FrED Factory Production Labs: An Experiential Activity Translating Product Design to Manufacturing in a Learning Factory

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Abstract

Bridging the gap between product design and manufacturing education remains a central challenge in academic institutions. This paper presents the FrED Factory Production Labs, an experiential learning activity that immerses students in the end-to-end process of translating product design to designing and operating a manufacturing system in a learning factory. Working in teams, students design, operate, and continuously improve a small-scale factory to assemble real shippable products, with the goal of maximizing production performance indicators such as throughput, yield, and quality. In the first week, teams translate product and process knowledge into a detailed manufacturing plan, designing workstation layouts, material flows, operator roles, and digital work instructions. In the second week, they conduct their first production run, assembling real products while collecting time and performance data to identify bottlenecks and opportunities for improvement. Between runs, teams analyze results and refine their layouts, then perform a second production run in the final week to test their redesigned system. The challenge integrates core manufacturing concepts, including design-to-manufacturing translation, production planning, data-driven continuous improvement, and team operations, giving students a hands-on understanding of how factory design impacts performance. To evaluate learning impact, a pre- and post-activity assessment was conducted using questions aligned with the intended learning outcomes, complemented by a survey based on the Intrinsic Motivation Inventory (interest/enjoyment, perceived competence, value/usefulness subscales) to explore motivational mechanisms. The FrED Factory Production Labs Challenge provides a replicable, authentic platform for integrating design and manufacturing education in a learning factory, cultivating systems-level thinking and practical skills essential for modern manufacturing engineers.

1. Introduction and Background

In manufacturing education and training, a common baseline has been traditional classroom instruction (lecture/presentation-centered), with limited proximity to authentic production problem-solving contexts [1]. This approach can build conceptual foundations, but it often leaves a gap between knowing manufacturing and doing manufacturing, particularly in terms of competence development for real production contexts, where learners must act within a production system and understand cause-and-effect through their own interventions [2]. Recent work in manufacturing education argues that relying heavily on classroom instruction tends to underexpose students to the messy, feedback-rich conditions of real production, where learning depends on iteration, data, and reflection [3]; similarly, universities have addressed this gap by using learning factories that let students learn and practice production systems directly in near-real settings [4].

Learning Factories have emerged specifically to close this theory-practice gap by providing reality-conform production environments where learners can plan and run production, observe system behavior, and improve the performance using real metrics [3]. The learning factory literature consistently frames learning factories as a bridge between education/research and industrial practice, enabling competency development in areas like production planning, lean improvement, and (in many modern implementations) Industry 4.0 technologies [5]. However, many learning factories still concentrate on modules (like lean tools, isolated process stations, technology demonstration) rather than the end-to-end lifecycle that manufacturing engineers face from product definition to an operational factory plan, from first run redesign based on evidence, and from individual technical tasks to coordinated team execution [6].

While some learning factories focus primarily on engineering and manufacturing education and on teaching core concepts, the FrED Factory stands apart from similar environments. The FrED Factory is a learning factory that produces low-cost educational Fiber Extrusion Devices (FrEDs) [7]. It is a learning factory at the Massachusetts Institute of Technology (MIT), where it produces and ships the previously mentioned devices as actual products to real customers; therefore, it presents itself as a realistic environment in which teaching new manufacturing concepts to students and peers is accompanied by providing actual, valuable output. For this reason, the FrED Factory provides an authentic environment for teaching new manufacturing concepts with hands-on experiences.

While one of the goals of FrED Factory is to mass-produce FrEDs, it also aims to teach; therefore, an immersive experiential learning activity was designed for students to allow them to create, plan, and run their own factory line layout, while also serving as a platform for actual factory production output. This activity, known as FrED Factory Production Labs, demonstrates a unique standpoint on manufacturing education in learning factories, where translating a product design to a manufacturing plan becomes the main focus and core concept, teaching participants how to properly design, measure, and run a factory. The activity teaches students valuable industry skills that are often overlooked in most university engineering programs, where learning how to manage a production line involves being present in a factory context, which academic environments often lack. This framing positions FrED Factory Production Labs as a learning-factory activity that preserves the "hands-on factory" benefits while extending them toward systems integration, iterative work with real performance data, and professional operations competencies that can be underdeveloped when manufacturing education remains predominantly classroom-based [8], while still operating within a university setting.

This paper presents the design and implementation of FrED Factory Production Labs, including its alignment with intended learning outcomes (ILOs), execution, and evaluation of student performance. The development framework and assessment methods are designed to be reliable, adaptable, and replicable for similar learning-factory activities, providing a practical methodology for manufacturing education in industrial learning environments. The paper positions FrED Factory Production Labs as a model for teaching core manufacturing scale-up concepts through hands-on experiences.

2. Activity Objectives and Design Approach

2.1. Activity Objectives

The objectives of FrED Factory Production Labs are two-fold: to deliver authentic education on the design and operation of manufacturing systems, and to achieve real factory throughput to support FrED Factory's production.

