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Shaping the Future of Engineering Education with Sustainable Design and Manufacturing Practices

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Abstract

The future of engineering education lies in equipping learners with the skills to harness cutting-edge design tools and sustainable manufacturing processes. Despite the availability of advanced technologies, knowledge gaps persist, limiting their adoption in academia and industry. This paper addresses these challenges by developing and implementing three innovative educational design and manufacturing modules that integrate sustainability and entrepreneurial thinking: 1) Generative Design using Autodesk Fusion software to optimize designs and streamline workflows, 2) Portable Sand Casting with "foundry-in-a-box" technology for hands-on learning, and 3) Green Manufacturing through the transformation of waste plastics into no-cost additive manufacturing (AM) printing filaments. These modules have been shared with Science, Technology, Engineering, and Math (STEM) educators via a training workshop and an open-access YouTube channel, providing educators and students with the tools to advance sustainable practices in engineering. This paper outlines the development and implementation of these modules, highlighting their potential to redefine STEM education and inspire the next generation of engineers.

1. Background

Project R2, titled *"Redesigning and Remanufacturing the Entrepreneurial Future,"* established a transformative framework for advancing education in design and manufacturing [1]. With a strong emphasis on innovation and sustainability, the project developed three entrepreneurial, concise, and impactful Open Educational Resources (OERs) [2]: 1) generative design and its application using Fusion software [3], 2) portable sand casting facilitated through a foundry-in-a-box unit [4], and 3) converting discarded plastic bottles into filaments for AM to create functional, everyday products [5]. These OERs are designed and developed to empower students, educators, and industry professionals by providing them with the knowledge and skills necessary to engage with cutting-edge technologies and trends in advanced manufacturing and design.

1.1. Generative Design

Generative design represents a revolutionary approach to product development, utilizing artificial intelligence (AI) and machine learning (ML) to autonomously generate a wide range of design alternatives optimized for specific performance, material, and manufacturing constraints [6]. This approach empowers designers to explore innovative solutions that would be difficult or impossible to achieve using traditional design methods. Despite its transformative potential, there is a critical gap in accessible, innovative, and entrepreneurial OERs for teaching generative design. To address this, Project R2 developed targeted knowledge blocks and practical exercises using Fusion, enabling learners to master this advanced design methodology and apply it to real-world challenges.

1.2. Recycling Plastics into Filaments for Additive Manufacturing

Transforming discarded water bottles into filaments for AM is a vital step toward sustainable production [7]. This process reduces the environmental impact of plastic waste while offering a cost-effective alternative to virgin plastic filaments, benefiting both businesses and consumers engaged in AM. As the demand for low-cost filaments continues to rise, meeting this need sustainably is essential [8]. However, no comprehensive OERs or hands-on practices currently exist to teach the practical and entrepreneurial aspects of filament production from recycled plastics [9]. Project R2 addresses this gap by creating unique instructional materials that showcase best practices, demonstrating how to produce affordable, high-quality filaments while promoting environmental stewardship.

1.3. Portable Sand Casting (foundry-in-a-box)

Metal casting, one of the oldest manufacturing techniques, continues to evolve with technological advancements and new applications. Staying competitive in this field requires not only technical expertise but also entrepreneurial skills, including knowledge of market strategies, financial management, and client relations [10]. Recognizing the lack of accessible OERs and hands-on training materials for casting, Project R2 developed practical exercises and demonstrations using commonly available metals and portable foundry-in-a-box kits [11]. These resources are designed to bring sand-casting education into classrooms and laboratories, empowering students and educators to explore this essential manufacturing process innovatively [12].

In summary, Project R2 bridges critical gaps in STEM education by providing innovative and practical OERs that integrate cutting-edge technologies with sustainability and entrepreneurial thinking. These resources empower learners to develop essential skills, drive innovation, and address global challenges in design and manufacturing.

2. Methodology

The project features three comprehensive OERs as can be seen in Figure 1. They were developed as video recordings and placed into a YouTube Channel named Project R2. Each OER has the following contents and applications.

