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Cocoa for ChemE: Using bulk chocolate manufacture as an introduction to chemical engineering

Dr. Noelle K Comolli, Villanova University

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Introduction to Engineering at Villanova University

The freshman year at our small private university introduces many of the fundamentals in math and science, and an overview of different types of engineering. The engineering overview is divided into four sections (each half of a 15 week semester). The first section is general to all students, and establishes some basic vocabulary and engineering concepts[1]. The next two sections, the students select from eight different "mini-projects" on topics such as Artificial Kidney Design[2], Biomass Conversion to Fuels and Absorption of Wastewater Contaminants. These "mini- projects" are project-based multi-disciplinary design experiences. The goal is to introduce some basic engineering concepts, as well as guide the students to which type of engineering they prefer to study[3, 4]. The final section of the course is then a discipline specific introductory course. Each department has chosen a different approach to this section, from teaching a broad overview using a seminar approach, to focusing on teaching specific software necessary for future courses.

Introduction to Chemical Engineering

The department faculty has adapted a project-based learning approach due to the large success shown in many other similar introductory level courses[3-7]. The goal was to introduce different unit operations through a fun process example that was simple enough for the students to follow. The process needed to involve simple chemistry and provide opportunities for introducing different unit operations, teamwork, ethics and sustainability. The other challenge, due to lack of laboratory space, the process ideally would not require the use of a chemical laboratory and with large class sizes (>80 students) would be inexpensive. The process chosen was the production of bulk chocolate and confection making. Since Villanova University is located very close to The Hershey Company, the course instructor was able to attend their "Chocolate 101" employee training session, and met with lead chocolate process engineers at the company.

After much discussion, the chemical engineering department faculty set forth the following broad objectives for this introductory course in chemical engineering;

1. Students will recognize the unique expertise of a chemical engineering compared to other engineering disciplines.
2. Students will understand the engineering requires hard work.
3. Students will experience working on a team to complete a task.

Those familiar with Bloom's taxonomy will recognize these are all lower level "knowledge" and "comprehension" based objectives. Since the course is introductory level, and only seven weeks, the faculty deemed this the appropriate level. Another challenge to this course is making the students aware that this level of learning is appropriate for high school/freshman year, but as they progress toward graduation the goal is performance at the "analysis", "synthesis" and "evaluation" levels. Bloom's taxonomy, and how it relates to their future education, is introduced in both the discipline specific and the introductory section. This paper will discuss how these objectives were applied to the fun example chosen of industrial chocolate manufacture. While this is not the first attempt at using food, or even chocolate, as a process to grab freshman students' attention, it is somewhat unique in its approach, and is presented as an option for others to consider for freshman, or upper level, engineering design examples(8). In order to do so, a brief background on the process of chocolate manufacturing is presented first.

Industrial chocolate manufacture

Chocolate comes from the seeds of Cacao tree (theombroma cacao), which is grown in tropical climates. Chocolate is essentially a fat based emulsion, which according to the Food and Drug Administration is simply roasted and ground cocoa nibs (essentially, unsweetened baking chocolate). The cacao nib is the inner part of the cacao seed. For those who have never tried unsweetened 100% cocoa chocolate bars, they are incredibly bitter, and taste more like a dark roasted espresso bean. The process of turning raw cocoa seeds into chocolate candies is obviously not as simple as collecting those seeds, and can be divided into four main steps: harvesting the beans, processing the nibs, bulk chocolate production and finally confection making, as seen in Figure 1(9-11).

