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Food for thought: Delicious problems for Process System Engineering (PSE) courses

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ABSTRACT

Active learning is widely recognized as an effective teaching approach that can improve classroom outcomes. This is enabled by providing the time for students to apply new knowledge, make mistakes, correct them, and repeat the process until mastery is achieved. One way to implement active learning is through the flipped classroom paradigm. However, to be effective, active learning depends on providing students with a variety of open-ended problems, ranging in difficulty from introductory to advanced levels. This paper presents four food-themed problems for use in numerical methods and process control courses:

1. *Formulating Willy Wonka's new chocolate bar*: An introductory linear programming problem focused on translating verbal descriptions into mathematical models.

2. *Optimal production for the Matrix Pizza company*: A more advanced mixed-integer linear programming problem involving multiple scheduling scenarios.

3. *Optimal frying time for fried ice cream production*: A transient heat transfer problem modelled by an initial-value partial differential equation.

4. *Control system design for Uncle Kane's pancake batter machine*: A control design problem involving uncertain process models and the selection of an appropriate operating mode and PI controller design.

These problems aim to engage students in practical, problem-solving activities central to the active learning process.

Keywords: Chemical engineering education, flipped classroom, active learning.

1. INTRODUCTION

Active learning is widely accepted as a collection of teaching paradigms that have the best potential to yield improved learning outcomes in classroom settings [1-3]. Traditional lecture-centred teaching often struggles to engage students effectively in a discipline characterized by complex processes and systems [4]. By incorporating active learning techniques such as peer instruction [2], problem-based learning [5], and gamification [6-7], educators can enhance student engagement, critical thinking, and real-world application of concepts [8-9].

Adopting the flipped classroom paradigm [10-11], which moves traditional lecture-based transfer of information to online lessons completed by students in advance of class activities, frees class time for the aforementioned student-centred activities. To adopt active learning, some class time needs to be allocated for students to experiment with the application of the newly acquired knowledge, giving them time to make mistakes, correct their errors, try again, and repeat this process as necessary. This cyclic activity is a variant of Kolb's [12] ideas about the cognitive processes involved in learning. One way to allocate time for effective learning would be to adopt the flipped classroom.

To be effective, this form of learning relies on the availability of sufficient open-ended problem sets to provide students with a rich source of practice materials. These should encompass a range of difficulty: from introductory level to "final exam level" and beyond. To that

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end, this paper presents a set of problems with an arbitrary common theme close to the author's heart ("the best way to a man's heart is through his stomach"), mostly intended to be utilized in a course on numerical methods, with one extra problem designed for a course on "good old" process control.

2. EXAMPLE FOOD-RELATED PROBLEMS FOR PSE COURSES

With "food, glorious food" as a theme, the four example problems presented in this paper are:

1. *Optimal formulation of Willy Wonka's new chocolate bar*. This is an introductory linear programming (LP) problem, which gives students practice in translation of a verbal description into a mathematical formulation, and its solution.
2. *Optimal production for the "Matrix Pizza" company*, a bakery providing quality pizzas to a college campus in mid-West USA. This is a more advanced mixed integer linear programming (MILP) problem including alternative scenarios that need to be accounted for in the optimal scheduling solution.
3. *Optimal frying time for "fried ice cream."* This is a transient heat transfer problem that is defined as an initial value partial differential equation (IVPDE) that needs to be solved numerically.
4. *Control system design for Uncle Kane's continuous pancake batter machine*. This is a single input – single output (SISO) control problem presented as a set of alternative operating modes, each with its own uncertain model description. The student needs to select the operating mode and design a suitable PI controller that meets required specifications.

Each of the above four example problems will be discussed next, focusing on the problem definition, the degree of difficulty, and the learning objectives. Because of space limitations, only sketches of the solutions will be presented here. Full solution outlines to all four problems will appear in the full version of this paper.

