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Computer-aided process design using Food Operations Oriented Design System Block Library

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Abstract

The comparison of design alternatives is a common design task for food process engineers. Foods Operations Oriented Design System Block Library (FOODS-LIB[©]) in conjunction with its economic analysis program (ECONANAL) can be used in this capacity. To demonstrate how FOODS-LIB can be used in a time efficient manner to perform analysis of design alternatives, a case study was conducted in which five alternative processes to manufacture whole milk powder were compared. The design goal was to minimize steam use and maximize 10 yr net present worth. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Computer-aided engineering; Food process design

1. Introduction

Process design encompasses a broad array of activities from process conceptualization to detailed process design. Flowsheeting is just one step in the design of any process. It is, however, the most labor and time intensive activity for any process engineer. Flowsheeting is defined to be the performance of steady-state calculations necessary to describe the behavior of a process and to determine key operating conditions (Peters & Timmerhause, 1991). This step includes performance of mass and energy balances, determination of process equipment parameters and detailed design, estimation of equipment and plant costs, and analysis of process economics.

Generally, the cost of process design is estimated to be 10% of total plant design costs with the decisions being made at this stage accounting for 80% of total capital costs (Winter, 1992). Front-end engineering can reduce cost, reduce time to market, and enable dramatic change (Datta, 1998). It is at the early design stages that computer-aided engineering (CAE) software can perform a critical role in the development of new and reengineered food processes. The inherent benefit of using CAE software is the reduction of process development time (Petrides, 1994). Tedious and repetitive computations can be handled in an efficient and consistent manner. This improves engineering accuracy and yields more robust processes. By reducing computation time, the food process engineer is able to screen more alternative process designs and focus on the most feasible designs. When used with sound engineering judgment, food process design software can efficiently aid the engineer in generating high quality designs with lower capital and production costs and improved safety and reliability (Winter, 1992).

There are many additional benefits to use a food process design software package. Waste (utility and byproduct) minimization schemes can be explored for further reduction in production costs (Balint, 1994). The software can provide a means for inexpensive training for students and engineers on how to design processes. Further, the use of a single or set of software packages can improve communication between process development groups working on the same project (Petrides, 1994).

The overall goal of this research was to develop a CAE tool that can be used by a food process engineer at any skill level to design and analyze *any* steady-state continuous food process. The resulting tool is the Food Operations Oriented Design System Block Library (FOODS-LIB[®]). This paper gives overviews of the FOODS-LIB package and the economic analysis

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Nomenclature		MSI _b	base Marshall and Swift Index
C_{a}	estimated equipment cost	S_{a}	estimated equipment size
$C_{\rm b}$	base equipment cost	S_{b}	base equipment size
D	log reduction time	с	cost capacity factor
MSI _a	current Marshall and Swift Index	Ζ	temperature change to achieve log reduction in D
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companion program (ECONANAL) and presents a case study in which FOODS-LIB and ECONANAL are used to study alternative whole milk powder process designs.

2. Process design tool

FOODS-LIB is a multi-level steady-state food process design tool for food engineers, food scientists, and food technologists (Diefes, 1997). This software is designed to aid the user in performing process conceptualization, steady-state mass and energy balances across operations, and continuous food operations design. Microbial load reduction and quality degradation due to thermal treatment may also be assessed. The MAT-LAB[®] computational software package and its SIMU-LINK[®] dynamic system simulation toolbox were used to develop the computational algorithms and the graphical user interface (GUI), respectively.

FOODS-LIB allows the user to flowsheet a food process by drawing a diagram (Fig. 1) comprising of copies of blocks from the software's library. Food process flowsheets developed using FOODS-LIB consist of three levels (Fig. 2). The highest level is the *flowsheet* *level*, which consists of a workspace in which the food process flow diagram is drawn. The process shown in Fig. 2 consists of streams entering and leaving one unit operation, a single effect evaporator. All flowsheets consist of a series of process input block (e.g., food, steam, water, and air), unit operations blocks, and process output blocks (e.g., product and waste) connected by streamlines. The design level is immediately below the flowsheet level. It provides the inport and outport hooks for drawing the steady-state process model at the flowsheet level and access to the *data entry level.* The lowest levels of the GUI are the data entry levels through which numerical data required for the design calculations are entered. The three GUI levels are pictorially shown in Fig. 2 which demonstrates the order in which blocks and sub-systems must be opened to reach a particular data entry level workspace.