2.1.Generative Design

Generative design is transforming engineering and manufacturing by leveraging AI and computational algorithms to create optimized, high-performance designs that would be difficult or impossible to conceive through traditional methods [13]. This approach allows engineers to input design constraints—such as material properties, weight limits, and load conditions—while the software autonomously generates and evaluates numerous design iterations to find the most efficient solution. By harnessing this computational power, generative design fosters innovation, sustainability, and efficiency, reducing material waste and improving product performance. It is particularly valuable in fields such as aerospace, automotive, and medical device manufacturing, where lightweight, structurally optimized components can lead to significant improvements in cost and functionality. Educating future engineers about generative design is crucial for preparing them to utilize these advanced tools effectively, ensuring they can tackle complex design challenges with data-driven methodologies [14].

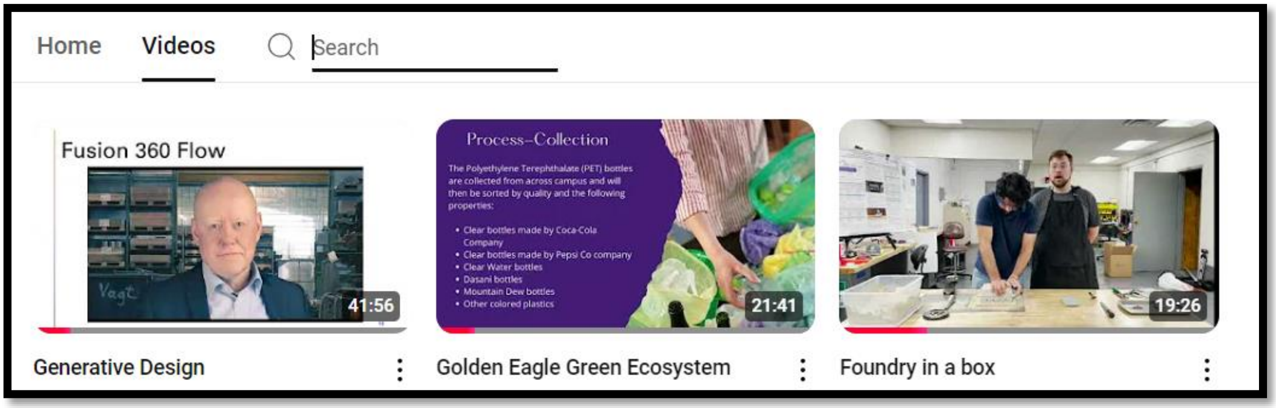


Figure 1: OERs developed for the Project R2

Making the YouTube module on generative design an OER significantly broadens its impact by providing free and accessible learning content to students, educators, and professionals worldwide. Unlike traditional learning materials that may be restricted by institutional access or cost barriers, an OER on YouTube ensures that learners from diverse backgrounds can engage with cutting-edge design methodologies without financial constraints. Additionally, YouTube's interactive features, such as comments and discussion threads, encourage a collaborative learning environment where viewers can ask questions, share insights, and refine their understanding. By contributing to this module as an OER, we support the democratization of knowledge, empower self-directed learners, and promote the integration of generative design principles into engineering education at all levels. This open-access approach aligns with the broader movement toward equitable and lifelong learning, ensuring that critical advancements in design technology reach a global audience.

Some of the unique features of the current module are given below:

- Synopsis

  This module presents the principles and applications of generative design, a cutting-edge approach that leverages AI and computational algorithms to optimize design solutions as can be seen in Figure 2.

- Content
  - Explanation of generative design concepts and their significance in modern engineering.
  - Step-by-step demonstrations of software tools and techniques.
  - Practical exercises for students to apply generative design in real-world scenarios.
- Applications
  - Classroom instructions in advanced design courses.

- Laboratory exercises focused on CAD tools and AI integration.
- Professional training for industries embracing digital transformation.