2.2. Backward Design Approach

FrED Factory Production Labs was designed around four ILOs that reflect core competencies required for manufacturing engineers. These outcomes focus on integrating product design knowledge with manufacturing system design, operational execution, and continuous improvement, which are widely recognized objectives of learning factory–based education in manufacturing [3][4]. The ILOs were defined before designing the activity, following a backward design approach [9]. In this approach, learning outcomes and assessment evidence are specified first, and the activity structure and constraints are then designed to ensure that students must produce that evidence through authentic performance [9][10]. They were used to guide the design process and structure of the learning factory experience, aligning with competency-oriented and outcome-based educational frameworks [2]. These outcomes provide a structured framework for developing professional and systems-level skills within a learning factory environment [11].

2.3. Intended Learning Outcomes (ILOs)

2.3.1. ILO1 - Design-to-Manufacturing Translation

Students will be able to translate a product design into a manufacturing plan that defines process selection, workstation setup, and material flow. This includes developing a factory configuration or layout proposal that links product structure, such as bills of materials or CAD models, to process steps and assembly operations, a core characteristic of effective learning factory implementations [4]. Through this outcome, students demonstrate an understanding of how design decisions influence manufacturability, process complexity, and production feasibility, a key competency developed through learning factory–based education [1]. Additionally, students are expected to reason about trade-offs between product design choices and manufacturing system performance, consistent with prior work emphasizing design and manufacturing integration in experiential manufacturing education [3].

2.3.2. ILO2 - Production Planning and Line Layout Optimization

Students will be able to design and justify a production layout that optimizes efficiency, material flow, and resource utilization while minimizing bottlenecks and unnecessary movement. This outcome requires students to apply analytical tools and techniques, such as process analysis and discrete-event simulation, to support layout decisions, aligning with analytical approaches commonly used in learning factories to foster production-planning competencies [2]. Students also apply core manufacturing concepts, including line balancing, Takt Time, and lean manufacturing principles, to achieve a stable and balanced production flow, as reported in multiple learning factory studies focused on operational excellence and continuous improvement [11]. Furthermore, students evaluate alternative layout configurations using quantitative performance metrics such as lead time, cycle time, work-in-process (WIP), and throughput, aligning with established evaluation practices in learning factory research [12].

2.3.3. ILO3 - Production Data Analysis and Continuous Improvement

Students will be able to identify performance bottlenecks and implement targeted improvements in layout, process design, or resource allocation to enhance overall system efficiency. This outcome highlights the importance of utilizing production data and system performance metrics collected during manufacturing runs to evaluate system behavior, a central element of continuous improvement learning in factory-based education [13]. Students analyze this data to diagnose inefficiencies and support evidence-based decision-making, drawing on findings from empirical studies on competency development in learning factories. Based on these insights, students develop and execute revised production strategies that reflect learning from previous iterations and support higher-yield, more scalable manufacturing systems [5].

2.3.4. ILO4 - Team Operations and Professional Practice

Students will be able to collaborate effectively within a production team by managing defined operator and support roles to meet shared performance goals. This outcome emphasizes the development of professional behaviors such as accountability, communication, and coordination, which are consistently identified as essential learning outcomes of learning factory environments [14]. Students are also expected to demonstrate safety awareness and professionalism during factory setup, operation, and reflection activities, aligning with prior learning factory implementations that emphasize authentic industrial practice [3]. Finally, students clearly articulate their methodology, outcomes, and reflections, explaining how planning, execution, and iteration contributed to overall factory performance, consistent with outcome-based education and structured assessment approaches [15].

3. FrED Factory Production Labs

3.1. Activity Overview

The goal of FrED Factory Production Labs is to design the most productive configuration of the FrED Factory to manufacture as many high-quality FrED Electronics and FrED Extruder subassemblies as possible, see Figure 1. Working in teams, students are challenged to configure a manufacturing system that balances throughput, quality, and resource utilization at the factory level. Teams prepare and execute two production runs using their proposed factory configuration. System performance is evaluated through a point-based scoring system that considers production throughput, yield, and quality outcomes. Only fully inspected and compliant pairs of Electronics and Extruder subassemblies contribute to the team score.

At the end of the two production runs, the team with the highest overall score is recognized as the winning team. The competitive structure provides a clear performance objective while reinforcing system-level thinking and trade-off analysis in manufacturing system design.

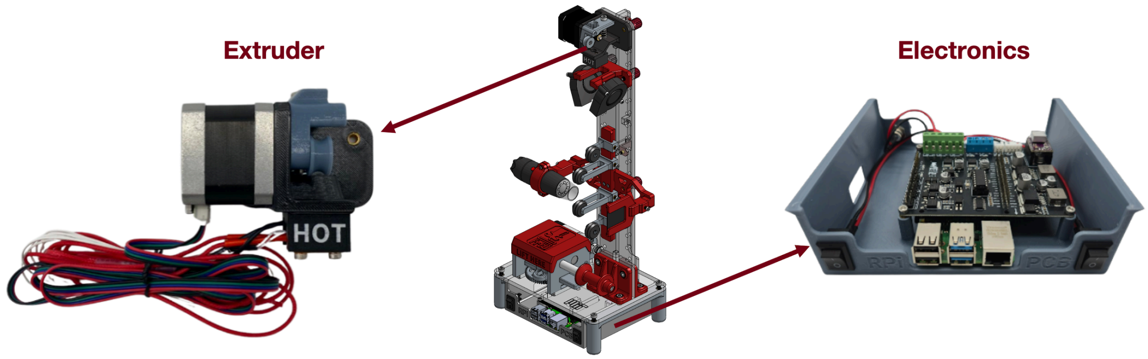

Figure 1. FrED Subassemblies produced during Production Labs

3.2. Activity Timeline/Schedule

FrED Factory Production Labs is conducted over a four-week period structured around a production planning phase followed by two production executions. The timeline is shown in Fig 2.

