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Teaching Modular Design: Mobile Processing Plants to Reduce Food Waste

Dr. Ronald Carl Hedden, Rensselaer Polytechnic Institute

Ronald C. Hedden is a Professor of Practice in the Dept. of Chemical and Biological Engineering at RPI. His research and teaching interests cover both Chemical Engineering and Polymer Science. Dr. Hedden's research has recently focused on the use of Virtual Reality in the classroom and laboratory.

Jingwen Tan, Rensselaer Polytechnic Institute
Caitlin Gee, Rensselaer Polytechnic Institute
Brad DeBoer, Rensselaer Polytechnic Institute
Kathryn Dannemann, Rensselaer Polytechnic Institute
Dr. Nihat Baysal, Rensselaer Polytechnic Institute
Prof. Joel L. Plawsky, Rensselaer Polytechnic Institute

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Introduction

This paper details a recent collaboration at RPI whereby undergraduate researchers and faculty from chemical engineering worked with capstone design students and instructors from four additional engineering departments on a collaborative, multidisciplinary project aimed at modular design of agricultural waste processing plants. Chemical engineering process simulations were integrated with concepts of modular manufacturing and transportable design over the course of two academic calendar years to achieve research and educational outcomes. The key pedagogical approach explored was to couple undergraduate researchers from chemical engineering with capstone design teams from other disciplines, thereby expanding the scope and potential impact of the capstone design projects.

Due to recent interest in transportable and modular plant designs, it has become attractive to incorporate concepts of modular design into engineering education. Modular design concepts are readily applicable to mobile processing plants, where distinct functions such as chemical processing, utilities generation, and product packaging can be implemented in a modular sense to facilitate transportation between sites. Batch processing of raw materials at field sites using transportable equipment poses unique design challenges that differ from fixed, large-scale plants. At a field site, operators are faced with space constraints, limited utilities and supplies, and on-site waste disposal restrictions that may not exist at a conventional plant. Engineering solutions for these challenges inherently embrace fundamentals of chemical, mechanical, electrical, and other engineering disciplines, and therefore may not fit neatly within the educational framework of any one degree program. Therefore, teaching mobile process design in a collaborative sense with students and faculty from multiple engineering disciplines can prove advantageous.

In particular, mobile processing plants are needed for applications in agriculture, where food waste reduction is a pressing issue.[1] Mobile processing plants that can rapidly be transported between sites to recover foodstuffs, chemicals, or other products from waste agricultural products are attractive, yet there are few reports of detailed designs in the literature. Mobile processing plants require the processing equipment to be packaged in a transportable format, necessitating compact equipment design and plant layouts with minimal on-site waste generation. Additionally, the need to supply utilities (power, water, steam) and packaging equipment in a transportable format poses inherent design challenges, presenting opportunities for educators to involve students from multiple engineering majors.

Our collaboration addressed the design of mobile processing plants that fit into shipping containers measuring (15 x 3 x 3.3) meters, which can be custom-configured and deployed quickly via rail or truck throughout the state or the country to reduce waste of crops or dairy products. The project objectives were to investigate the technical feasibility of these plants and estimate the capacities of raw agricultural materials they can potentially handle. With extramural support through a grant from the New York State Pollution Prevention Institute,[2] multidisciplinary student teams at RPI tackled the design of processing plants that are both modular and transportable to address issues pertaining to food and agricultural waste. Five plants were designed to fit into shipping containers: a waste apple processing plant, a milk pasteurization plant, a cannabis waste processing plant, a utilities plant, and a packaging plant.

Students investigated the technical feasibility of mobile processing plants, gauged the capacities of raw materials they may be able to handle, and estimated their consumption of resources. Students from chemical engineering designed modular units aimed at processing of milk, apples, and cannabis waste, while the utilities and packaging plants were designed by students from other engineering disciplines. Process simulations were carried out in SuperPro Designer software by students in chemical engineering to quantify material and energy balances. Students from the O.T. Swanson Multidisciplinary Design Laboratory at RPI (hereafter abbreviated MDL) were responsible for equipment selection, visualizing plant layouts, and preparing detailed designs for specialized process equipment such as heat exchangers. This paper reviews our findings regarding design guidelines and the educational aspects of multidisciplinary design for modular processing plants.

Student and Faculty Engagement

The overall design effort supported involvement of 21 undergraduate students and several faculty members from multiple departments. Two students from chemical engineering participated via semester-long, paid independent study experiences, rather than through a conventional design course. Three teams of students (19 total) from other engineering disciplines completed their required capstone design projects through the MDL while collaborating with the undergraduate researchers from chemical engineering. The project tasks were divided among students in different disciplines over an 18-month period (Fig. 1).