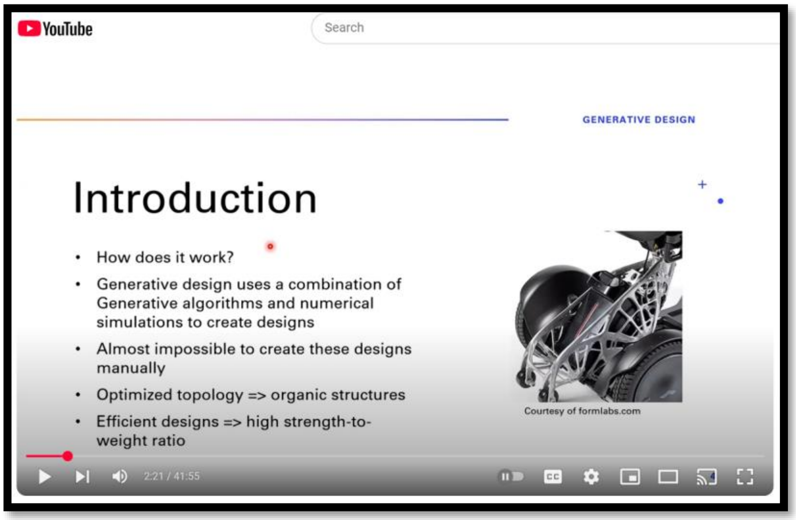


Figure 2: Generative Design Module

2.2. Golden Eagle Green Ecosystem

The Golden Eagle Green Ecosystem project represents a significant step toward sustainability by transforming plastic waste into valuable 3D-printable filaments. With the increasing global concern over plastic pollution, repurposing discarded plastic bottles into usable manufacturing materials not only reduces environmental waste but also supports a circular economy. This project enables students and researchers to explore innovative recycling techniques, demonstrating how engineering and technology can drive sustainable solutions. By converting plastic waste into high-quality filament for AM, the initiative fosters hands-on learning and problem-solving, empowering future engineers to incorporate sustainability into their design and manufacturing processes. The ability to create functional parts from recycled materials aligns with broader sustainability goals, making this an essential topic for engineering education and industry adoption.

Developing and sharing the Golden Eagle Green Ecosystem module as an OER on YouTube ensures that knowledge about sustainable AM practices reaches a global audience. By making this educational content freely accessible, we provide students, educators, and makers with the tools to implement similar recycling strategies in their own communities. YouTube's interactive platform facilitates knowledge exchange, allowing viewers to engage in discussions, share experiences, and contribute to the growing movement of sustainable manufacturing. This open-access approach lowers the barriers to entry for those interested in environmentally conscious AM and strengthens the collective effort to reduce plastic waste through technological innovation. By disseminating this module widely, we not only advance engineering education but also inspire real-world applications that support environmental responsibility.

Some of the unique features of the current module are given below:

- Synopsis

  This module explores sustainable practices in AM, focusing on converting waste materials like plastic bottles into usable filaments for AM (see Figure 3).

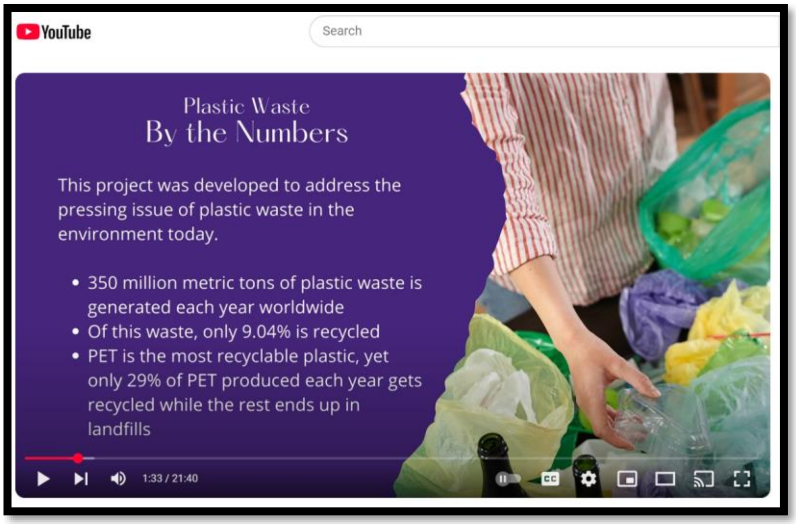


Figure 3: Recycling Plastics into Filaments for Additive Manufacturing Module

- Content
  - Theoretical insights into recycling and remanufacturing processes.
  - Practical demonstrations of bottle-to-filament conversion using specialized equipment.
  - Best practices for sustainable manufacturing in academic and professional settings.
- Applications
  - STEM classroom and laboratory activities focused on environmental engineering.
  - Outreach initiatives promoting sustainability in local communities.
  - Recruitment efforts showcasing the intersection of engineering and environmental stewardship.