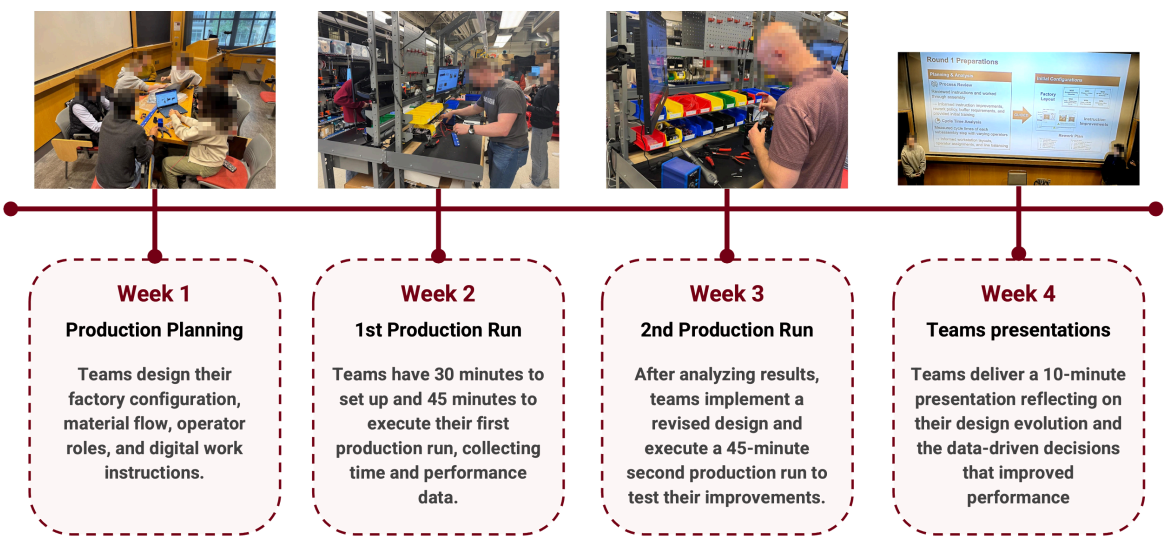

Figure 2. Timeline of FrED Factory Production Labs

During Week 1, teams design the factory configuration for assembling the Electronics and Extruder subassemblies. Teams are required to define factory and workstation layouts, define material flow, assign roles, define rework strategies, and create standardized digital work instructions. To support this planning phase, teams are provided with a common set of reference materials, including the factory layout, assembly manuals for both subassemblies, a factory configuration template, the bill of materials, and CAD models of the components. These resources establish a shared technical baseline and enable teams to understand product structure and assembly requirements before designing their production system.

Week 2 is dedicated to the first production run, during which teams execute their planned factory configuration under fixed operational constraints. This run serves as the baseline evaluation of system performance and generates the data required to assess throughput, quality, and system behavior. Between runs, teams analyze the results of the first execution and revise their factory configuration based on observed bottlenecks, inefficiencies, and quality issues. The second production run is conducted in the third week, in which teams implement their redesigned configuration under the same conditions as the first run. Performance across both runs is used for final scoring and evaluation.

The activity concludes in Week 4, when teams deliver their final presentation, outlining their design decisions and reflecting on what they have learned.

3.3. Scoring

Team performance in FrED Factory Production Labs is evaluated using a scoring system that links production output, quality, and cost considerations. Points are awarded exclusively for fully inspected and compliant pairs of Electronics and Extruder subassemblies. Individual subassemblies produced without a corresponding pair do not contribute to the team score. This rule adds realism to production planning, since only a corresponding pair constitutes a shippable product.

The scoring system rewards value-added production by assigning points proportional to the economic value of each completed subassembly pair, while defective parts, scrap, and damaged components result in point deductions based on their associated unit costs. This structure explicitly penalizes poor quality and inefficient material usage, requiring teams to balance throughput with yield and rework decisions.

Scores are accumulated across both production runs, and the final ranking is determined by total points earned. By tying performance directly to paired output and quality-controlled production, the scoring mechanism reinforces system-level trade-offs among speed, quality, and resource utilization, rather than optimizing isolated workstations.

3.4. Factory Setup

Prior to each production run, teams are given 30 minutes to set up their factory. This includes configuring each workstation with the required tools, storage bins, unit components, and digital work instructions.

3.4.1. Factory Layout

FrED Factory Production Labs is conducted within a predefined learning factory floorplan comprising six assembly workstations and one centralized quality control (QC) station, as shown in Figure 3. Teams assign assembly tasks and operators to these workstations based on their production plan, while the QC station is operated exclusively by instructors. The fixed spatial layout establishes common physical constraints across all teams, necessitating system-level decisions on task allocation, flow paths, and coordination among parallel subassembly lines.