2.1 Optimal formulation of Willy Wonka's new chocolate bar

Problem definition: Willy Wonka has hired you to formulate a new chocolate bar called "Super-Choc," weighing 100 grams. The bar consists of sugar, and two types of chocolate: African and Belgian. The optimal mass of each component needs to be specified to minimize costs, while meeting the following five requirements:

1. Each bar should contain no more than 60 grams of chocolate
2. The amount of African chocolate should not exceed the amount of Belgian chocolate by more than 10 grams.
3. The bar's Sweetness (S) should not exceed 30 units per bar, where each gram of African chocolate reduces S by 0.3 unit (relative to sugar), while each gram of Belgian chocolate raises S by one unit.
4. The bar's Mouth Feel (M) should be at least 40 units. Each gram of African chocolate increases M by 2.2 units, while each gram of Belgian chocolate raises M by one unit.
5. The bar's Luster (L) should be at least 70 units. Each gram of African chocolate increases L by one unit, while each gram of Belgian chocolate raises L by 3.9 units.

If the cost of Belgian chocolate is three times the cost of African chocolate, and the cost of sugar can be neglected, compute the optimal composition of a bar of "Super-Choc."

Degree of difficulty: A practice problem to train basic application of LP methodology.

Learning objectives: The student will demonstrate the ability to develop an LP based on a written problem description, and to graphically solve the LP to obtain the optimal solution.

Sketch of solution: Defining x_1 and x_2 as the mass in grams, of African and Belgian chocolate, respectively, the problem as defined can be translated to the following LP:

$$\min_{x_1,x_2} J = x_1 + 3x_2 \text{ (B costs 3 times more than A)}$$

Subject to:

$$\begin{aligned}
x_1 + x_2 &\le 60 \text{ (chocolate content of at most 60 g)}\\
x_1 - x_2 &\le 10 \text{ (A content must be up to 10 g more than B)}\\
-0.3x_1 + x_2 &\le 30 \text{ (S must be at most 30)}\\
2.2x_1 + x_2 &\ge 40 \text{ (M must be at least 40)}\\
x_1 + 3.9x_2 &\ge 70 \text{ (L must be at least 70)}\\
x_1, x_2 &\ge 0
\end{aligned} \qquad (1)$$

The graphical solution is shown in Figure 1, indicating that the active constraints are those on M and L, and that 56% of the optimal bar is sugar!

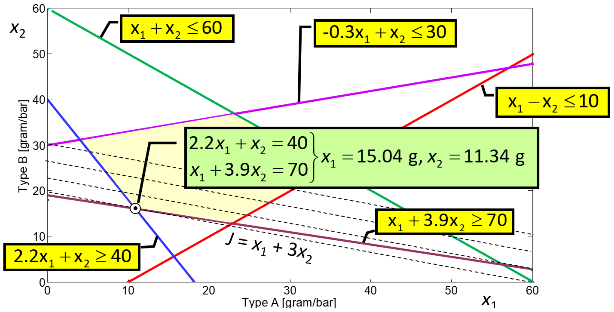

Figure 1. Graphical solution for Willy Wonka's chocolate

bar formulation.

2.2 Optimal production for the “Matrix Pizza” company

Problem definition: “Matrix Pizza” is a pizza bakery that provides quality pizza pies to the college campus in mid-West USA. The bakery produces three types of pizza pies: **Matrix Special**, sold for $10/pie, **Matrix Pro**, sold for $7/pie, and **Matrix College**, sold for $5/pie. The three types of pizza differ only in the toppings, as listed in Table 1.

Table 1: Recipes for the Pizzas (quantities of each topping, in grams, on each pizza).

	Special	Pro	College	Cost ($/kg)
Price ($/pie)	10	7	5	
Tomatoes (g)	200	250	350	2
Mozzarella (g)	200	250	350	2
Parmesan (g)	100	100	0	15
Olives (g)	100	100	0	20
Tuna (g)	100	0	0	10

In addition to the cost of the toppings, the production costs of the pizza pies also need to account for staff costs estimated at $1 per pizza pie, as well as operating and maintenance costs of the pizza oven, estimated at $1,000 per oven per week. For each oven installed, the production capacity is 1,000 pizzas per week. There is no limit on the number of pizza pies that can be produced in the bakery per day, so long as the daily demands, listed in Table 2, are not exceeded on a weekly basis. Your tasks are:

(a) Formulate a MILP whose solution is the optimal quantities of each type of pizza that should be produced each week, including the number of ovens that should be installed in the bakery to maximize profits.
(b) Solve the MILP formulated in step (a).
(c) The college’s football team is planning to hold home games each Saturday night. How will this affect the optimal solution if the home games change the pizza demand on Saturdays according to Table 3.

Table 2: Typical Demand (pizzas/day for each type).