FOODS-LIB currently contains 11 unit operation models that are developed to varying design levels. Each model is based on fundamental engineering principles rather than empirical models. Each unit operation model is divided into a maximum of four design levels (Fig. 3). These divisions correspond to stages of the design. At the lowest design level, mass balances around



Fig. 1. Whole milk powder process design alternatives I with steam from a source for all heat transfer operations.



Fig. 2. The three graphical user interface levels for flowsheets drawn using FOODS-LIB.

a particular unit operation are performed. At the energy balance level, all feed, intermediate, and exit stream enthalpies are determined so energy balances can be performed. The next design level is termed the basic transport level. The purpose of this level is to make quick estimates of equipment capacity or size so unit operations can be costed. The highest design level coded within a unit operation model is the advanced transport level. Based on specific equipment configuration information, the overall momentum, heat, and mass transfer



Fig. 3. FOODS-LIB unit operation design levels.

variables specified at the basic transport level are replaced with values computed from fundamental models. Detailed design information including operating conditions, materials of construction, and equipment dimensions are specified at the FOODS-LIB GUI. To complete design at this level, the unit operation algorithms rely heavily on the thermo-physical property estimation libraries. Models to estimate density, thermal conductivity, and viscosity are among those required by the unit operation models.

Upon completion of data entry to the flowsheet, a steady-state simulation can be executed. Results of the simulation include mass and energy balances around each unit operation in the process. Basic and advanced transport design results may also be generated. In addition, a simple microbial and quality assessment based solely on the thermal conditions of the process can be made.

3. ECONANAL

The ECONANAL provided with FOODS-LIB acts as a separate program from FOODS-LIB. However, the GUI and supporting algorithms parallel those of FOODS-LIB. When a process design is created and simulated in FOODS-LIB with the economic analysis option turned on, two economic data files are created. The first is the stream cost data file which includes the mass flow rate, cost or value, and inflation rate of each process stream. The second is the unit operations cost data file, which includes the size and cost scaling information for each unit operation in the process. ECON-ANAL requires that these two data files be available for execution of an economic analysis.

Like FOODS-LIB, the ECONANAL GUI consists of three levels. At the *flowsheet level* is a single block which

provides access to the *design level* (Fig. 4). At the design level, all economic information, which must be provided by the user, is broken into a number of categories represented by sub-systems. Each design level sub-system provides access to *data entry levels*.

For each design level available in FOODS-LIB, there is a comparable economic analysis level provided by ECONANAL. For instance, if only mass balances were performed on a given FOODS-LIB simulation, ECONANAL can be used to generate a stream cost/ value report (Level 1). Based on user-specified operating hours, simple gross earnings are computed by subtracting the annual raw materials and waste discharge costs from the annual product(s) income. Level 2 corresponds to the energy balance level in FOODS-LIB. At this level, annual utility and labor costs are subtracted from the gross earnings found in Level 1 to yield the total gross earnings.

If basic or advanced transport level of design was completed on a process, then ECONANAL can be used to estimate the initial cost of purchasing equipment (Level 3). For each unit operation in a FOODS-LIB process design, six cost scaling pieces of information are requested: base cost C_b , base Marshal and Swift Index MSI_b, base size S_b , cost capacity factor c, and minimum and maximum equipment size for application of baseline data. These parameters are set by the user for each unit operation in FOODS-LIB. An estimated equipment cost C_a is determined by scaling and applying a current Marshall and Swift Index MSI_a as

$$C_{\rm a} = C_{\rm b} \left(\frac{\rm MSI_{\rm a}}{\rm MSI_{\rm b}} \right) \left(\frac{S_{\rm a}}{S_{\rm b}} \right)^c.$$

Level 4 is the highest economic analysis level and allows capital investments and manufacturing costs to be assessed over the project life. Economic analysis



Design Level

Fig. 4. ECONANAL flowsheet and design graphical user interface levels.

methods used at Level 4 follow Peters and Timmerhause (1991) as described by Diefes (1997).