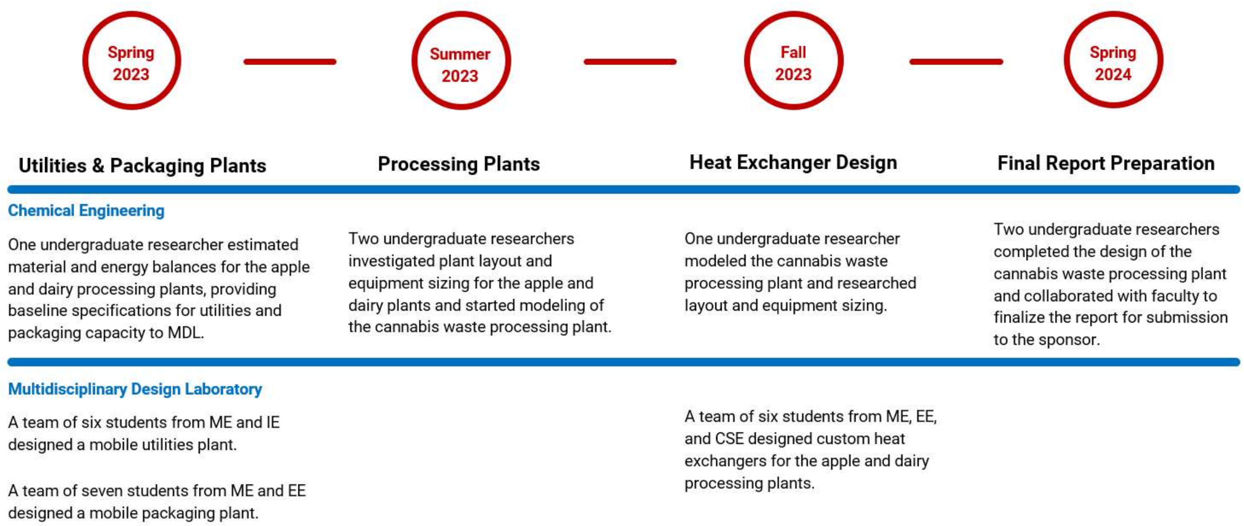

Fig. 1. Project timeline and workflow illustrating synergism between Chemical Engineering and the Multidisciplinary Design Laboratory. (ME = Mechanical Engineering; EE = Electrical Engineering; IE = Industrial Engineering; CSE= Computer & Systems Engineering).

The timeline for the project spanned three academic semesters and a summer session. Chemical engineering personnel conducted initial modeling of material and energy balances for the apple processing and dairy processing plants. Given estimates of production capacity and utilities consumption, the capstone design teams in MDL designed mobile utilities and transportable packaging plants in parallel. During summer of 2023, undergraduate researchers worked with faculty on the plant layout and equipment sizing and selection for the apple and dairy processing plants. As the project moved forward, it became apparent that detailed design of custom heat exchanger equipment in both the apple processing plant and the dairy pasteurization plant was necessary. Thus, a third MDL design team was appointed to design heat exchangers and pasteurizers in fall semester of 2023. During this time frame and continuing into spring of 2024, two undergraduate researchers worked on the design and equipment selection for the cannabis waste processing plant. Final report preparation for the sponsor was completed by summer of 2024.

The two chemical engineering students who participated in the project served as paid research interns advised by faculty in chemical engineering. RPI strongly encourages undergraduate students to spend a semester away from traditional studies, pursuing internships, independent study experiences, or research experiences. The two students satisfied their "semester away" requirements by participating in the project. Both students also completed our senior capstone design courses, working on design projects unrelated to the present work. Chemical engineering program educational outcomes were met through our standard core design courses, while the research internships served to foster their interests in research and design.

In contrast, the students who participated in the project through the MDL did so through the required capstone design course in their respective majors. The MDL at RPI supports capstone design experiences that preferably address open-ended, real-world problems proposed by extramural sponsors, including industrial partners. Once a project opportunity is identified, faculty in participating departments and project engineers from the MDL select teams of up to seven students from various engineering disciplines to work together to solve design challenges that are tailored to their abilities and backgrounds. Students in the MDL program work closely with a designated Project Engineer who supervises technical aspects of the design efforts, organizes meetings, and receives deliverables such as written reports and presentations. The pedagogical approaches and assessment methodology adopted by the MDL at RPI have been described in more detail elsewhere.[3]

Through the MDL, a total of 19 senior-level undergraduate students worked on three modular design projects as multidisciplinary design teams. A key aspect of the project management strategy was that chemical engineering faculty served as clients, furnishing students with required technical specifications and performance expectations. Communication between students and a client or project sponsor is a common (but not required) practice with MDL design projects. The advantages of these interactions are to ensure that technical specifications are being met while fostering exchange of ideas. Chemical engineering faculty attended mid-semester and final presentations at the MDL in order to deliver feedback and provide guidance to the participating students.

Student Accomplishments

The ensuing sections of this paper describe representative student accomplishments in designing the five modular plants.