Day	Special	Pro	College
Monday	20	60	60
Tuesday	0	80	80
Wednesday	0	60	140
Thursday	20	80	160
Friday	40	40	120
Saturday	140	60	20
Sunday	100	100	20
Weekly Total	320	480	600

Table 3: Revised Demand on Saturdays (pizzas/day for each type).

Day	Special	Pro	College
Saturday	340	160	120

Degree of difficulty: A more advanced MILP problem.

Learning objectives: The student will demonstrate the ability to develop a MILP based on a written problem description, and to either solve the problem graphically or using the Simplex method.

Sketch of solution: (a) Formulation of the problems as set as a MILP; (b) Solution using a MILP solution method such as Branch-and-bound or by using the Simplex method on separate scenarios.

2.3 Optimal frying time for “fried ice cream.”

Problem definition: “Fried ice cream” is the house specialty of the “Sea Waves” restaurant, overlooking Haifa bay. A portion of ice cream is wrapped in pastry dough and deep-frozen. Just before serving, it is deep fried for a short time in high-temperature oil. A typical portion of “fried ice cream” is shown in Figure 2. You have been hired by the chef to provide an estimate of the time needed to fry the pastry-wrapped ice cream such that the pastry is crispy, and the ice-cream stays frozen.

Figure 2. Fried ice cream

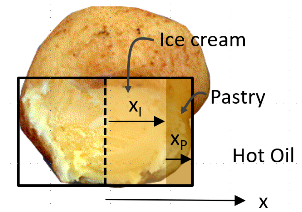

Figure 3. Coordinate system

A mathematical model is set up to compute the temperature of the pastry and ice cream as functions of time and position. For simplicity, a one-dimensional model is constructed making use of symmetry, as shown in Figure 3:

$$\text{For ice cream: } \frac{\partial T_I}{\partial t} = \alpha_I \frac{\partial^2 T_I}{\partial x^2},\ T_I(x,0) = T^0,\ 0 \le x \le x_I \tag{2}$$

$$\text{For pastry: } \frac{\partial T_P}{\partial t} = \alpha_P \frac{\partial^2 T_P}{\partial x^2},\ T_P(x,0) = T^0,\ x_I < x \le x_P \tag{3}$$

The following boundary conditions apply:

$$@\ x = 0:\ \frac{\partial T_I}{\partial x} = 0 \qquad @\ x = x_I:\ \alpha_I \frac{\partial T_I}{\partial x} = \alpha_P \frac{\partial T_P}{\partial x}$$

$$@\ x = x_I : T_I(x_I, t) = T_P(x_I, t) \qquad @\ x = x_P:\ \frac{\partial T_P}{\partial x} = \beta\left(T_{oil} - T_P(x_P, t)\right)$$

Degree of difficulty: This problem tests the ability to apply numerical methods for the solution of initial value partial differential equations (IVPDEs).

Learning objectives: The student will demonstrate the ability to discretize an IVPDE and its boundary conditions and solve it to ensure a stable numerical solution.

Sketch of solution: Development of discretized approximation of the original PDE using a backward difference approximation for the time-differential term to impart unconditional stability on the numerical solution (Crank-Nicolson’s method).

2.4. Control system design for Uncle Kane's continuous pancake batter machine.

Problem definition: Uncle Kane, the famous chemical engineer and expert chef, has developed a continuous process for the production of pancake batter. A controlled stream of liquid, consisting of milk, eggs, and vanilla, F_1, is fed to a mixing vessel together with a continuous stream of solid feed consisting mostly of flour and sugar, F_2. Uncle Kane has noticed that the frequency of the sound made by the mixer head is related almost linearly to the viscosity of the mixture, which also affects its quality. He has developed an automatic control system that uses a microphone to measure the sound in the mixing vessel, which sends a feedback signal to a controller that manipulates the control valve installed on stream F_1. The control system is illustrated schematically in Figure 4.

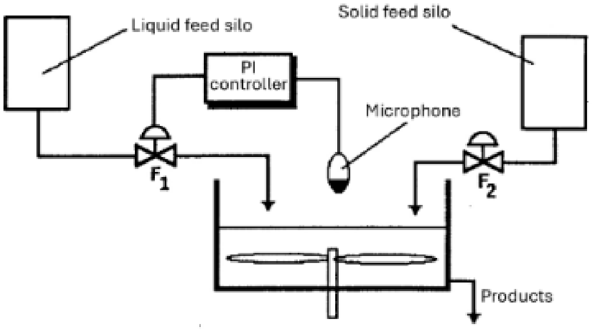

Figure 4. Uncle Kane's continuous pancake batter production unit.