4. Design statement

A whole milk powder process was designed wherein 10,000 kg/h of 3.5% fat milk is converted to 97% total solids (w/w) whole milk powder (Pisecky, 1995). During processing, the microbial load of *Mycobacterium tuber-culosis*, a food pathogen, undergoes a required minimum 15-log reduction. Maintenance of 95% of the thiamin was desired. Process alternatives were evaluated for minimum steam use and maximum 10 yr net present worth.

The general flowsheet for this process consists of four unit operations. First, the whole milk is passed through a heat exchanger that brings the temperature of the milk up to the pasteurization temperature. The hot milk is then passed through a holding tube to reduce the microbial load to comply with federal or state laws or company policy. Next the whole milk is pre-concentrated to increase the total solids before the milk is spray dried. Fig. 1 shows the FOODS-LIB process flowsheet for design alternative I. In this design, source steam (e.g., from a boiler) is used by each unit operation that requires a heating medium for heat transfer. This process flowsheet was used to establish a baseline set of operating conditions.

The composition of raw whole milk fed to the process was taken to be 3.5% protein, 4.9% carbohydrate, 3.5%fat, and 0.7% ash (Watt & Merrill, 1975). The feed temperature was set to a typical storage temperature of 3° C (Varnam & Sutherland, 1994). The saturated steam source pressure is set to 1 MPa; this enables heating of the air in the spray dryer, which operates at the highest process temperature. Ambient air brought into the indirect heating section of the spray dryer was assumed to be at 15° C and 50% RH.

The kinetic parameters for *M. tuberculosis* were $D_{250 \text{ F}} = D_{65.56 \text{ C}} = 0.6 \text{ min}$ and $z = 5^{\circ}\text{C}$ (Geankoplis, 1993). The kinetics for thiamin were assumed to be $D_{121 \text{ C}} = 20 \text{ min}$ and $z = 38^{\circ}\text{C}$ (Hallström, Skjöldebrand & Trägårdh, 1988). A comparison of the *D* values for *M. tuberculosis* and thiamin shows that in the pasteurization temperature range, thiamin is more heat stable than the microbe. This fact made design of a process that maintains 95% thiamin possible.

For each whole milk powder process design alternative, the following economic information was used. Stream economic analysis parameters that were set at the FOODS-LIB interface include the raw milk price, the whole milk powder value, and the stream inflation rates. A purchasing price for raw milk which yields a minimum 15% rate of return based on discounted cash Table 1

Unit operation	Base size	Base MSI ^a	Base cost	Size range	Scaling index
Heat exchanger ^b (m ²) Holding tube ^c (m diam) Evaporator ^b (m ²)	13.9 0.1016 92.9 2268 0	300 904 300 300	5500 164 23000	9.3–18.6 0.0178–0.508 0.930–9290.3 113.4 9071.8	0.650 0.973 0.680 0.710

Unit operation costing information for whole milk powder process design alternatives

^a Marshall and Swift Index (Peters & Timmerhaus, 1991).

^bSee Woods (1975).

^c Stainless steel schedule 40 pipe cost data yields \$/m length of pipe (Peters & Timmerhaus, 1991).

flow for the base-line design alternative was used. Raw milk price was estimated to be \$0.29/kg based on an estimated 1994 price of \$13.12/100 lb (USDA, 1996). The value of the whole milk powder was assumed to be similar to that of non-fat dry milk powder; the price was reported to be \$2.37/kg (\$1.075/lb) by Hoard's Dairyman (1997). A zero inflation rate was assumed for both the raw milk and the whole milk powder. No waste discharge costs were assessed. Unit operation costing parameters were set as in Table 1. Each piece of equipment was assumed to have a life of 10 yr with a salvage value of 10% of the initial value.

Operating labor for the evaporator and the spray dryer were set at 0.25 and 1 man h/h of operation, respectively (Peters & Timmerhause, 1991). Operating labor for the heat exchanger and holding tube were set at 0.125 man h/h of operation. Maintenance labor for each piece of equipment was set at 6% of the operating labor value (Woods, 1975).

The following specifications were made in ECON-ANAL. The annual operating time was assumed to be 4800 h/yr for a project life of 10 yr; the plant was assumed to be at full capacity each year of operation. The current Marshall and Swift Index was set at 1036. Steam cost was set at \$0.0072/kg. Operating and maintenance labor costs were set at \$25/man h. Fluid processing capital investment ratio factors and intermediate manufacturing cost ratio factors were used (Peters & Timmerhause, 1991). All inflation rates were fixed at 4%, and they were calculated using the compounding method. A corporate tax rate of 34% was assumed.