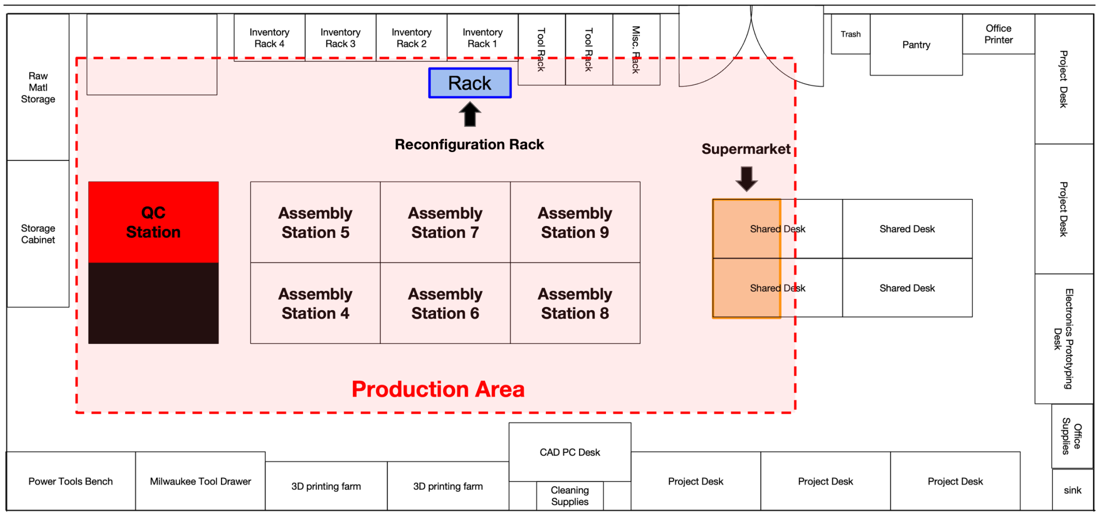

Figure 3. FrED Factory Production Labs Layout

3.4.2. Workstation setup

During the setup period, teams configure their assigned workstations by retrieving materials, bins, and selected equipment from a centralized supermarket and a reconfiguration rack. All components required for both subassemblies are stored in standardized bins, and material usage is logged to maintain inventory traceability. Hand tools are available at each workstation, while powered equipment is limited. These shared resources introduce intentional constraints that require teams to plan tool allocation, task sequencing, and material flow as part of their factory design. Figure 4 shows the resources available for factory setup, and Figure 5 shows an example of a configured workstation.

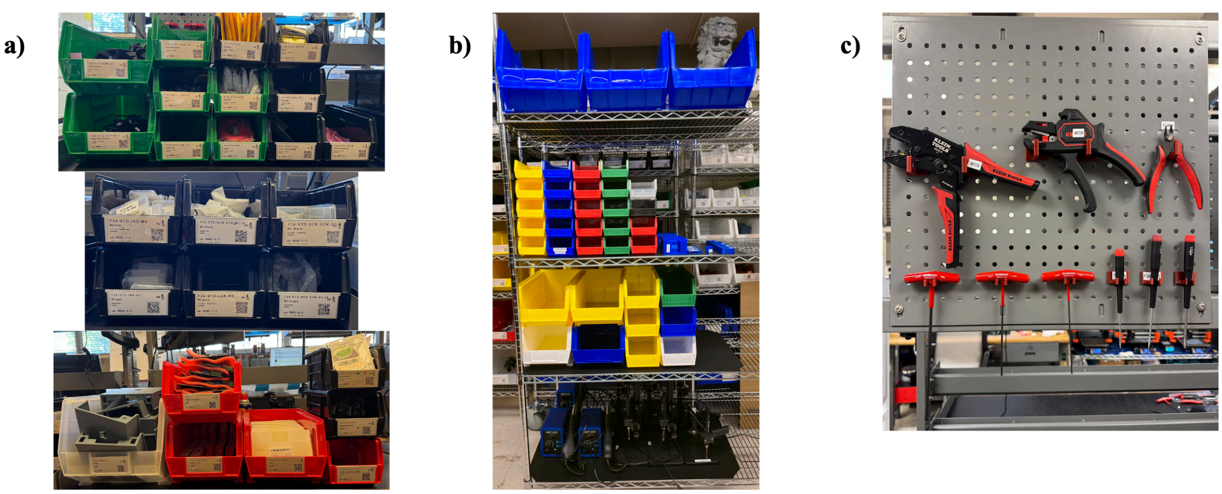

Figure 4. (a) Supermarket (b) Reconfiguration rack (c) Tool wall

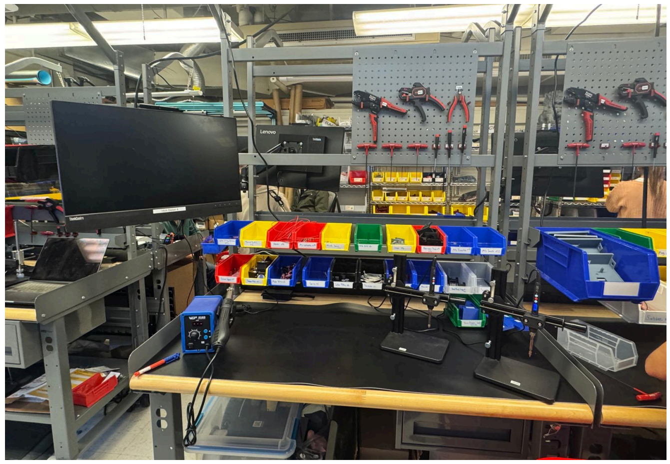

Figure 5. An example of a configured workstation

3.4.3. Work Instructions

As part of the production planning phase, teams design standardized digital work instructions for each workstation, defining task sequences and required confirmations. Teams would submit their work instructions to the instructors prior to the production run. These instructions are implemented and deployed by the teaching team using Tulip Interfaces, ensuring consistency across production runs. Figure 6 shows examples of work instructions that teams have made.

