Department of Biosystems and Agricultural Engineering
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Biosystems Design Projects

Nature's Pulse: Mass Producing an Innovative Pulse-Based Snack

Grace Dickerson, Sebastian Hawkes, Ella Hubbard, and Tessa Versace
Client: MSU FSC PD Team   Faculty Advisor: Dr. Kirk Dolan

Background

Every year, the MSU FSC Product Development team enters the Institute of Food Technologists (IFT) and Mars product development competition. This year they submitted a new product, Nature's Pulse, which consists of three different trail mix flavors. The three flavors are a sweet citrus berry mix, a fiery Korean chili mix, and a savory peanut butter chocolate mix. The main ingredient in all these trail mixes will be pulses.

What are pulses?

Pulses are the edible seeds of plants in the legume family. They are highly valued for their nutritional benefits, being rich in protein and dietary fiber.

Problem Statement:

Design a process line to produce 3 different pulse-based trail mixes, shown in Figure 1. Production rate should be reasonable for a processing plant and be profitable based on market estimates.

Figure 1. Nature's Pulse trail mix

Objectives

- Keep cost of production per unit 35% below expected market value of product
- Achieve payback period of below three years
- Produce final product weight of 2.75 oz per package (single serving)
- Develop packaging with zero waste components (100% recyclable or biodegradable)
- Achieve stable shelf-life of minimum 1 month

Constraints

- Final product quality must be identical to the initial bench scale product
- Dough in baking process must be cooked to a minimum of 70 C
- Dry beans must reach an internal temperature of 100 C for 10 minutes during boiling process
- Internal rate of return (IRR) must be greater than the weighted average cost of capital
- Moisture content of the cracker after drying must be 5% or less (wet basis)

Design Alternatives

The design alternatives for the processing of the pulse dough included these four methods:

- Oven Baking
- Puff Extrusion
- Freeze Drying
- Vacuum Drying

To evaluate the best fit for the project, the team looked at the following criteria:

- Cost
- Production rate
- Product quality
- Longevity
- Safety
- Sustainability

Each category was weighed based on the team's goals and objectives. The scores attributed to each alternative are shown below in Table 1.

Table 1. Decision matrix for baking process. Puff extrusion received the highest score overall.

Design criteria	Weight (%)	Oven baking	Puff extrusion	Freeze drying	Vacuum drying
Cost	30	8	6	3	4
Production rate	25	6	10	4	7
Quality	20	3	5	10	8
Longevity	10	9	6	7	7
Safety	10	7	6	8	8
Sustainability	5	6	9	4	5
Weighted Total	100	6.4	**6.95**	4.6	**6.3**

Selected Design

Vacuum drying was chosen as the drying process. The specific dryer used is shown below in Figure 2. Puff extrusion scored higher in the decision matrix, but the MSU Product Development team did not have access to one. Due to the difference in product quality, the process design had to use a vacuum dryer to fit Constraint 1.

Vacuum dryers slightly reduce pressure to allow for evaporation of water below 100ºC [1]. Baking at this lower temperature preserves product quality and shape [2].

Figure 2. Vacuum dryer model used for process design

Optimization

Model

Vacuum drying was modeled using mass transfer properties [3]. Figure 3 shows how the convective mass transfer coefficient was determined.

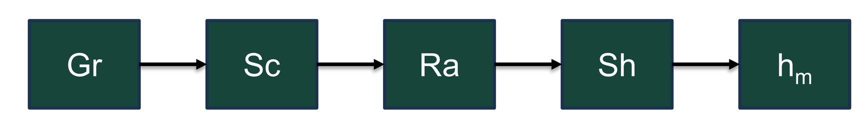

Figure 3. Process of calculating the convective mass transfer coefficient (variables are Grashof, Schmidt, Rayleigh, and Sherwood respectively)

Heisler charts were then used to solve for drying time.

The mass transfer variables shown above require properties of air to be identified. Certain properties, such as air density and the diffusivity of water vapor through air, change as the temperature and pressure of the vacuum dryer change [4].

Optimization

The team looked at optimizing two variables, drying time and product quality, which have opposite relationships with pressure.

To quantitate the product quality, the team used the change dry bulk solids density. A smaller change in this value is desired. The equation below was used to relate dry bulk solids density to pressure.

$$\rho_{bo} = 0.55P^{0.1}$$

Using this relationship and the model, values were found for a range of pressures. This data was then normalized using cumulative fractions.