A. Mobile Apple Processing Plant

A mobile apple processing plant was designed to convert 500 kg/h of waste apples into 40 kg/h of apple juice powder and 125 kg/h of apple pomace. Material and energy balances were carried out by undergraduate researchers in chemical engineering using SuperPro Designer software. Apples were modeled as a mixture of 25 % solids and 75 % apple juice;[4] the juice was assumed to contain 1.5 % pectin, 10.57 % sucrose, and 87.93 % water by weight.[5-6] Fig. 2 shows the process flow diagram for the apple processing plant, which carries out four main processing operations: juice extraction, condensation, drying, and solids treatment. The juice extraction section includes washing, crushing, extracting, filtering, and centrifugation. The condensation section employs a multi-effect evaporator to reduce the volume of apple juice, which reduces energy consumption in pasteurization and drying. The drying section includes pasteurization, mixing, spray drying, and final cooling processes. The solids treatment section isolates and dries the apple pomace.

Detailed design of the pasteurization process was carried out by a student design team in the MDL.[5] Two custom heat exchangers replace a traditional pasteurization unit. HX-104 is a counter-current, shell-and-tube type exchanger that pre-heats incoming apple juice. Students utilized a state-space model to quantify process dynamics and tailor HX dimensions to specified inlet/outlet temperatures while minimizing residence time. The pre-heater HX-104 is followed by the pasteurizer HX-103, a commercial unit with a typical residence time of about 10 s.[6] Addition of a drying agent (maltodextrin) is followed by spray drying using air at 140 °C. Hot apple juice powder (T > 90 °C) exiting the spray dryers is discharged into a screw conveyor and transported into a solids cooler, where it cools down to 25 °C. Cooled apple juice powder is sent to the packaging plant, where it is packaged in pillow bags with a capacity of 13 lb. All remaining solid components are combined to form apple pomace, which is processed in a continuous rotary dryer and heated by air at 140 °C to form powder or pellets, which are packaged in ULINE bulk bags. The apple processing plant requires electricity, hot and chilled water, and saturated steam at 150 °C from the mobile utilities plant; it releases only steam and warm air into the environment as waste products.

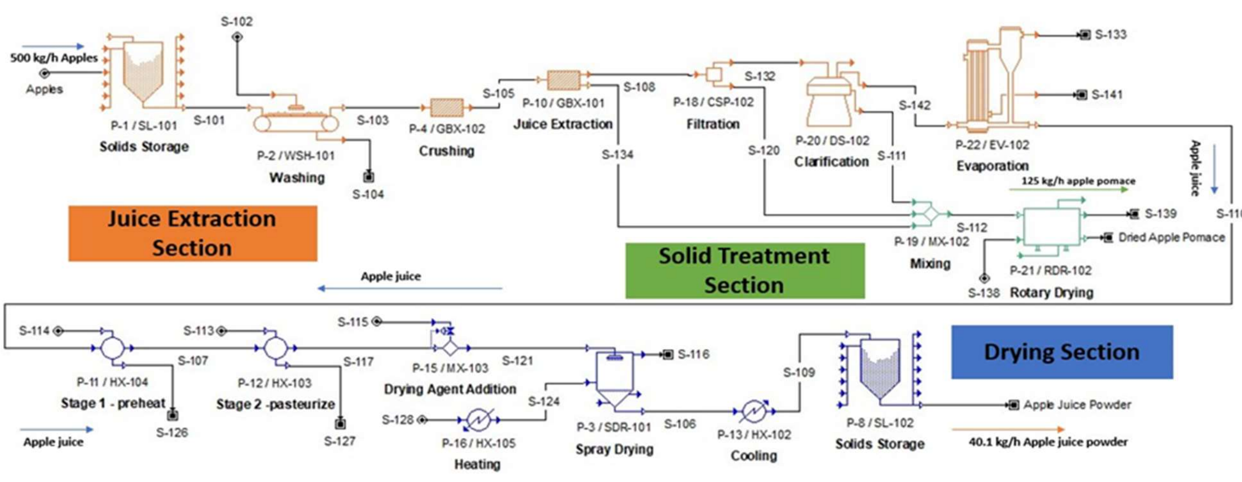

Fig. 2. Process flow diagram for the mobile apple processing plant prepared by undergraduate researchers from chemical engineering.[7]

Process simulations yielded stream tables containing composition and temperature of all material streams. Equipment sizing and selection focused on commercially available units that meet the design requirements and fit into shipping containers. SolidWorks CAD software was used to create simplified 3D models of the equipment to illustrate the layout of the apple processing plant in a shipping container (Fig. 3).