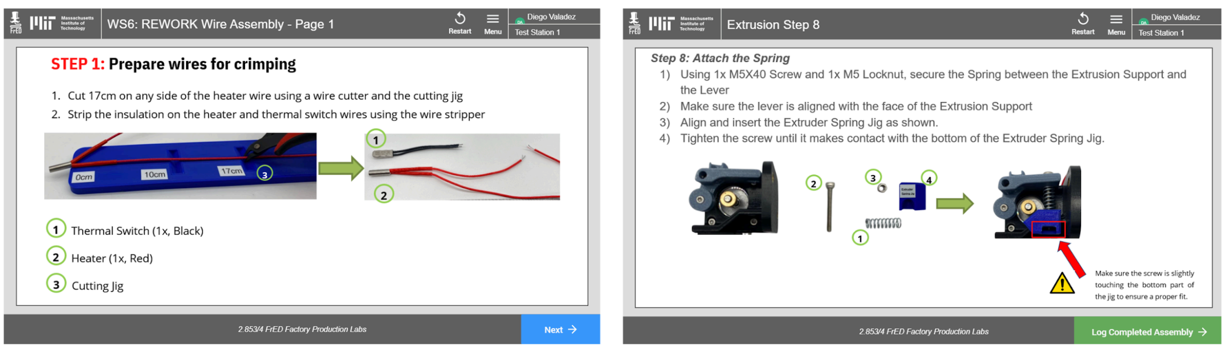

Figure 6. Two example Digital Work Instructions made with Tulip Interfaces

During production, operators must follow the displayed instructions and confirm task completion in real time. Tulip Interfaces' built-in time-study functionality enables the collection of task-level cycle-time data, making production performance transparent and comparable. The availability of structured execution data supports data-driven analysis and informs system redesign between production runs.

3.5. Production Run

Each production run is executed as a fixed-duration manufacturing session consisting of a 30-minute setup period followed by a 45-minute production window. Once production starts, teams must operate strictly within their predefined factory configuration. Workstation configurations and resource assignments may not be modified to simulate real production startup conditions, emphasizing the importance of upfront system design.

3.5.1 Quality Control

All completed subassemblies are submitted to an instructor-operated quality control station for inspection against predefined acceptance criteria, shown in Figure 7. Only subassemblies that pass inspection are counted as valid output and contribute to team scoring. If a subassembly fails inspection, it is returned to the final workstation with the reason for failure specified. Teams must then decide whether to scrap the unit and accept the associated point deduction, or route it through rework if rework procedures were explicitly designed into the factory configuration. This quality control structure ensures that production performance reflects not only throughput, but also yield, rework strategy, and system robustness.

a)

b)

Extruder Quality Check

Line No.	Inspection	Pass/ Fail
1	The inspector must make sure that the idler pulley does not have trouble freely spinning; it should be untight but not loose.	
2	The lever should be easy to press and move, without creating too much friction with the extruder support or its screw.	
3	The motor is attached with four screws into the printed Extruder support.	
4	Ensure that the motor connector and its wires are facing downward, as this is the correct orientation.	
5	The driver gear in the stepper motor shaft is correctly oriented. It is important that the side with the tightening screws of the gear is facing against the motor.	
6	The heater, the thermistor and the thermal switch cannot be pulled out with ease. The inspector should slightly pull the wires to verify they are attached to the heatblock.	
7	The Stepper motor wires must be connected to the motor and they must be bundled up with a twist tie.	

Figure 7. a) Extruder subassemblies accepted by QC inspection. b) QC checklist

3.6. Alignment of Activity with ILOs

Within this structure, each intended learning outcome is explicitly instantiated through the required activities and generated artifacts. The production planning phase, supported by product documentation, MBOMs, and CAD models, targets ILO1 by requiring teams to translate product designs into executable manufacturing systems. The design and justification of full factory configurations, coupled with paired-subassembly production and point-based performance evaluation, operationalize ILO2 by forcing teams to balance flow, capacity, and resource utilization at the system level. The two-run experimental structure, supported by standardized data collection and performance metrics, embeds ILO3 by making evidence-based diagnosis and redesign central to the activity. Finally, the role structure, safety constraints, and requirement to formally document and present outcomes situate technical work within authentic professional and team-based manufacturing practice, directly supporting ILO4.