2.3. Foundry in a Box

The foundry-in-a-box project brings hands-on metal casting education to students in an accessible and engaging way, allowing them to explore the fundamentals of metal casting without requiring a full-scale foundry [15]. This initiative introduces participants to key manufacturing concepts, including mold-making, molten metal handling, and solidification processes, all within a controlled and portable setup. By providing a simplified yet realistic casting experience, the project helps students understand the principles of metallurgy, manufacturing, and material science in a practical setting. This hands-on approach fosters experiential learning, making abstract engineering concepts more tangible while sparking interest in traditional and modern foundry practices. As industries continue to seek skilled professionals in advanced manufacturing, the foundry-in-a-box project serves as an effective educational tool to bridge the gap between theory and application.

By developing the foundry-in-a-box module as an OER on YouTube, we expand access to valuable manufacturing education beyond traditional classroom settings. Metal casting is often perceived as resource-intensive and inaccessible to many students due to equipment costs and safety concerns, but this module democratizes learning by providing step-by-step guidance and demonstrations in a digital format [16]. Through YouTube, students, educators, and hobbyists worldwide can learn about foundry techniques, engage with the content through discussions, and apply the knowledge in their own learning environments. Making this module freely available supports the broader mission of engineering education by fostering inclusivity, promoting hands-on learning, and encouraging interest in manufacturing careers. By leveraging the power of open-access resources, this initiative ensures that foundational knowledge in metal casting reaches and inspires the next generation of engineers and makers.

- Synopsis

  Aimed at P-16 STEM education, this module introduces "foundry-in-a-box," a portable sand casting training kit (see Figure 4). It enables schools and institutions without traditional foundries to access hands-on casting experiences.

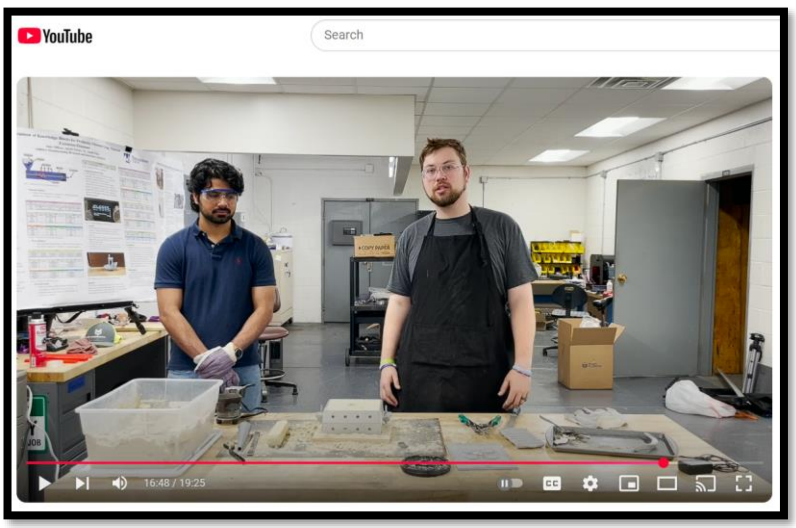


Figure 4: Portable Sand Casting Module

- Content
  - Fundamentals of sand casting and its applications in manufacturing.
  - Demonstrations of using the kit to create metal components.
  - Exercises designed to teach material properties, casting techniques, and safety.
- Applications

- Classroom and laboratory use for introducing manufacturing concepts.
- Outreach programs to inspire young learners in STEM pathways.
- Recruitment activities showcasing tangible, hands-on engineering practices.

3. Unique Features of the Developed Modules

The uniqueness of the developed OER modules lies in their hands-on, application-driven approach, which bridges the gap between theoretical knowledge and real-world engineering practices. Unlike traditional lecture-based content, these modules provide step-by-step demonstrations, practical insights, and industry-relevant applications, making complex engineering concepts more engaging and accessible. Each module—whether focused on generative design, sustainable AM, or metal casting—incorporates high-quality visuals, clear explanations, and real-time demonstrations, ensuring that learners can grasp both fundamental principles and advanced techniques. Additionally, these modules emphasize problem-solving and innovation, encouraging students to explore emerging technologies such as AI-driven design, circular economy strategies, and modern foundry practices in a way that is both interactive and approachable.