After much soul-destroying research, Uncle Kane has succeeded in developing a model relating the flowrate of F_1 to the frequency of sound picked up by the microphone, ϕ:

$$\frac{\phi}{F_1}(s) = p(s) = \frac{K_p(-\alpha s+1)}{(\tau s+1)^2} e^{-\theta s} \tag{4}$$

Table 4: Parameters for the model in Eq.(4) as a function of the flow rate F_2.

F_2 (kg/h)	K_p	α(s)	τ(s)	θ(s)
750	$0.9 \le K_p \le 1.1$	5	5	1
1,000	$2 \le K_p \le 4$	1	1	0.2
1,250	$0.8 \le K_p \le 7.2$	5	5	1

His experimental work has also discovered three possible operating points for the production unit, each around a given flow rate of the solid feed, F2. Table 4 presents values of the model parameters in Eq.(4) at each operating point. Design a PI controller to control ϕ by manipulating F_1 so that the following specifications are satisfied: (a) Robust stability; (b) Bandwidth of the Internal Model Controller (IMC) filter of at least 0.3 rad/sec; (c) Maximizing production.

Degree of difficulty: A typical problem in robust control design.

Learning objectives: The student will demonstrate the ability to adequately represent the model uncertainty for design purposes and use it to compute PI controller parameters, designed via the IMC parametrization, that meet all the specifications.

Sketch of solution: (a) Development of multiplicative approximation accounting both for parametric uncertainty and the consequence of 1st order model implied by the requirement of PI control; (b) Computing stability limit in terms of the time constant of the IMC filter; (c) Usage of these tools to determine the most suitable operating mode and corresponding PI controller tuning.

3. INTEGRATION WITH THE FLIPPED CLASS PARADIGM

It would be appropriate to discuss how the problems presented here could be incorporated into the flipped classroom paradigm. While organizational, evaluation and student feedback are addressed in our published papers [10,11], a full version of the paper would provide space to cover these issues in more details.

4. DISCUSSION

The use of active learning in engineering education, particularly in courses involving numerical methods and process control, offers numerous benefits over traditional lecture-based teaching [10,11]. Active learning strategies, such as problem-based learning (PBL), peer instruction, and gamification, have been shown to improve student engagement, critical thinking, and long-term retention of knowledge [1-3]. The example problems introduced in this paper, which leverage the flipped classroom paradigm, not only align with these findings but also offer a practical framework for implementing active learning in technically demanding fields such as PSE. They offer a diverse and engaging way to introduce students to fundamental concepts in optimization, heat transfer, and control system design. By utilizing scenarios that range from the formulation of a new chocolate bar to the design of a control system for a pancake batter machine, students are exposed to real-world problems that require both analytical rigor and creative problem-solving skills. This thematic approach—framed around the relatable and engaging concept of food production—appeals to students' interests and can foster a deeper connection to the material, leading to improved motivation and learning outcomes.

4.1 Active learning and student engagement

A central goal of active learning is to increase student participation and engagement in the learning process, which can be particularly challenging in disciplines like PSE where abstract concepts and complex systems are common. Traditional teaching methods often rely on passive learning, where students listen to lectures and absorb information, usually without the opportunity to immediately apply their knowledge for themselves. In contrast, implementing the flipped classroom paradigm, transfers the responsibility of covering the lecture materials to the students as pre-class preparation, and reallocates in-class time for active, hands-on problem-solving.

The problems outlined in this paper facilitate this active learning model by encouraging students to work through open-ended, real-world challenges. This type of problem solving not only reinforces technical knowledge but also helps develop critical thinking, adaptability, and decision-making skills. As students work through problems such as optimizing pizza production or controlling the frying time of ice cream, they learn to balance conflicting objectives, and select appropriate methods for solving complex, dynamic problems. By solving problems iteratively and experimenting, students can internalize the underlying concepts more deeply, improving their ability to transfer this knowledge to new and unfamiliar contexts.