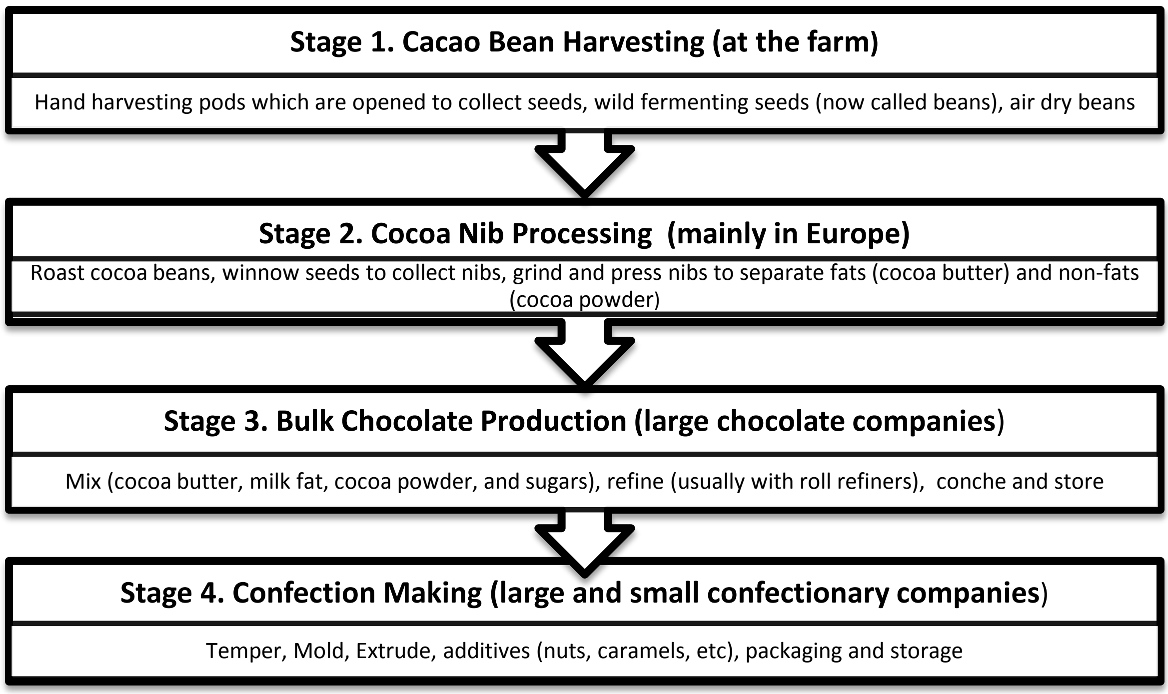

Figure 1. Industrial chocolate manufacturing process.

During the harvesting stage, pods (which grow on the cacao trees and contain 20-40 seeds each) are hand-picked, split open and seeds are collected on a bed of banana leaves. The seeds are then covered and allowed to sit for 2-3 days and undergo wild – fermentation which kills the seed, and when done correctly, can enhance the flavor of the resulting cocoa bean(10). Now referred to as beans, they are spread out in a flat layer and allowed to dry prior to shipment to a nib processing facility (stage 2 in Figure 1). The beans are first roasted to enhance flavor, and further dry out the shell which is removed from the inner desired part (the nib) in a mechanical process known as winnowing(10, 11). The nibs are then ground in pin grinder to create a fluid known as chocolate liquor. This liquor stage is what the F.D.A. refers to as chocolate, or when reading a consumer label, the "cocoa content". Most often for optimal mixing in later stages, the liquor is divided into its fat content (cocoa butter) and non-fat content (cocoa powder) by extruding the liquid through a filter press (fat) and saving the cake collected (non-fats)(10). These preliminary ingredients are then processed by chocolate manufactures into bulk chocolate (stage 3) which can be used by confectionary makers to make chocolate treats (stage 4, most of this stage is trade secret)[9].

Bulk chocolate is produced by mixing the fats (cocoa and milk fats are only allowed), with non-fats (cocoa powder, sugars) and any mixing/flow agents used to help processing (lecithin is common)[9-11]. The mixed liquid is then refined to create an optimal texture (size of the non-fat particles) which leads to changes in mouth feel (creamy versus chewy) and density/hardness of the resulting chocolate final product. The refined chocolate is then aerated and mixed in a process known as conching. This allows undesired volatiles to be removed that create "off" flavors. Bulk chocolate can then be stored prior to use for making confections.

Stages in making the confections are often kept as trade secrets[9], but some general practices for tempering (controlled cooling to control the crystallization of the sugars and fats), as well as common molding techniques are reviewed with the students[10].

The Chemical Engineering Aspects of Chocolate

In order to meet the broad objectives set forth by the department, the fourteen class periods were divided into a mix of lectures and hands on labs. This allowed ample teamwork experience and kept with the "hands on" theme that Villanova University encourages during its freshman year engineering course sequence. The concept map for the course is provided in Table 1.

CHE Concept	Chocolate Process	Lecture/Lab/Assignment	Objective
"Unit Operations"/ Chemical Processes	The overall process	Lecture/ Project	1
Mass balances/ Reactors	Fermentation	Lecture/Lab	1/2/3
Fluid Mechanics	Chocolate Liquor	Lecture/Lab	1/2/3
Heat & Mass Transfer	Crystallization/Confection	Lecture/Project	1/2/3
Material Properties	Crystallization/Confection	Lecture/Lab/Project	2/3
Process Safety	Food safety QC	Lecture/Project	1/2/3
Statistics	Product unit packaging	Lecture/Lab	2/3

Ethics & Catholic Social Teaching	Bean Harvesting/At the farm/ Fair Trade	Lecture/Essay	4
Sustainability	Life Cycle Analysis	Lecture/Project	4

Table 1. Course Content Map for Intro to Chemical Engineering.