Another key distinction of these OER modules is their accessibility and adaptability, enabling global reach and diverse learning opportunities. By being freely available on YouTube, these resources remove financial and institutional barriers, allowing students, educators, and industry professionals worldwide to engage with cutting-edge manufacturing and design content at their own pace. The interactive nature of YouTube fosters a collaborative learning environment, where viewers can ask questions, share ideas, and provide feedback, creating a dynamic educational experience that evolves over time. Furthermore, the modular format makes it easy for instructors to integrate the content into existing curricula or for self-learners to tailor their learning paths. By combining open access, hands-on demonstrations, and industry relevance, these OER modules stand out as powerful tools for democratizing engineering education and fostering a deeper understanding of modern manufacturing technologies.

When the project was initiated, the following components were identified as the core for the development.

3.1. Objectives of the Project

- Educational Enhancement: Provide educators with high-quality, accessible resources to improve classroom and laboratory instruction.
- Outreach and Recruitment: Use engaging, practical demonstrations to attract prospective students to STEM disciplines.
- Sustainability Awareness: Promote environmentally conscious practices in manufacturing and design.
- Equity in Education: Bridge gaps in access to resources by providing affordable, scalable solutions like "foundry-in-a-box."

3.2. Pedagogical Impact

Project R2's resources are structured to cater to a wide range of learners, from high school students to college-level and professional audiences. Including real demonstrations, lectures, and practice exercises ensures that learners gain theoretical knowledge and practical skills. These resources support:

- Active Learning: Interactive content that encourages learners to engage with the material through practice and experimentation.
- Problem-solving skills: Real-world applications that help learners develop critical thinking and creative problem-solving abilities.
- Cross-disciplinary Connections: Integration of design, manufacturing, and sustainability concepts to prepare learners for multidisciplinary challenges.

3.3. Accessibility and Usability

The YouTube-based format ensures that the resources are:

- Free and Open Access: Available to anyone with an internet connection, eliminating financial and geographic barriers.
- Flexible: Suitable for both in-class and remote learning environments.
- Reusable: Educators can incorporate these modules into existing curricula or adapt them to specific needs.

3.4. Broader Impacts

The broader impact of these three OER modules—Generative Design, Golden Eagle Green Ecosystem, and Foundry in a Box—extends beyond classroom education, shaping the future of engineering, sustainability, and workforce development. By providing free, high-quality instructional content, these modules equip students, educators, and industry professionals worldwide with the knowledge and skills to engage with cutting-edge design and manufacturing technologies. The Generative Design module fosters innovation by introducing AI-driven optimization techniques that are transforming industries, while the Golden Eagle Green Ecosystem module promotes environmental responsibility by demonstrating how plastic waste can be repurposed into functional AM materials, reinforcing the principles of a circular economy. Meanwhile, the foundry-in-a-box module preserves and modernizes traditional metal casting techniques, making them more accessible to learners who may lack access to full-scale foundry facilities. Collectively, these modules contribute to the democratization of engineering education, reduce barriers to hands-on learning, and inspire future generations to pursue careers in advanced manufacturing, sustainable design, and digital fabrication. By leveraging the reach of YouTube as an OER platform, these modules not only enhance STEM education but also empower global learners to develop practical solutions to engineering challenges, fostering a more skilled and sustainability-conscious workforce.

Some of the unique broader impact features of the current development are given below:

- The resources are ideal for outreach programs targeting high school and community college students. They offer an engaging introduction to STEM concepts and careers.
- Demonstrations of sustainability practices and innovative technologies inspire learners to consider STEM pathways.
- Highlighting hands-on, practical aspects of engineering education helps attract prospective students by showcasing the dynamic nature of STEM fields.
- The focus on sustainability and innovation aligns with current trends, appealing to environmentally conscious learners.
- Industry professionals can use the developed modules to upskill in emerging technologies.
- STEM educators can adapt and implement the modules in their courses and laboratory practices.
- Since the modules are publicly available, they can be used in several train-the-trainers workshops and training activities.

4. Contributions

In an era where global challenges such as resource scarcity and environmental degradation demand innovative solutions, the integration of sustainability and entrepreneurial thinking into education has become essential [17][18]. The three OERs developed under this project address these challenges head-on, offering practical, accessible, and scalable learning modules. Each OER serves as a cornerstone for equipping learners with the knowledge and skills to tackle real-world problems through sustainable practices and innovative approaches. By emphasizing resource efficiency, waste reduction, and creative problem-solving, these modules foster a mindset that combines environmental responsibility with entrepreneurial vision. Together, they provide a transformative framework for shaping the future of engineering education, empowering students to create impactful, market-ready solutions that prioritize sustainability and innovation.