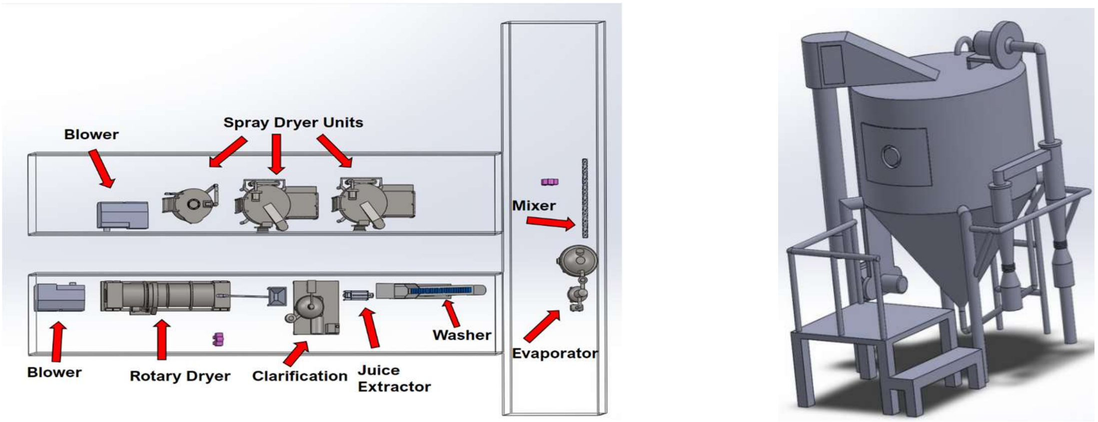

Fig. 3. One possible layout of the mobile apple processing plant using three standard shipping containers (left). Student-generated CAD model of a spray dryer unit (right).[7]

<u>B. Mobile Dairy Pasteurization Plant</u>

The dairy pasteurization plant was designed for converting 3,060 kg/h of raw milk into ultra-pasteurized milk on-site. Raw milk must be heated from its feed temperature of 5 °C to the pasteurization temperature of 140 °C, followed by cooling to 15 °C and packaging. This plant was designed to minimize waste of milk during start-up and shut-down, while consuming as little in the way of utilities as possible. Fig. 4 shows the process flow diagram for the pasteurization plants including inputs, control elements, and sensors. Pasteurization is achieved by passing raw milk through a series of three plate-and-frame heat exchangers (preheater DHX-1, pasteurizer DHX-2, and cooler DHX-3). Pasteurized milk at 15 °C is transported to the packaging plant.

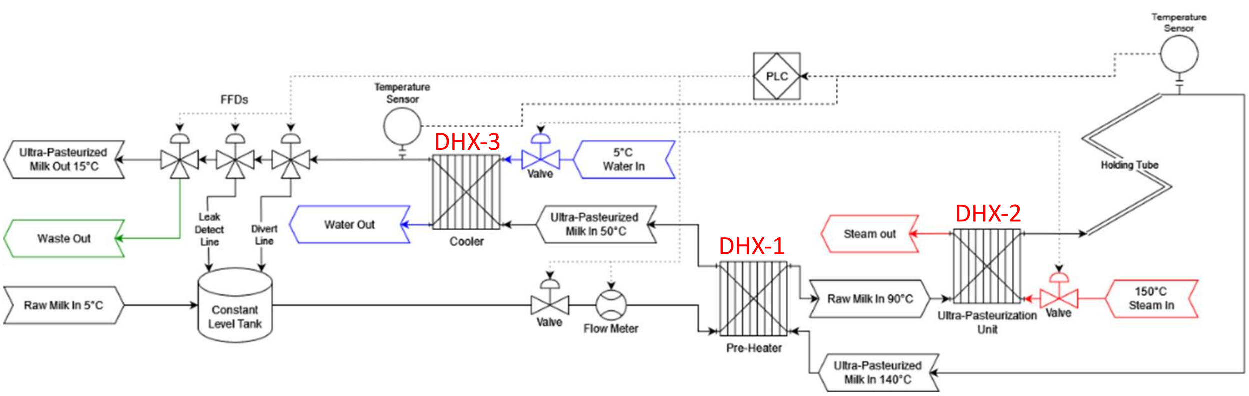

Fig. 4. Process flow diagram for the mobile dairy pasteurization plant prepared by a MDL design team comprised of students from ME, EE, and CSE.[8]

The detailed design of the plate-and-frame dairy heat exchangers (DHX) for pasteurization was a critical project component for one of the MDL design groups. This student team was tasked with designing portable, compact DHX that heat milk to targeted temperatures for specified amounts of time, permit disassembly and cleaning on-site, and meet FDA standards for milk ultrapasteurization. The heat exchanger design team was ultimately responsible for the overall pasteurization system design; the number of heat exchangers and their interactions with each other were not initially specified. Students decided upon a system of three heat exchangers, including a pre-heater that reduces consumption of steam from the utilities plant. The pre-heater unit DHX-1 exchanges heat from outgoing ultra-pasteurized milk at 140 °C with incoming raw milk at 5 °C to conserve thermal energy. Pre-heated milk at 90 °C then enters the ultra-pasteurizer unit DHX-2, which uses saturated steam at 150 °C to heat the milk above 138 °C for at least 2 s. The milk is returned to DHX-1 for heat recovery, exiting at 50 °C. Before packaging or storage, the milk flows through the cooler DHX-3 and is chilled to 15 °C using 5 °C water as the cooling fluid.