The course began with an overview of the history of chemical engineering, and how the concept of "unit operations" evolved. This was followed by a lecture on the chocolate process itself before breaking it into each desired content area listed in Table 1. The content areas were introduced at the very basic level, and always began with reference to what part of the chocolate process we were discussing. The topic (for example mass balances/reactors) was discussed in relation to the chocolate process, and what general principles were needed to understand that specific example. A few extensions of how this concept would be used in future applications and what courses it would be taught was also discussed. When discussing the fluid mechanics, for example, chocolate liquor was actually a more difficult example as it is a non-Newtonian fluid. This allowed, however, for discussion of Newtonian vs non-Newtonian fluids, as well as the concept of viscosity and Reynolds number.

The use of a "fun" process allowed more discussion of topics that are often times viewed as "boring" to the students, such as process safety and ethics. The concept of process safety critical control points for hazard analysis (as recommended by the FDA for food process safety) was discussed, as well as potential food safety issues that would arise in industrial scale and "home" scale processes (their project). In order to introduce the concepts that Villanova University prides its engineers in having a solid foundation in (ethics, Catholic Social Teaching, and Sustainability) by focusing on the location of the farming stage in primarily third world countries. This allowed for interesting discussion on Fair Trade regulations, as well as the amount of transportation of bulk materials and its effect of the sustainability of chocolate production. To really push the students thinking on ethics and catholic social teaching, a discussion on the journal article "The Science of Junk Food"[(12)] and the optimization of the bliss point (the exact ratio of sugar/salt/fat/mouth feel/texture) for a specific sub group to desire/crave a food is introduced in class. Each group is then to decide if they believe chocolate manufactures are responsible for adverse health effects on the general population for selling a high sugar/ high fat food (similar, for example, to tobacco companies), or is it simply genius engineering at work and the consumer is responsible for their own health.

Student Teamwork Experiences: Labs and Project

The students were divided into teams of four, with the aid of the Team Maker function on catme.org [13]. The survey questions focused on the students work preferences (early, last minute, nights/weekends), time available, and was not single out any one gender (i.e., no groups of 3:1). Students kept these teams for the entire 7 week course, since this allowed time to for the students to face conflicts within the teams, and have to develop strategies to cope. Students were not provided much guidance on team conflict resolution, but were required to create a team contract on the first day teams were assigned. In this contract teams had to state their expectations of all team members, followed by defined consequences for violating team expectations. Having this in hand when the project was going on seems to have helped many student groups overcome issues before having to involve the instructor.

Four “labs” as well a final project were given during the seven weeks. The first of the labs looked at fermentation of sugar using rapid acting baker’s yeast as the catalyst. Students were able to monitor the progress of the reaction by watching the formation of product (CO_2) by counting bubbles formed and trapped in the bubble traps (Figure 2). The reaction only required table sugar, baker’s yeast, water, Erylenmyher flasks, a bubble trap and a hot pot to keep the reaction warm. This low cost experiment does a reasonable job of showing the lag and exponential growth stages of the yeast (if students monitor closely enough). More importantly it introduces students to importance of significant figures, scientific writing, record keeping during experiments, and a simple biochemical reaction example. The difference of an “open” versus a “closed” system and how this restrains “batch” versus “continuous” processes in many applications was also discussed.

Figure 2. Fermentation lab set up. The bubble trap was held in place on the flask with a rubber stopper and filled with tap water to monitor bubble (CO_2) formation during the fermentation of table sugar with baker's yeast.

The next lab students performed was looking at chocolate flow and observed flow rates (since estimating viscosity for the non-Newtonian fluid was more complex than desired for freshman level, adapted from[11]). Students were again given glass flasks, glass funnels, hot pots, and samples of either 100% cocoa bars (Baker's brand baking chocolate) or milk chocolate (Hershey's brand milk chocolate bars). Students were to melt their chocolate by making a double boiler in the hot pot, then measure how long it took to for a set volume of chocolate to flow through the funnel (that was warmed in the hot pot to prevent chocolate sticking to it). Two additives were also encouraged to be tested if time permitted, the addition of water and the addition of lecithin (a flow agent used in industrial practice[9]). The biggest challenge students had was melting their chocolate slowly and not having it burn. Groups from each section combined their average time to flow results (three trials each) to compare if the addition of milk fats and sugar to the milk chocolate had an effect of flow. Ideally they would have seen lecithin thinned the solution and made the flow faster, and water caused the chocolate to fall out of the fat emulsion (resulting in chocolate water with globs of cocoa fats). While at first the students thought this experiment had "failed" the discussion afterwards lead to an improved understanding of emulsions and what could affect the flow/viscosity of the chocolate. Results from a post course survey, to the instructor's surprise, found this was the lab students felt they learned the most from.