4. Evaluation of Learning Outcomes

4.1. Study Objectives and Research Questions

A study was conducted to investigate the effectiveness of FrED Factory Production Labs. The study focused not only on learning gains but also on motivational effects grounded in Self-Determination Theory (SDT). Based on these objectives, the following research questions were elaborated to guide the present investigation:

- **RQ1:** To what extent does participation in Production Labs improve students' understanding of concepts on design and operation of manufacturing systems?
- **RQ2:** How does Production Labs influence students' interest, perceived competence, and value in the design and operation of manufacturing systems tasks?
- **RQ3:** How do students describe their learning experiences, design decisions, and perceived challenges when designing and operating a factory?

4.2. Study Instruments

Concept Inventory (CI). Student learning gains are primarily measured through a CI pre- and post-activity test, aligning with RQ1. The assessment comprised nine technical multiple-choice questions that addressed all four intended learning outcomes.

Intrinsic Motivation Inventory. Student engagement was evaluated using the Intrinsic Motivation Inventory (IMI) [16][17], a multidimensional instrument designed to assess participants' subjective experience of an activity. A total of nine questions from three subscales, Interest/Enjoyment, Perceived Competence, and Value/Usefulness, were chosen and formulated as a pre- and post-test. The pre- and post-test aims to investigate the change in students' engagement due to the activity, aligning with RQ2.

Open-Ended Questions. Open-ended questions were asked in the post-activity survey to further gain insights into students' experience and challenges during the activity, aligning with RQ3.

The specific questions and results are presented and discussed in a later section.

4.3. Study Procedures and Participants

The activity was deployed in a graduate-level Manufacturing Systems course at MIT in the Fall 2025 semester. Students were asked to complete the pre-activity survey, attend all activity sessions, and finally complete the post-activity survey. All students in the course are required to participate in the activity as one of the lab components. Before the activity, all students had attended lectures and completed homework on topics relevant to the activity, such as operations management and line design, which exposed them to theoretical concepts. This course activity is attended by 25 students, split into three teams. Out of these, $n = 14$ consented to participate in the study and completed both pre- and post-activity surveys. The study is IRB exempt.

5. Results and Discussion

5.1. RQ1: Learning Gains

Table 1 summarizes the percentage of correct responses for each question before and after the activity. Overall, students demonstrated a high level of prior knowledge (overall mean score of 86.67%) before the intervention, with pre-activity scores exceeding 80% on eight of the nine CI items and reaching 100% on four items. As a result, limited overall gains were observed across most questions, indicating a ceiling effect that constrained measurable improvement.

No changes were observed for items aligned with ILO2, and minimal increases were observed for items aligned with ILO1, where pre-activity performance was already high (80-100%).

However, performance on ILO4 remained stable for one item and decreased slightly for one item (CI 9: -6.67%), though scores remained above 90%. Notable improvements were observed for items aligned with ILO3, with increases of +13.33% for both items. These gains indicate improved student reasoning about production metrics and system-level trade-offs in continuous improvement.

Taken together, the results indicate that while overall conceptual gains were limited due to high baseline performance, the FrED Factory Production Labs activity contributed positively to learning outcomes related to production data analysis and system-level reasoning, which were central to the hands-on design and operation tasks emphasized in the activity.

Table 1. Pre- and post-activity Concept Inventory questions and scores (n = 14)

ID	Concept Inventory Questions	Pre-Scores (%)	Post-Scores (%)	Delta Scores (%)
ILO1: Design-to-Manufacturing Translation		**96.67**	**100.00**	**3.33**
CI 1	In linking a product's BOM to process steps, what principle ensures the manufacturing plan accurately represents assembly dependencies?	100.00	100.00	0.00
CI 6	During time-study analysis, one operator reports performing additional handling tasks not captured in the standard work. What should the team conclude?	93.33	100.00	6.67
ILO2: Production Planning and Line Layout Optimization		**86.67**	**86.67**	**0.00**
CI 2	Two alternative line layouts yield the following metrics in simulation. Which layout demonstrates a better system-level trade-off?	80.00	80.00	0.00
CI 3	If the target takt time is 45 seconds and one station's cycle time is 60 seconds, which action is most effective for balancing the line?	100.00	100.00	0.00
CI 4	A team observes that WIP accumulates between Stations 2 and 3 despite both having similar average cycle times. Which hypothesis best explains this?	80.00	80.00	0.00
ILO3: Production Data Analysis and Continuous Improvement		**63.33**	**76.67**	**13.33**
CI 5	After implementing layout changes, the team notes: cycle time ↓ 10%, throughput ↑ 5%, but WIP ↑ 30%. What likely occurred?	46.67	60.00	13.33
CI 7	In the second production run, yield improves but throughput decreases. What systemic issue could explain this?	80.00	93.33	13.33
ILO4: ILO4 - Team Operations and Professional Practice		**100.00**	**96.67**	**-3.33**
CI 8	A misunderstanding occurs because two operators use different terminology for the same assembly step. What preventive strategy should have been in place?	100.00	100.00	0.00
CI 9	If operators rely on spontaneous problem-solving without informing others, what risk emerges?	100.00	93.33	-6.67
Overall Score		**86.67**	**89.63**	**2.96**

5.2. RQ2: Intrinsic Motivation Inventory

Table 2 summarizes the mean scores and standard deviations for each subscale before and after the activity. Overall, students reported high baseline levels of interest and perceived value prior to the intervention, with pre-activity means exceeding 6.0 on a 7-point scale for both the