The MDL students selected plate-and-frame designs for each of the DHX, rather than shell-and-tube exchangers, in order to occupy minimal floor space within a shipping container and to facilitate cleaning and sterilization. Students undertook conventional heat transfer calculations and computational fluid dynamics (CFD) modeling studies in order to estimate the dimensions and number of plates required in each DHX. CAD Models and drawings for the main components of DHX-1 and DHX-3 generated in Siemens NX software are shown in Fig. 5. All DHX were designed with the idea that disassembly, cleaning, and re-assembly may be necessary every time a mobile processing plant is deployed to a new location.

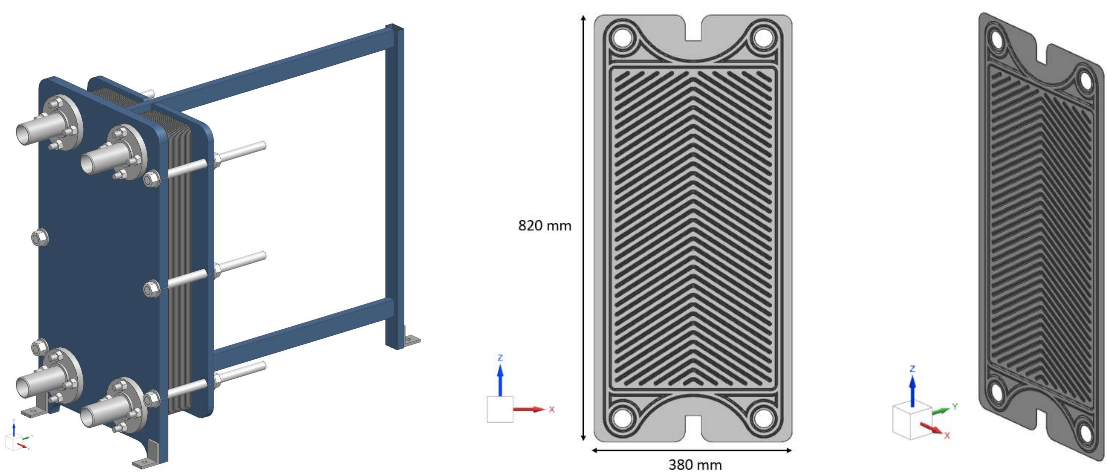

Fig. 5. CAD models of DHX-1/DHX-3 Frame Design (left) and DHX-1/DHX-3 Plate Design prepared by MDL heat exchanger design team.[8]

C. Mobile Cannabis Waste Processing Plant

Dry cannabis (hemp) waste is an emerging source of agricultural waste that could be used to produce value-added chemicals or other products. According to the USDA,[9] the amount of floral hemp waste in America generated during 2021 was 1.8 million kg (about 5,000 kg/day). Residual hemp biomass after oil extraction amounts to 771-816 kg per day.[10] This mobile plant was designed to treat a 500 kg batch of lignocellulosic cannabis waste to produce 243.2 kg of succinic acid over a period of two days. The plant was designed by undergraduate researchers and faculty in chemical engineering, who performed process modeling in SuperPro Designer, followed by equipment sizing and selection from commercially available units.

Fig. 6 shows the process flowsheet for the cannabis waste processing plant.[7] The major process operations are 1) pretreatment of lignocellulosic biomass to yield mixed sugars, 2) fermentation, and 3) downstream product (crude succinic acid) recovery. The composition, temperature, and mass flow rate of each stream in the cannabis waste processing plant were found after modeling the key reaction steps, enzymatic hydrolysis and fermentation via *Actinobacillus succinogenes*. Modeling of fermentation posed some challenges, given the scarcity of reaction kinetics data with hemp waste as feed. The variable composition of the feedstock, the presence of more than one fermentation pathway, and the presence of inhibitory compounds in the hydrolyzed feed each added uncertainty to the analysis. Downstream processes separate the succinic acid from the fermentation broth, yielding a solid powder consisting of succinic acid and mixed organic fermentation by-products. The plant consumes 500 kg of lignocellulosic cannabis biomass in two days to produce 243.2 kg of crude succinic acid. Isolation of high-purity succinic acid from other organics in a mobile plant would require separations equipment that may preferably be located in fixed processing plants. Thus, the packaging plant receives the crude succinic acid product as a dry powder for sale to specialty chemical companies.