4.1. Generative Design

- By leveraging AI-driven optimization tools in generative design, learners are introduced to resource-efficient strategies that minimize material waste and energy consumption, promoting sustainable engineering practices [19].
- This module empowers students to adopt a forward-thinking, entrepreneurial mindset by exploring innovative design approaches that challenge conventional manufacturing paradigms [20].
- It demonstrates how computational tools can transform the product development process, encouraging the creation of environmentally conscious solutions tailored to market needs.

4.2. Green Manufacturing (Bottle-to-Filament Conversion)

- This module addresses the global challenge of plastic waste by demonstrating how discarded bottles can be transformed into functional filaments for AM, advancing the principles of sustainable resource use [19].
- It nurtures entrepreneurial thinking by encouraging learners to identify waste streams as untapped opportunities, turning them into viable, cost-effective manufacturing inputs [20].
- By integrating sustainability with AM, this OER highlights the potential for creating value while reducing environmental impact, inspiring students to innovate within green economies.

4.3. Portable Sand Casting (foundry-in-a-box)

- This OER democratizes access to traditional manufacturing techniques, making sand casting feasible for schools and communities without foundry infrastructure, reducing the environmental and financial barriers to hands-on learning.
- It emphasizes the circular economy by showing how cast components can be repurposed, repaired, or recycled, fostering a culture of sustainable manufacturing.
- By simplifying a historically complex process, this module inspires entrepreneurial innovation by enabling users to prototype and fabricate unique metal products on a small scale [20].

4.4. Collective Impact

- Together, these modules serve as a holistic platform for embedding sustainability and entrepreneurial thinking into STEM education. They teach learners to approach challenges with a mindset focused on innovation, resource optimization, and environmental stewardship.
- The project reinforces the idea that sustainability and entrepreneurship are not just compatible but essential for addressing modern engineering challenges, preparing students to become leaders in a rapidly evolving global economy.
- By making these resources freely available, the initiative amplifies its impact, equipping educators and students worldwide with the tools to drive meaningful change in their communities and industries.

5. Beta Testing

In the summer of 2024, a hands-on training workshop was held to present the developed modules to STEM educators (see Figure 5). The attendees were diverse in terms of roles, age, race/ethnicity, and gender. Among the attendees, 55.6% were STEM graduate students, while 44.4% were STEM educators. The majority, 55.6%, were in the 25-34 age range, with smaller percentages in the 35-44, 45-54, 55-64, and 65-74 age ranges, each representing 11.1% of the attendees.

Figure 5: Hands-on Activities held during the Workshop

In terms of race and ethnicity, 55.6% identified as White, 33.3% as Asian, and 11.1% as Arab. Gender identification was predominantly male, with 88.9% identifying as male and 11.1% as female (see Table 1). Overall, the group was mainly composed of young to middle-aged STEM graduate assistants and educators, with a higher representation of males and a significant presence of White and Asian individuals.