5. Process design alternatives

5.1. Alternative I: base-line

The unit operations of process design alternative I were studied individually to establish feasible operating parameters. The iterative nature of these studies is emphasized within the discussion of the selection of the design parameters for the evaporator.

The pasteurization temperature was set to achieve a combination of holding tube diameter and length which are of reasonable size when pasteurizing for a 15-log reduction in *M. tuberculosis*. A pasteurization temperature of 77°C was selected to give a holding tube length between 1 and 10 m. A holding tube inner diameter of 0.0525 m and an outer diameter of 0.06033 m, which are standard schedule 40 steel pipe dimensions, were set (Geankoplis, 1993). For these specifications, a holding tube 4.27 m in length is required. Fluid flow is turbulent (Reynolds number is 1.124×10^5) and the minimum residence time is 2.32 s.

The raw milk temperature is brought up to 77° C in a plate heat exchanger with heat transfer occurring between condensing source steam and the raw milk. The steam requirement for this operation is 1420 kg/h. Analysis of this operation consisted of varying the overall heat transfer over the range 3000–7000 W/m² K (Raju & Bansal, 1986), the plate size over the range 0.03-2.23 m², and the spacing (gap) over the range 1.5-5 mm. Based on the heat exchanger analysis, a high overall heat transfer coefficient of 5000 W/m² K was selected since steam is used on one side rather than water. The plate dimensions were set at 0.23 m wide and 0.46 m long with a gap of 2 mm. For this design, six plates are required. Turbulent flow is achieved for both milk and steam.

A single effect evaporator was selected to preconcentrate the whole milk to 48% total solids (Varnam & Sutherland, 1994). An inner tube diameter was set to a schedule 40-pipe diameter of 0.0525 m with a wall thickness of 3.91 mm. The thermal conductivity of the pipe was taken to be that of steel, 162 kJ/h m² K (Geankoplis, 1993). Operating temperatures for evaporation of milk fall in the range 40-80°C. Exit temperatures between 60°C and 80°C are preferred since these elevated temperatures reduce concentrate viscosity and improve solubility (Varnam & Sutherland, 1994; Pisecky, 1995). These characteristics facilitate the spray drying process. A forced circulation evaporator was first considered for inclusion in the design. Table 2 shows the design results for four simulation cases. The first two cases were run with the operating pressure set to

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Table 2

Single effect forced circulation evaporator design results for preconcentration of whole milk initially at 77°C to 48% total solids

Forced circulation evaporator design specifications	Recycle ratio ^a	Residence time ^b (min)	Thiamin retention (%)
Case 1 Velocity = 2 m/s Operating pressure = 0.02 MPa $D_i = 0.0525$ m; $x = 3.91$ mm	59.6	164	43
Case 2 Velocity = 5 m/s Operating pressure = 0.02 MPa $D_i = 0.0525$ m; $x = 3.91$ mm	149	273	25
Case 3 Velocity = 2 m/s Operating pressure = 0.0096 MPa $D_i = 0.0525$ m; $x = 3.91$ mm	150	247	45
Case 4 Velocity = 2 m/s Operating pressure = 0.0096 MPa $D_i = 0.04089$ m; $x = 3.68$ mm	36.1	67.5	80

^a Recycle ratio = recycle mass flow rate/liquid concentrate mass flow rate.

^bResidence time taken as time for 90% of feed to be removed from evaporator.

0.02 MPa; this corresponds to a saturation temperature of 60°C. The product velocity was set to 2 m/s in the first case and 5 m/s in the second case (Geankoplis, 1993). In both cases, high recycle ratios were required to achieve the specified average velocities. High recycle ratios result in long residence times, which have deleterious effects on thiamin retention. In the third case, the operating pressure was dropped to 0.0096 MPa (45° C saturation temperature) in order to minimize quality degradation. Only a 2% increase in thiamin retention could be achieved. In the last case, the inner tube diameter was reduced to 0.04089 m (wall thickness 3.68 mm). By decreasing the tube diameter and increasing the number of tubes, the residence time can be substantially reduced. Still, only 80% thiamin retention can be achieved.