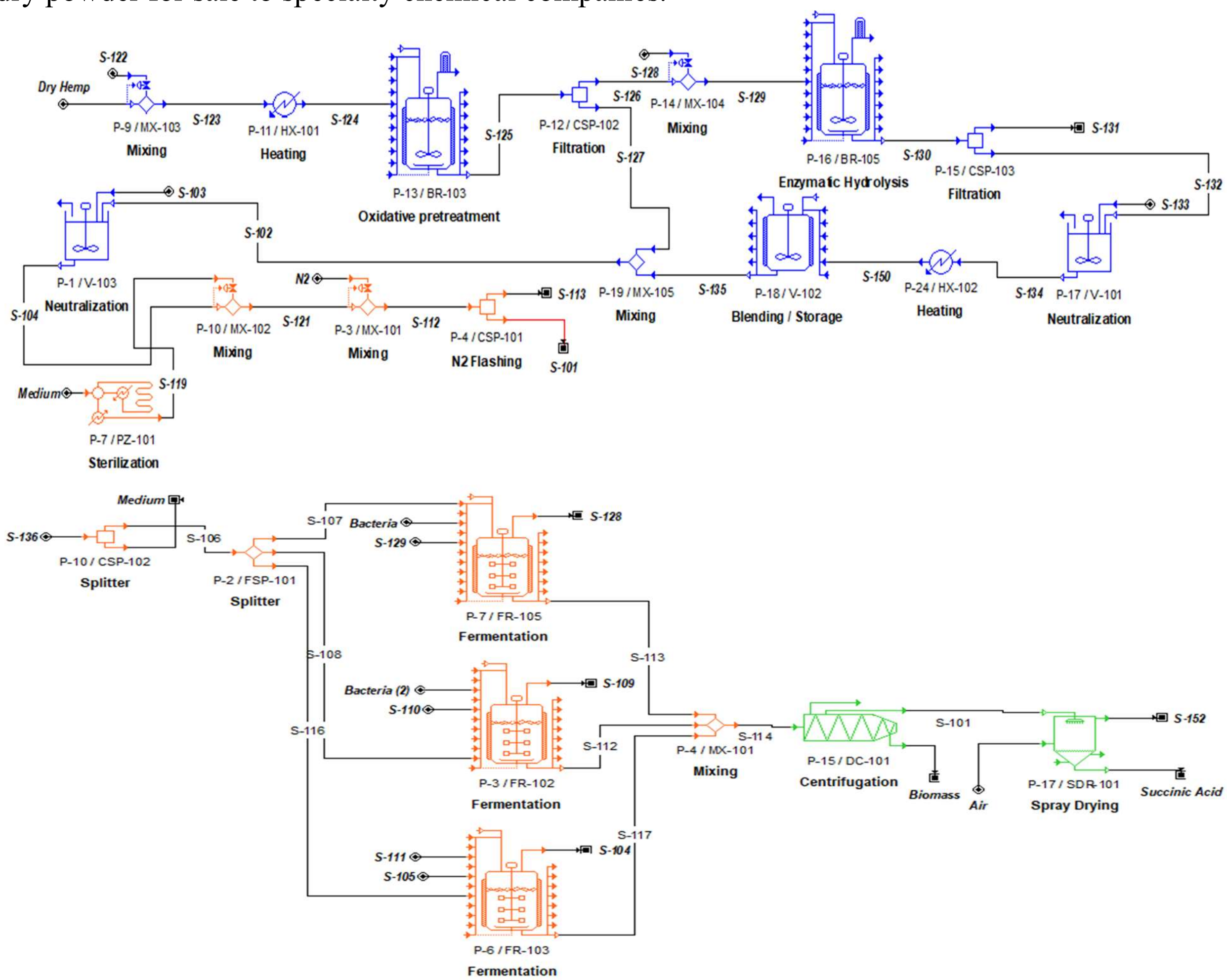

Fig. 6. Process flow diagram for the mobile succinic acid production plant prepared by chemical engineering students.

D. Transportable Central Utilities Plant

To support operation of the apple, dairy, and cannabis plants, a transportable central utilities plant was designed by students in the MDL[11] in response to process requirements provided by the teams from chemical engineering. The utilities plant supplies saturated steam, cooling water, hot water, compressed air, and electricity to each of the three processing plants. Table 2 compares the utilities supplied by the plant with the usage from each processing plant. Black text indicates where each plant consumes less than the maximum amount the utility plant can provide. Red text indicates where continuous recycling of water streams between plants is required to make the operations feasible based on the available resources.