Table 1. Attendee Demographics

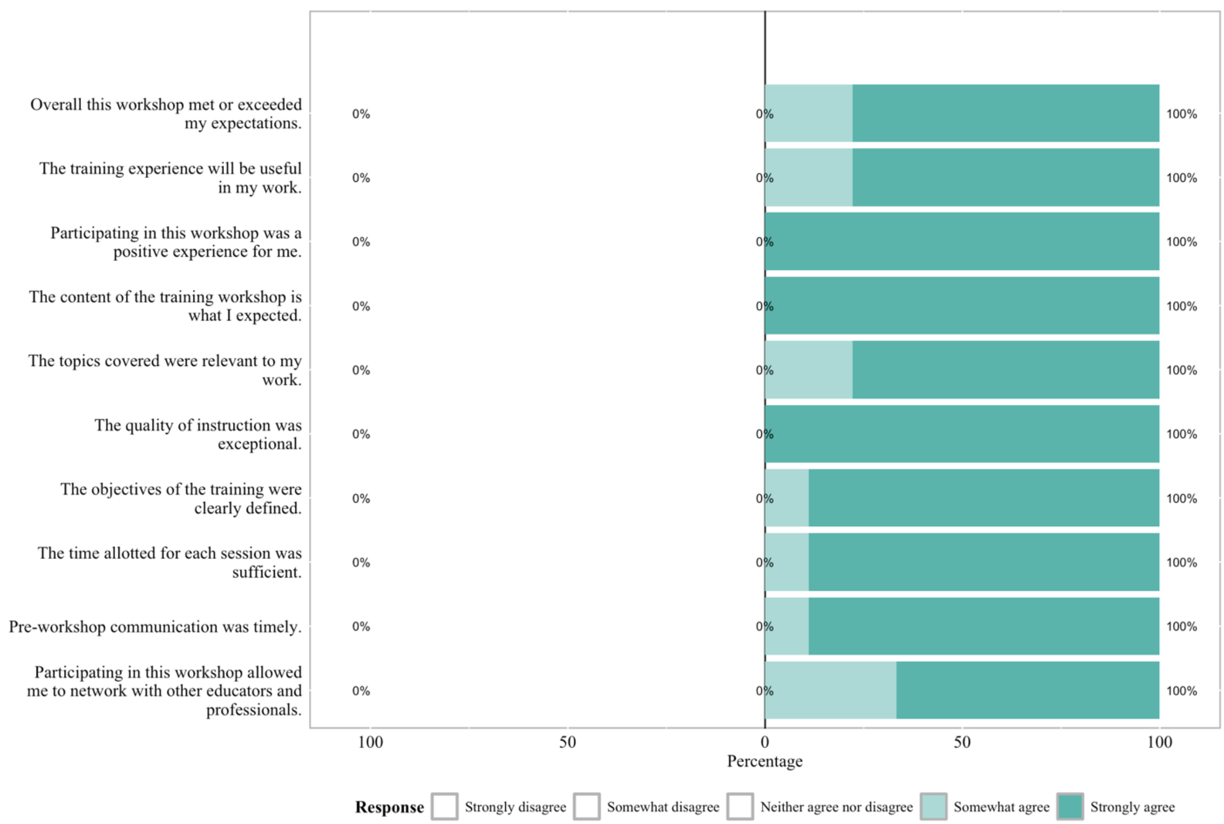
Attendee Role Distribution		
	Frequency	Percent
STEM Educator	4	44.4
STEM Graduate student	5	55.6
Total	9	100.0
Age Distribution		
	Frequency	Percent
25 - 34	5	55.6
35 - 44	1	11.1
45 - 54	1	11.1
55 - 64	1	11.1
65 - 74	1	11.1
Total	9	100.0
Race/Ethnicity Distribution		
	Frequency	Percent
White	5	55.6
Asian	3	33.3
Arab	1	11.1
Total	9	100.0
Gender Distribution		
	Frequency	Percent
Male	8	88.9
Female	1	11.1
Total	9	100.0

5.1. Satisfaction with Overall Workshop

Workshop attendees were asked about their satisfaction with several aspects of the workshop. Table 2 presents the participants' responses. Notably, every participant agreed with all the statements, indicating unanimous satisfaction across all measured items. Specifically, 100% of respondents felt that the workshop met or exceeded their expectations and found the training experience useful in their work. They unanimously agreed that participating in the workshop was a positive experience and that the content matched their expectations. Additionally, all respondents agreed that the topics covered were relevant to their work and that the quality of instruction was exceptional.

Moreover, participants strongly agreed that the training objectives were clearly defined and that the time allotted for each session was sufficient. They also confirmed that pre-workshop communication was timely. Lastly, everyone agreed that the workshop provided valuable networking opportunities with other educators and professionals. This unanimous agreement across all survey items highlights the workshop's overall success and the high level of satisfaction among its participants.

Table 2: Attendee Overall Satisfaction with Various Aspects of the Workshop



5.2. Perceived Improvement in Content Knowledge

Table 2 presents the results of retrospective pretest items assessing participants' self-reported knowledge gains in three specific areas after attending the workshop. Participants responded to the statement, "As a result of attending the workshop, I now have better knowledge of…" using a 5-point Likert scale ranging from "Strongly disagree" to "Strongly agree." The results for each item are as follows:

- *Producing products with no-cost filament via green manufacturing technologies:* Half of the participants (50%) strongly agreed that they now have better knowledge of producing products with no-cost filament using green manufacturing technologies as a result of attending the workshop. The other half (50%) somewhat agreed with this statement, indicating a high level of knowledge improvement among all participants.
- *Transforming casting to daily life using foundry-in-a-box technology:* All participants (100%) strongly agreed that their knowledge of transforming casting to daily life using foundry-in-a-box technology has improved due to the workshop. This unanimous agreement indicates that the workshop was highly effective in enhancing participants' understanding in this area.
- *Generative Design using Fusion:* A majority of participants (75%) strongly agreed that they gained better knowledge of generative design using Fusion 360 from the workshop. The remaining 25% somewhat agreed.