Interest/Enjoyment and Value/Usefulness subscales. As a result, only small increases were observed for these dimensions following the activity. Mean Interest/Enjoyment increased from 6.083 (SD = 1.016) to 6.367 (SD = 0.860), and mean Value/Usefulness increased from 6.222 (SD = 0.742) to 6.400 (SD = 0.580). In contrast, a substantial increase was observed for Perceived Competence. The mean perceived competence score increased from 3.733 (SD = 1.132) prior to the activity to 5.600 (SD = 0.949) after the activity, corresponding to a mean gain of 1.867 points. Both items in this subscale exhibited similar improvements, indicating that students felt significantly more skilled and capable in design and operation tasks following participation in FrED Factory Production Labs.

Taken together, these results indicate that while the activity had a limited impact on students' already high interest and perceived value, it was particularly effective in enhancing students' perceived competence in manufacturing system design and operation, a key motivational construct within Self-Determination Theory.

Table 2. Pre- and post-activity Intrinsic Motivation Inventory questions and scores (n = 14)

ID	**IMI Questions** **Options:** Not at All True (1) – Somewhat True (4) – Very True (7) **Note:** Items marked with (R) are reverse-coded prior to analysis so that higher values consistently indicate higher intrinsic motivation.	**Pre-Mean (SD)**	**Post-Mean (SD)**	**Delta Mean (SD)**
Interest / Enjoyment		**6.083 (1.016)**	**6.367 (0.860)**	**0.283 (-0.156)**
IMI 1	(Pre) This activity sounds fun to do. (Post) Production Labs was fun to do.	5.867 (1.506)	6.467 (0.834)	0.600 (-0.672)
IMI 2	(Pre) I think the design and operation of manufacturing systems is boring. (R) (Post) I thought Production Labs was a boring activity. (R)	6.133 (1.407)	6.400 (0.910)	0.267 (-0.497)
IMI 3	(Pre) The design and operation of manufacturing systems does not hold my attention at all. (R) (Post) Production Labs did not hold my attention at all. (R)	6.267 (1.223)	6.400 (0.737)	0.133 (-0.486)
IMI 4	(Pre) I would describe the design and operation of manufacturing systems as very interesting. (Post) I would describe Production Labs as very interesting.	6.067 (0.799)	6.200 (1.082)	0.133 (0.284)
Perceived Competence		**3.733 (1.132)**	**5.600 (0.949)**	**1.867 (-0.183)**
IMI 5	(Pre) I think I am pretty good at the design and operation of manufacturing systems. (Post) I think I am pretty good at Production Labs.	3.933 (1.100)	5.800 (1.014)	1.867 (-0.086)
IMI 6	(Pre) I am pretty skilled at the design and operation of manufacturing systems. (Post) I was pretty skilled at Production Labs.	3.533 (1.407)	5.400 (1.056)	1.867 (-0.352)
Value / Usefulness		**6.222 (0.742)**	**6.400 (0.580)**	**0.178 (-0.162)**
IMI 7	(Pre) I believe the design and operation of manufacturing systems could be of some value to me. (Post) I believe Production Labs could be of some value to me.	6.267 (0.961)	6.267 (0.704)	0.000 (-0.257)

ID	**IMI Questions** **Options:** Not at All True (1) – Somewhat True (4) – Very True (7) **Note:** Items marked with (R) are reverse-coded prior to analysis so that higher values consistently indicate higher intrinsic motivation.	**Pre-Mean (SD)**	**Post-Mean (SD)**	**Delta Mean (SD)**
IMI 8	(Pre) I think this activity will be important to do because it can increase my understanding of the design and operation of manufacturing systems. (Post) I think Production Labs is important to do because it can increase my understanding of the design and operation of manufacturing systems.	6.000 (1.195)	6.467 (0.640)	0.467 (-0.555)
IMI 9	(Pre) I think doing this activity could help me to enhance my design and operation of manufacturing systems skills. (Post) I think doing Production Labs could help me to enhance my design and operation of manufacturing systems skills.	6.400 (0.737)	6.467 (0.640)	0.067 (-0.097)

5.3 RQ3: Experience and Feedback

To address RQ3, student responses to the four open-ended post-activity survey questions were analyzed using an inductive thematic analysis approach. Responses were reviewed to identify recurring patterns related to students' learning experiences, design reasoning, perceived challenges, and suggestions for improvement. Initial codes were iteratively grouped into higher-level themes that captured common perspectives across participants. Representative excerpts are used below to illustrate each theme.

Below are the four questions asked to students:

- **OE1.** What was the most valuable or interesting part of Production Labs for you, and why?
- **OE2.** What insights or skills did you gain from participating in Production Labs?
- **OE3.** What did you find the most challenging or troublesome during Production Labs?
- **OE4.** What can be improved about Production Labs?

Taken together, the qualitative findings indicate that FrED Factory Production Labs fostered strong experiential learning through hands-on engagement, iterative redesign, and data-driven system reasoning. Students' reflections provide qualitative support for the quantitative results reported for RQ1 and RQ2, particularly the gains in production data analysis and perceived competence. At the same time, the identified coordination challenges and proposed improvements offer concrete guidance for refining role design, instructional scaffolding, and iteration structure in future implementations.