Table 2. Total utilities furnished by mobile utility plant vs. requirements of mobile processing plants

Utility	Amount Available	Amount Used (Apple)	Amount Used (Milk)	Amount Used (Cannabis)	Amount Used (Packaging)
Power	600 kW	125 kW	15 kW	15.7 kW	22.45 kW
Compressed Air @ 100 PSI	200 CFM	As Needed	0 kg/s	As Needed	As Needed
Water at 95 °C	13.6 kg/s	*17.25 kg/s**	*19.88 kg/s**	0.015 kg/s	0 kg/s
Water at 30 °C	17.9 kg/s	1.16 kg/s	*18.05 kg/s**	0.001 kg/s	0 kg/s
Water at 5 °C	2.7 kg/s	*3.52 kg/s**	*3.78 kg/s**	0.002 kg/s	0 kg/s
Steam @ 150 °C and 4.76 bar	0.08 kg/s	0.05 kg/s	0.04 kg/s	0.03 kg/s	0 kg/s

The Utilities design team also researched the locations of agricultural production hubs and their accessibility via rail and road in the state of New York. Production hubs were overlaid on a map with the highway and rail transportation lines, electric power transmission lines, and three-phase power lines to formulate logistical guidelines for deployment of mobile processing plants during harvest times.

E. Mobile Packaging Plant

The mobile packaging plant was designed to encapsulate multiple types of products (apple juice powder, apple pomace, ultra-pasteurized milk, or crude succinic acid powder) for transportation to their intended destinations. Like the utilities plant, the packaging plant is designed to be deployed in tandem with each of the waste processing plants, so it offers multiple capabilities (Table 3). Products can be packaged in plastic pillow bags, Liquibox bags, or bulk bags as needed. The packaging plant can operate up to 16 hours per day, filling 96 pillow bags/min, 24 Liquibox bags/min, and 16 bulk bags/hour.

Table 3. Capabilities of the plant developed by the MDL packaging design team.[12]

Product	Bag Type	Capacity (product/bag)	Required bags per day
Succinic Acid	Pillow bag from ROVEMA Vertical Seam Symmetric	13 lbs.	17
Ultra-pasteurized Milk	Liquibox EVOH-Polyethylene bags with dispensing tap	6.8 lbs.	15,772
Apple Juice Powder	Pillow bag from ROVEMA Vertical Seam Symmetric	13 lbs.	50
Apple Pomace	ULINE Bulk bag	531.2 lbs.	16

The MDL student design team responsible for the packaging plant created a layout blueprint, generated a bill of materials for all equipment that would be required, formulated standard operating procedures for the packaging processes, and investigated environmental impacts.[12] The blueprints for the plant, which occupies four shipping containers, are shown in Fig. 7.

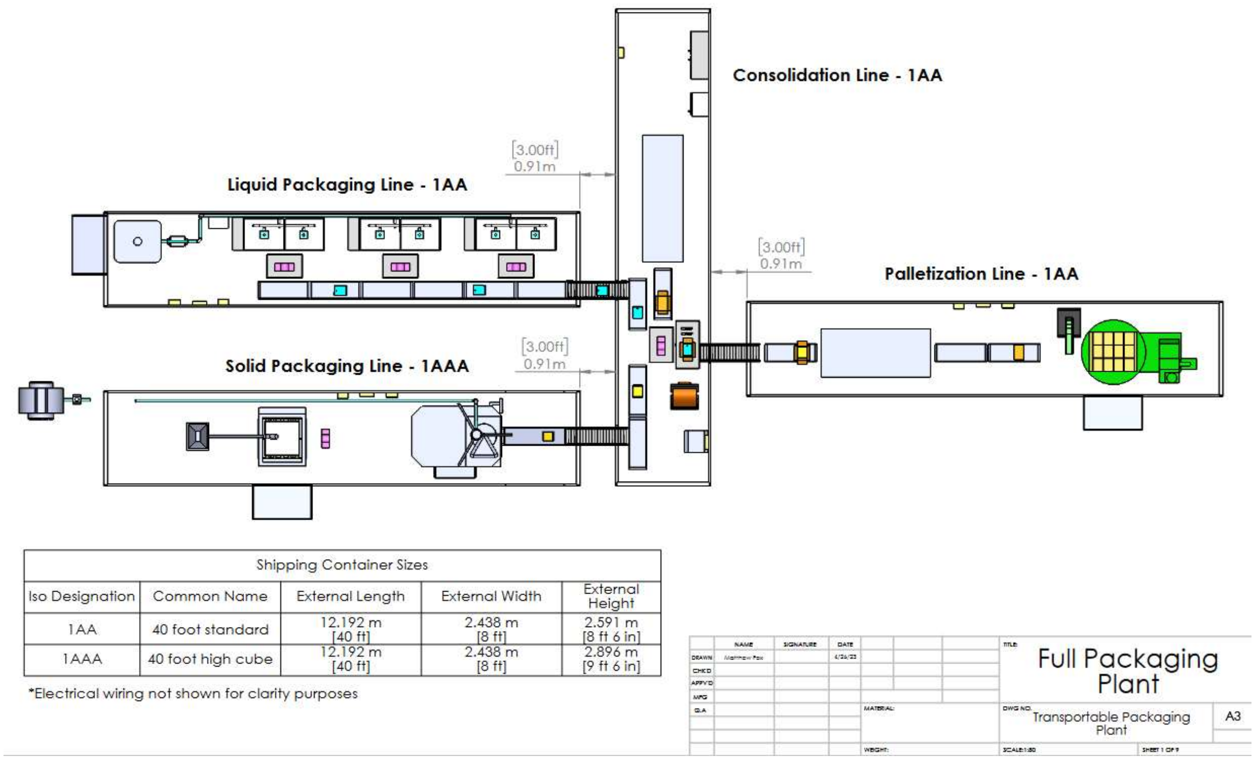

Figure 7. Blueprints for the plant developed by MDL packaging design team.[12]