The data was then plotted, and regressions were done to produce equations for drying time and product quality based on pressure. Once equations were identified, Solver was used to determine the optimal pressure to operate the vacuum dryer at. This optimal pressure corresponds to a temperature based on vaporization tables. The drying time was then found using the Excel model. The optimal conditions were as follows:

- Pressure = 57.2 kPa
- Temperature = 84.7ºC
- Time = 13.87 hr

COMSOL

COMSOL was used to validate our findings. Figure 4 shows 5% MC at 13.75hr.

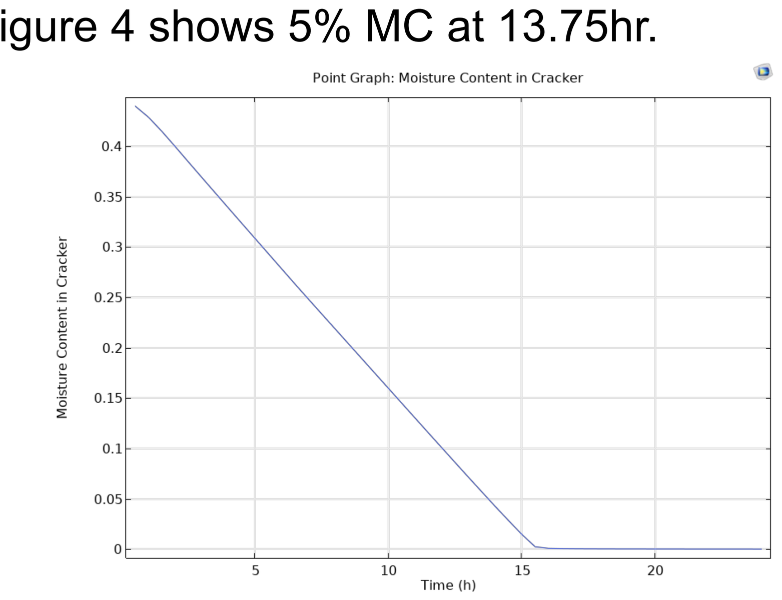

Figure 4. COMSOL moisture content (MC) vs time graph

Design Parameters

One of three flavorings and one of three beans are chosen for each run. These are mixed to form the dough and shaped into crackers using an extruder. The crackers are then baked in a vacuum dryer. Additional mix-ins are added based on the flavor chosen. This is then packaged into trays and run through an X-Ray for a final safety check.

A vacuum dryer takes about 14 hours to process 3600 crackers. The three vacuum dryers run in staggered format, with start times a few hours apart. This maximizes equipment usage allowing for 3 batches to be in process at the same time. This process is shown in Figure 5.