5.3. Participants Main Takeaways from the Workshop

Participants were asked to express in their own words what their main takeaways from the workshop were. The verbatim statements by the attendees are organized in Table 3, categorized into two themes: 1. Engaging the learners with hands-on activities and 2. Newly developed OER modules and their applications.

The participants valued the hands-on experience with foundry-in-a-box, gained significant knowledge about casting and generative design, and appreciated the practical applications of the developed modules, especially for educational purposes in high schools. The live demo by the project leaders was a standout component of the workshop.

Table 3: Participants' Takeaways from the Training Workshop

Hands-on activities	**OER modules and their applications**
- *Casting process, Fusion software, Filament making* - *Foundry-in-a-box experience and generative design knowledge* - *Gained knowledge about casting and generative design* - *Intro to casting in a box and resources for generative design* - *Learning about casting and generative design* - *The best thing is working with foundry-in-a-box with a live demo*	- *Three OER modules developed were presented* - *They are all STEM-based and useful for state-of-the-art manufacturing education* - *These are all interesting applications for high schools*

5.4. Overall Evaluation Summary

Participants reported significant knowledge gains in three key areas: producing products with no-cost filament using green manufacturing technologies, transforming casting to daily life using foundry-in-a-box technology, and generative design using the Fusion software tool. The Net Promoter Score (NPS) was a perfect 100, indicating that every participant would highly recommend the workshop [21].

Verbatim feedback highlighted participants' appreciation for the opportunity, the organization of the event, and the need for more such workshops. Key takeaways included hands-on experience with foundry-in-a-box, knowledge about casting and generative design, and the practical applications of developed STEM-based modules for high school education. The live demonstration of the foundry-in-a-box was a standout component. Participants also expressed the need for further support in specific areas such as casting in a box and more details on generative design software. Overall, the workshop was deemed highly successful and beneficial.

Conclusion

Project R2: Redesigning and Remanufacturing the Entrepreneurial Future represents a significant contribution to STEM education. By offering accessible, high-quality resources that integrate cutting-edge technologies and sustainable practices, the project equips educators, students, and professionals to thrive in an increasingly complex and interconnected world. Whether in classrooms, laboratories, or outreach events, these OERs serve as powerful tools for fostering innovation, sustainability, and inclusivity in STEM education.

Future Work

While the initial evaluation of the three OER modules was conducted in a retroactive format, future research should incorporate pre- and post-assessments to quantitatively measure knowledge gains among participants. A structured evaluation framework will provide deeper insights into how effectively these modules enhance conceptual understanding compared to traditional instructional methods. Additionally, comparative performance studies between students using the OER modules and those following conventional learning approaches will help assess their pedagogical impact and identify areas for further refinement. By systematically analyzing learning outcomes, we can refine content delivery, improve engagement strategies, and optimize instructional design for broader adoption.

Future work will also investigate potential barriers to adoption, such as infrastructure requirements, instructor readiness, and student accessibility. Some institutions may lack the necessary hardware, such as 3D printers or metal casting kits, limiting the practical implementation of certain modules. Additionally, educators may require training and professional development to effectively integrate these OER resources into their curricula. Research on digital accessibility is equally important, ensuring that students across different socio-economic backgrounds can benefit from these resources.

Another key direction for future work is expanding the reach of these OER modules to a broader audience beyond the initial group of STEM educators. While the feedback suggests that participants found the content appropriate and useful, further research could explore how different learner groups—such as community college students, industry professionals, or high school educators—engage with and benefit from these resources. Additionally, refining the modules based on participant feedback can help target specific areas for improvement, such as enhancing interactive components, incorporating more case studies, or developing supplementary materials like quizzes or discussion guides. Future research could also examine the long-term retention of knowledge gained through OERs and investigate ways to integrate these resources into formal accreditation programs or continuing education initiatives. By identifying the most impactful next steps, the research can guide strategic improvements and broader adoption of these OERs in diverse educational settings.

Acknowledgments

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