4.2 Problem complexity and cognitive development

The problems presented span a broad spectrum of difficulty, catering to students at different levels of expertise. The introductory LP problem on chocolate bar formulation, for example, provides a relatively simple application where students practice translating verbal descriptions into mathematical models. This offers an excellent opportunity for students to gain foundational skills in optimization. On the other hand, more advanced problems—such as the MILP problem for pizza production and the control system design for the pancake batter machine—challenge students to apply more sophisticated mathematical techniques and consider the implications of uncertainty, robustness, and system dynamics.

This range of problem complexity is essential for promoting cognitive development and ensuring that students progress from basic to advanced levels of understanding. By providing a series of problems that increase in complexity, students are able to gradually build their knowledge and skills while reinforcing their learning through multiple iterations. This approach mirrors Kolb's [12] experiential learning cycle, where concrete experience is followed by reflective observation, abstract conceptualization, and active experimentation. Furthermore, the inclusion of open-ended problems allows students to explore different solution paths, promoting deeper cognitive engagement with the material. In the case of the MILP problem for the Matrix Pizza company, for instance, students must navigate the intricacies of balancing resource constraints, demand forecasts, and cost optimization, while considering alternative production schedules. This requires not only mathematical proficiency but also the ability to model and solve real-world optimization problems with multiple variables and constraints.

4.3 Interdisciplinary learning and real-world applications

One strength of the food-themed problems is their ability to connect mathematical and engineering concepts to real-world applications. Using familiar scenarios like chocolate bar formulation or fried ice cream production helps students understand the practical implications of the methods they are learning. This connection is vital in engineering education, where students may struggle to relate abstract concepts to real-world problems.

The interdisciplinary nature of the problems also helps students link different areas of study. For example, the optimal frying time problem applies numerical methods to heat transfer, while the control system design for the pancake batter machine highlights the importance of robustness in engineering design. These problems demonstrate that real-world challenges often require skills from multiple fields, enriching students' chemical engineering education.

By framing problems around food production, the paper shows that complex engineering concepts can be communicated in an engaging and accessible way. This approach encourages students to think beyond traditional boundaries and explore diverse applications of chemical engineering.

4.4 Limitations and future directions

While the approach described in this paper has considerable promise, there are several limitations that should be considered. One challenge is ensuring that students have the necessary background knowledge to tackle more advanced problems. For example, while the introductory problems on linear programming and optimization may be accessible to students with a basic understanding of mathematics, the more complex problems involving MILP and robust control system design may require additional support in terms of prerequisite knowledge or instructional resources.

Another limitation is the time required for students to engage with these open-ended problems. The flipped classroom paradigm depends on students completing preparatory work outside of class, which may not always be feasible for all students, particularly those who struggle with self-directed learning. To mitigate this, instructors can provide additional support, such as pre-class tutorials, practice exercises, or discussion forums, to ensure students feel confident in their ability to solve the problems [10,11]. Additionally, incorporating peer collaboration into the learning process—such as through group problem-solving sessions—could help foster a more supportive and dynamic learning environment [2].

Future research could explore the specific impacts of these types of problems on student outcomes, such as academic performance, engagement, and retention of knowledge. It would also be valuable to assess how students respond to the food-themed problems, or other themes, in terms of motivation and interest, and whether these themes contribute to a greater sense of relevance and enjoyment in the learning process.

Finally, one could expand the problem sets presented here to include even more interdisciplinary scenarios, incorporating areas such as environmental sustainability and even space exploration applications [13]. This would not only broaden the applicability of the problems but also encourage students to think about engineering challenges in a more holistic and interconnected way.

CONCLUSIONS

The use of active learning strategies, particularly within the context of the flipped classroom paradigm, offers significant potential for improving student engagement and learning outcomes in process systems engineering courses. By presenting food-themed problems that span a range of difficulty levels and disciplines, this approach allows students to develop critical thinking, problem-solving, and technical skills in a more interactive and experiential way. Although there are challenges to implementing this approach, the potential benefits for both student learning and motivation are considerable, and future research should explore the broader impacts of such active learning strategies in engineering education. The author has used all of the exercises presented here over decades of teaching with great success. Each of them was used just once in exams and repeatedly since then in the classroom as open-ended practice problems. In the last 10 years, the incorporation of the flipped classroom paradigm in his teaching has released additional contact time to utilize for open-ended problem solving using exercise problems like the ones showcased in this paper.

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