5.3.1 Theme 1: Experiential Learning and Theory–Practice Integration

Students consistently emphasized the value of hands-on engagement and the opportunity to connect theoretical concepts to real-world behavior in manufacturing systems. Many described the activity as their first immersive exposure to factory operations and highlighted how physically building products and operating the line made abstract concepts tangible. This theme highlights that the embodied and experiential nature of FrED Factory Production Labs was a central contributor to strengthening conceptual understanding through situated learning.

- "Creating actual product."
- "Seeing how the calculation we made played out in real life."
- "Learning how real production issues—bottlenecks, variability, line balancing—show up in practice."
- "Seeing the impact of small changes on flow, WIP, and throughput made the concepts feel concrete."

5.3.2. Theme 2: Iteration, Continuous Improvement, and Data-Driven Reasoning

A dominant theme was the importance of iteration, feedback, and performance analysis. Students valued the two-run structure, which enabled reflection, redesign, and measurable improvement between production runs. Many described feedback loops and iteration as key mechanisms for learning. Many highlighted gains in interpreting cycle times, throughput, and quality metrics, as well as in reasoning about system-level trade-offs during continuous improvement. This theme aligns closely with the observed learning gains in continuous improvement and production data analysis reported under RQ1.

- "Being able to do 2 runs and improve in the second."
- "Seeing how crucial feedback loops were."
- "Being able to evaluate after week 1 and improve for week 2."
- "It's important to understand cycle times and predict end performance."

5.3.3. Theme 3: System Design, Workflow Optimization, and Adaptive Planning

Students frequently discussed system-level design decisions related to workstation configuration, task assignment, and workflow coordination. Several described experimenting with flexible stations and distributed workloads to improve flow and balance. These reflections indicate that the activity promoted adaptive planning and design-to-manufacturing reasoning under realistic operational constraints.

- "Strategizing of creating workstations that had a distributed workload."
- "We were flexible with stations that floated between the two subassemblies and it worked well."
- "Planning is great, but you have to be flexible and continuously update plans."

5.3.4 Theme 4: Teamwork, Coordination, and Communication Challenges

Students commonly described coordination and communication as major challenges, particularly during planning and early production runs. These difficulties were often linked to uncertainty in early planning and evolving task assignments.

- "Working with my peers to ensure we all have the same strategy."
- "Ensuring good communication."
- "Having everyone try to have the same cycle time."

5.3.5. Theme 5: Desired Improvements: Iteration, Role Design, and Course Integration

Students proposed extending the activity over more sessions, increasing opportunities for iteration, and formalizing meaningful roles for all participants. Additional suggestions included clearer instructional materials, mid-run reflection breaks, and improved ergonomics.

- "Instead of 2 production labs, 3 so that you can at least get it perfect once."
- "Allow spectators to roam and be factory managers or process engineers."
- "Production Labs should be incorporated as a semester-wide project."

5.4. Production Throughput

Finally, to serve the secondary purpose of productive factory throughput, the subassemblies produced during FrED Factory Production Labs are readily shippable to real customers. The activity, run over four weeks, with 1.5 hours/session * 3 teams * 2 sessions = 9 hours of learning factory time, was able to produce a total of 51 Electronics and 57 Extruder subassemblies. This would correspond to contributions to at least 51 FrED devices that can be shipped out of the FrED Factory. A summary of the team's results is shown in Table 3.

Table 3. FrED Factory Production Labs Team Performance

Team	Electronics made	Extruders made	Pairs made	Points generated	Scrap	Final Score
1	17	18	17	$1,025.95	-$105.79	$920.16
2	13	21	13	$784.55	-$36.40	$748.15
3	21	18	18	$1,086.30	-$34.44	$1,051.86
Total	51	57				

6. Conclusion and Future Work

This paper presented the design and evaluation of FrED Factory Production Labs, an experiential learning activity that immerses students in translating product design into a functioning manufacturing system within a learning factory. By combining factory planning, execution, data-driven redesign, and competitive performance evaluation, the activity provides an authentic platform for developing systems-level manufacturing competencies while contributing real production output.

Results indicate that the activity was particularly effective in strengthening students' ability to reason about production data and continuous improvement. Although overall conceptual gains were limited by high baseline performance, improvements were observed in learning outcomes related to production data analysis and system-level trade-offs. Motivational results showed a substantial increase in perceived competence, while qualitative findings highlighted strong theory–practice integration, iterative redesign, and adaptive workflow planning, as well as coordination challenges that inform future refinements. Beyond educational outcomes, the activity produced more than 50 shippable subassemblies, demonstrating the feasibility of integrating authentic production with instruction.

Future work will focus on expanding the scale and scope of the activity and strengthening the assessment framework to increase sample size and incorporate longitudinal measures of retention and transfer. From an instructional design perspective, future iterations will explore additional production runs, expanded managerial and process-engineer roles, enhanced instructional scaffolding, and deeper integration with course topics across the semester.

Overall, the FrED Factory Production Labs activity demonstrates a replicable model for integrating design-to-manufacturing translation, continuous improvement, and professional practice within a learning factory, advancing experiential systems-level manufacturing education.

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