The statistics lab was more of an "experience" than a lab, and was done using jelly beans rather than a chocolate product (so that all the students could eat the candy at the end and avoid food allergy issues). After a lesson on population statistics and some Excel basics (focused on statistics and graphing), each team was provided a bag of jelly beans from the same company. Teams were to compare their number of each type (flavor) of jelly bean to the total number as well as the results for all of the teams in the class. A survey of the student's favorite flavor was also done to compare to see if the most popular flavor (s) were the most prevalent in the population. While the "lab" was simple, and many of the students were aware of the statistics required already, almost none of the students had Excel knowledge. The post course survey indicated that students overwhelmingly feel the addition of more Excel into this section (or this course in general) would be of great benefit.

The final lab was for chocolate hardness testing and quality control of chocolate products. A sample of a variety of different % cocoa bars from various manufacturers was provided to each group. The groups had to use the hardness tester (shown in Figure 3) provided, which is essentially a form of indent testing using a roll of pennies and golf tee (adapted from [11]). To test the hardness of the chocolate, each sample was placed in the device, the weight was dropped, the sample removed and the diameter of the hole the weight indented into the chocolate was recorded. The manufacture's quality control was also evaluated by tasting the chocolate for appearance flavor (tails, holes, sugar or fat bloom), mouth feel and texture. The bars flavor (bitter, milky, cheesy, sour, smokey, off-flavors) was also recorded and students were then to link the taste to steps (good or bad) in the process of making this chocolate. Students were encouraged to use the company's website to find information about the process/bean sourcing and write a report on their results. To the instructor's relief, students took this lab very seriously, and did a nice job linking what they saw and tasted in the chocolate to what they learned about the process of making the candies in class. Overall students ranked the value of this lab equal to the fermentation lab, but below the chocolate flow.

Figure 3. The chocolate hardness tester with a sample of dark chocolate is shown. The “weight” attached to the top of the indenter is a roll of pennies.

The instructor’s survey for the value of each lab experience varied (on a scale of I learned from each lab 5 -a great deal, 3 -somewhat, 1- none at all). The lab students found most valuable was the chocolate flow lab (3.8/5), followed by the hardness/quality control (3.3/5), the fermentation lab (3.2/5) and finally the statistics (2.8/5). Based upon these results, this upcoming year’s statistics experience is currently being redesigned to include more Excel training, and more complicated data sets (provided to students). Methods to improve the students experience in the fermentation and hardness lab will also be considered.

The final project for the course was for each team to create their own university themed chocolate treat, starting with the basic ingredients (as basic as the F.D.A. and US customs allows) - 100% cacao bars and their choice of sweeteners (different sugars) and added fats (milk fats). Students were asked to include a diagram of their “scaled-down” process. They were encouraged to think about the cost, quality, ethics and sustainability when creating their own unique chocolate treat. A final presentation was given to the class to review their process choices, and samples were given to their classmates to evaluate the taste/appearance of their product. The rubric for the final product was based upon: 30% created a final product safe enough to eat, 5% taste, 40% thought into “unit operations” (namely did they just mix and bunch of things, or think about the process we learned in class and try to actually scale it down), 5% sustainability, 5% ethics, 5% cost analysis, 10% creativity in product and presentation. A sample of one of the better final products from the course is shown in Figure 4.

A. 

Figure 4. Final chocolate project. A. A sample of one group's Villanova themed chocolate treats.

Conclusions

In order to determine how well the course objectives were met, students were given a combination of a post-course survey from the instructor, as well as the usual course evaluations run by the university. The first objective was to keep use a "fun" process to introduce the students to what makes chemical engineers unique from other types of engineers. The course evaluations found that the students generally were positive in their comments about the "chocolate theme" for the course, and their overall experience (rating the value of the course a 4.0 out of 5.0). The instructor's survey, given after the 2014 sections, found that most of the students believed that had a better understanding of what makes chemical engineering unique (with a 3.9/5.0 score, 1 – disagree to 5-agree scale). The department is happy with this score.

The second objective was for students to understand that engineering requires hard work. The university based course evaluation includes a question "Hard work was required to succeed in this course" for students to rank 1 (disagree) to 5 (agree). The average score over the last two years for this course was a 4.2/5.0. This is right around the department average score (4.1/5.0) for this question, however, the instructor recognizes each freshman class has a different (usually increasing) level of knowledge/skills and must adapt this course accordingly.

The third goal was to have the students experience teamwork through their lab experiences and team project. While there are always students unhappy with their team, the overall experience seems to be positive based on the instructors observations. Students evaluated on the instructors survey (1-5 scale) that they did feel the course helped them prepare for the amount of teamwork necessary for chemical engineering (3.8/5.0). The department has discussed the potential to improve this experience by the addition of some lectures on teaming and conflict management.

Overall, the department has been happy with the results, and the students seem to find the use of a familiar food product an easy to follow, and enjoyable example for their first introduction to chemical processes and chemical engineering unit operations.

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