Educational Outcomes and Conclusions

Our effort to design processing plants for production of agricultural products from surplus apples, milk, and cannabis waste ultimately introduced 21 undergraduate students to modular and transportable design fundamentals. All students met design challenges related to space limitations, compact equipment design, on-site utility generation, on-site packaging capabilities, and on-site waste minimization that were more stringent than the constraints placed on traditional fixed plant designs. While addressing the engineering challenges specific to modular design, students also gained an appreciation for the advantages of flexible, modular processing plants: transportability to remote sites via rail or other means, the ability to process perishable materials that cannot be transported to central facilities, and the beneficial impacts of waste reduction. Students thereby gained familiarity with design strategies that could potentially be effective to combat contemporary, global issues facing agricultural producers or other industries.

The projects completed by ME, IE, EE, and CSE students were distinguished from the traditional design curriculum by the modular nature of the plants and the multidisciplinary design teams. While capstone design teams typically consider stand-alone systems or components, each student team in this effort designed a critical component of a larger processing plant in conjunction with students from related disciplines. The remaining modules were designed by students from other teams and/or disciplines, requiring clear communication and cooperation between design teams working in parallel (during the same semester) or in sequence (using design reports from a past semester). This collaborative interaction between multiple design teams is valuable for its ability to simulate cooperation between divisions within a large company or research organization, better preparing graduates to function as members of interdisciplinary teams.[13] Our work reinforces the idea that a multidisciplinary approach to engineering design education is beneficial to students by encouraging them to develop competencies in related disciplines through collaboration.[14] For example, the heat exchanger design team brought together students who worked on fluid dynamics, process control, and mechanical engineering fundamentals, while all students broadened their horizons by learning some aspects of chemical process design, a distinguishing aspect of this work. While numerous other institutions offer multidisciplinary capstone design experiences to engineering students,[15-18] programs including chemical engineering students are less common.

The cooperation between students from multiple disciplines opens the door to new design project opportunities that require specialized expertise. For example, students from MDL design teams were able to achieve educational outcomes specific to their own capstone design experiences, despite the need for chemical process modeling that is not normally part of their curriculum. This challenge was overcome by collaborating with students and faculty from chemical engineering who had specialized knowledge in process simulations. No published reports about mobile apple or cannabis processing plants existed prior to this work, but the chemical engineering students and faculty were able to provide the MDL students with the material and energy balances for each unit operation needed to design and size equipment.

Likewise, students and faculty in chemical engineering benefited from the expertise of the MDL students and faculty in designing the mechanical and electrical components of systems and generating equipment models, layouts, and blueprints. Without their participation, the chemical engineering students would likely have limited their designs to chemical process modeling and equipment selection. Thus, the interdisciplinary design approach can be fairly stated to broaden the scope of the available design projects, encouraging students to adopt more holistic views of engineering solutions. The project outcomes from the MDL students were viewed favorably by faculty in the participating departments; both the packaging and heat exchanger design teams were recognized with MDL Outstanding Design Project awards presented to approximately 10 to 15 % of student design teams annually.

Considering the chemical engineering students involved, the novel aspect of this work was completing an additional design project as an independent study experience, on top of the standard capstone design courses. This approach ensures the educational outcomes achieved in the required design courses are met, while providing the instructors a great degree of flexibility in the scope of the independent study project. One of the students remarked (paraphrasing) that the independent study experience was satisfying because it gave her a chance to apply fundamentals learned in other courses (e.g., Transport Phenomena and Chemical Reactor Design) to design a system to address emerging processing challenges. Despite the small sample size of two students, the educational outcomes suggest that the independent study experience fostered interest in research careers; one student has entered a Ph.D. program at RPI, and the second student has recently applied to Ph.D. programs in chemical engineering.

Concerning the educational takeaways from this work, the following observations may appeal to design educators at other institutions. First, it is worth considering the potentially valuable impacts of broadening the scope of senior capstone design projects by asking students to collaborate with design teams in other disciplines. Doing so introduces a new dynamic of interdisciplinary communication that will likely benefit students later in their careers. Second, encouraging students to pursue additional design project opportunities through independent study provides the students and instructor with great flexibility, and may serve to foster students' interests in research or design careers. The specialized expertise generated through independent study experiences can be of great value to collaborating design instructors who wish to pursue interdisciplinary engineering solutions that may not lie entirely within the scope of their curriculum.

Acknowledgements

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