explanations of system behavior under specific operating conditions, compare alternative design approaches, or summarize safety procedures based on regulatory constraints. The quality and usefulness of the generated responses depend strongly on the clarity, specificity, and structure of the prompts, reinforcing the importance of deliberate prompt design.

Prompt engineering also supports scaffolded learning approaches commonly used in ET programs. Instructors can guide students through progressively refined prompts—beginning with high-level conceptual questions and advancing toward constrained, application-specific queries. This process encourages critical evaluation of AI-generated outputs, reinforces engineering judgment, and promotes responsible tool usage.

When paired with instructor oversight and domain validation, prompt engineering can enhance student engagement while preserving the rigor and applied focus of engineering technology education.

8. Conclusion

8.1 The impact of effective prompt engineering on ChatGPT performance

Effective prompt engineering significantly enhances the performance, reliability, and applicability of large language models such as ChatGPT. By incorporating structured instructions, explicit constraints, contex-tual guidance, and iterative refinement, users can substantially improve output accuracy, clarity, and task alignment.

From a performance perspective, well-designed prompts reduce ambiguity and minimize irrelevant or inconsistent responses. The inclusion of constraints (e.g., format, length, tone, or domain specification) improves controllability and reproducibility of outputs. Furthermore, iterative refinement—modeled as a feedback-driven optimization loop—enables systematic improvement in response quality across successive prompt versions.

In educational contexts, structured prompting improves conceptual explanations, problem-solving guidance, and instructional clarity. In enterprise environments, prompt engineering enhances automation reliability, decision-support systems, and workflow efficiency. In domain-specific applications, carefully designed prompts help align model outputs with professional standards and technical requirements.

Overall, prompt engineering transforms interaction with language models from ad hoc querying into a structured optimization process. This shift enables more predictable, interpretable, and application-ready AI-assisted outputs, reinforcing the importance of systematic prompt design in modern AI deployment.

8.2 Future directions in prompt engineering research and applications

As the field of AI and natural language processing advances, new research and applications will emerge in prompt engineering. Potential areas of exploration include developing more sophisticated prompt strategies, integrating external resources and APIs, and creating interactive, multi-turn conversational systems. These advancements will pave the way for AI language models like ChatGPT to become even more versatile and valuable tools across numerous applications.

8.3 Encouraging creativity and collaboration in the ChatGPT community

Fostering creativity and collaboration within the ChatGPT community is crucial for the continuous improve-ment of prompt engineering best practices. By sharing experiences, innovations, and successes, users can contribute to the ongoing development of the field and inspire new ideas. This collective effort will drive innovation in prompt engineering and help AI language models like ChatGPT reach their full potential.

8.4 Limitations and future work

While this article offers foundational methods and best practices for prompt engineering, several limitations remain. First, prompt behavior is highly dependent on the version and interface of the language model. Outputs may vary between GPT-3.5 and GPT-4 (or other current and future models), or between ChatGPT and API-based calls, even for identical prompts. Second, prompt strategies are often domain-specific. A prompt that works well for creative writing may fail in legal or scientific contexts due to different knowledge structures and response constraints. Third, generalizing best practices across diverse models and tasks remains challenging. Without standardized benchmarks, prompt evaluation is often anecdotal or ad hoc. Future work should explore methods for prompt auditing, evaluation frameworks for output quality, and adaptation strategies for specific application domains. Longitudinal studies of prompt evolution and human-in-the-loop feedback are also promising directions.

Additionally, the quality and stability of prompt outputs are affected by the model version and user access level. Free-tier users often interact with GPT-3.5, while paid subscribers may use GPT-4, leading to discrepancies in reproducibility and performance.

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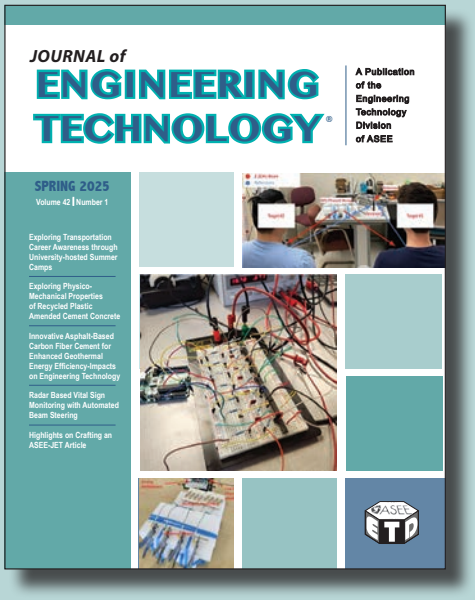
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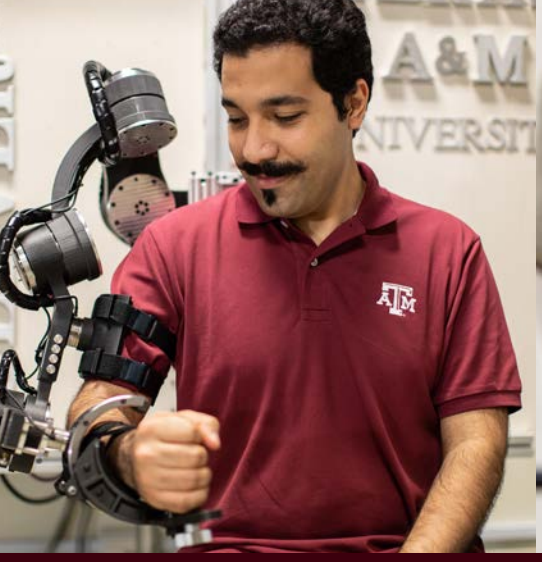
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