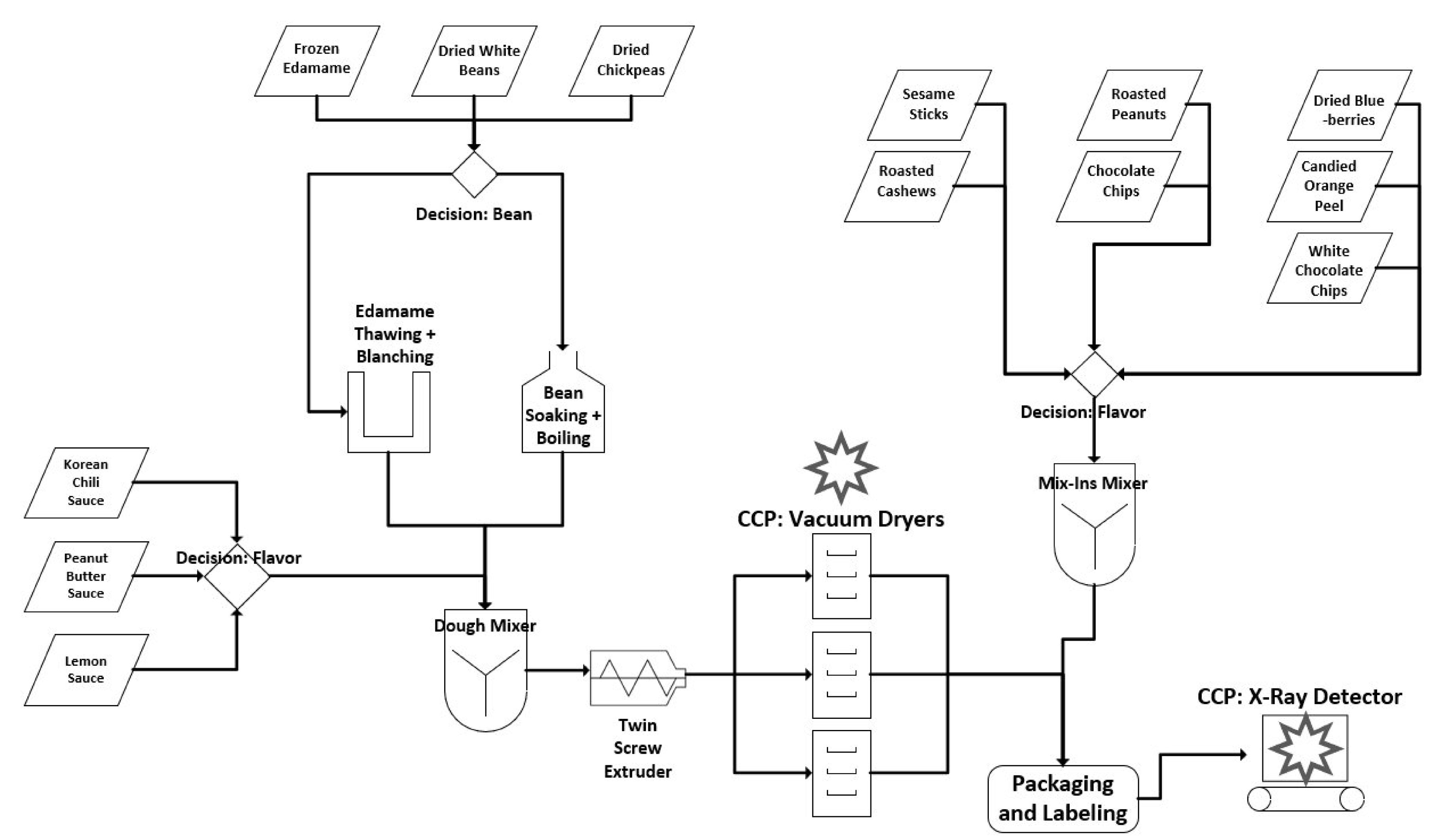

Figure 5. Process flow diagram (PFD) of processing line for Nature's Pulse trail mix

Economics

The project is analyzed by looking at costs and benefits, with costs being broken down into capital and annual. Table 2 summarizes these.

Costs

- Capital Cost Breakdown
  - Equipment – 100%
- Annual Cost Breakdown
  - Raw materials – 21.3%
  - Utilities – 0.4%
  - Labor – 49.8%
  - Maintenance – 28.4%

Benefits

- Production Rate of 600,000 Units/Year
  - 400 Units per Batch
  - 3 Batches in 16 hours
  - 8,000 Hours per Year
- Minimum profit of $2.83/Unit
  - Single serving size cost $3.50
  - Bulk deal of 6 for $16.99
  - Used most conservative value

Table 2. Economic results from process

Economic Summary	
Capital Costs	$604,510
Annual Costs	$1,275,549
Annual Benefits	$1,698,000

The per-unit cost of production is $2.13. With a single serving cost of $3.50, this leaves a 39% profit margin. The net annual profit is $423,000, resulting in a payback period of 1.43 years. The equation below was used to find the present value of costs and benefits.

$$P = A\left[\frac{1-(1+i)^{-n}}{i}\right]$$

Using this, an NPV of $3,000,000 and IRR of 70% were calculated.

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Select References

[1] Parikh, D. M. (2015). Vacuum drying: Basics and application. *Chemical engineering*, 122(4), 48-54.

[2] Ries, F. R. (2014). *Vacuum drying for extending food shelf-life*. Springer. https://doi.org/10.1007/978-3-319-08207-3

[3] Nadi, F., Rahimi, G. H., Younsi, R., Tavakoli, T., & Hamidi-Esfahani, Z. (2012). Numerical simulation of vacuum drying by Luikov's equations. *Drying technology,* 30(2), 197-206. https://doi.org/10.1080/07373937.2011.595860

[4] Dandy, G., Walker, W., Daniell, T., & Warner, R. (2017). *Planning and design of engineering systems* (3rd ed.). Taylor & Francis Group. https://doi.org/10.1201/9781351228121