The design of a single effect falling film evaporator was next investigated. The inner tube diameter was again set to 0.0525 m. A film thickness of 0.5 mm and an average velocity of 2 m/s were assumed. Table 3 shows the results for simulations run at three different operating pressures. In each case, the single pass residence time was 0.02 min and the thiamin retention was 99.99%. Since thiamin retention is not an issue with this evaporator design, selection of design parameters is based on minimum steam use and low heat transfer surface area. These criteria result in selection of an operating pressure of 0.02 MPa.

Selection of operating conditions for the spray dryer had no significant effect on thiamin retention. To minimize steam use and equipment capacity, the following operating conditions were selected. The temperature of the air entering the drying chamber was set to 170°C (Filková & Mujumdar, 1995). It is this temperature which established the steam source state conditions; a 10°C temperature differential is possible between the air and steam (Pisecky, 1995). The air outlet temperature was assumed to be 90°C and the product temperature was fixed at 75°C which falls in the air-product temperature differential range discussed by Knipschildt (1986). A rotary atomizer with a rotating speed of 120 003 rpm and a disk diameter of 0.25 m was selected. Vanes (#36) were assumed to have a height of 0.03 m (Masters, 1985). The density of the powdered product was estimated to be 605 kg/m³, and the critical moisture

Table 3

Single effect falling film evaporator design results for concentration of whole milk initially at 77° C to 48% total solid where film thickness is 0.5 mm, average fluid velocity is 2 m/s, and inner tube diameter is 0.0525 m

Operating pressure (MPa)	Steam mass flow rate (kg/h)	Heat transfer area (m ²)	Tube length (m)	Overall heat transfer coefficient (kJ/h m ² C)
0.0200	8330	13.3	2.39	10 700
0.0312	8432	14.3	2.80	10 998
0.0474	8535	15.6	2.58	11 304

Table 4

Number of effects	Operating pressure (MPa)	Boiling temperature in each effect (°C)	Steam demand (kg/h)	Thiamin retention (%)
2	0.020	122.6/62.0	4699	97.9
	0.012	125.9/51.3	4694	98.6
	0.007	123.9/40.9	4631	99.1
3	0.007	135.4/101.3/40.9	3392	97.1

Effect of number of effects and last effect operating pressure on feed forward falling film evaporator system steam demand and thiamin retention

content was set at 0.25 w/w (Pisecky, 1995). As specified by Masters (1985), the drying chamber height to diameter ratio for a concurrent flow pattern and a rotary atomizer was set to 1; the cone angle was set to 60° . A spray dryer designed with the above specifications requires an ambient air intake of 3.99×10^4 kg/h. The atomizer produces a droplet diameter of 119 mm which is at the upper limit expected for a rotary atomizer (Masters, 1985). The droplet analysis estimates that the constant drying rate period is 0.028 s, and the falling rate period is 0.512 s.

5.2. Process alternative II

Process design alternative II is a slight variation on the first. In an attempt to reduce the spray dryer steam demand, the hot wet air is recycled from the spray dryer exit back to the indirect heat exchanger. The userspecified air recycle fraction was 50%.

5.3. Process alternative III

Process design alternative III builds on the steam saving measure taken in the second alternative. Rather than using source steam to operate the heat exchanger, heat is recovered from the steam condensate leaving the evaporator. The user-defined heat transfer coefficient is reduced to $3000 \text{ W/m}^2 \text{ K}$, this action is taken as this is now more closely a water–water system. The resulting heat transfer area is 2.66 m².

5.4. Process alternatives IV and V

For the final process design alternatives, the single effect evaporator is replaced with an *N*-effect feed forward evaporator; alternative IV incorporates two effects (Fig. 4) while alternative V incorporates three effects. These design alternatives reduce steam use by recovering the latent heat from the vapor leaving precursory effects. In each simulation, a falling film evaporator with tube 2.5 m in length and an average fluid velocity of 2 m/s was specified.

Table 4 shows the effect of selection of the last effect operating pressure and number of effects on steam demand and thiamin retention. As the last effect operating temperature for a given number of effects is increased, the steam demand increases due to lower temperature differentials in each effect. The thiamin retention is decreased due to higher operating temperatures. The aim of the multiple effect evaporator algorithm is to establish intermediate mass flow rates and operating temperatures in effects 1 to N - 1 which yield equal heat transfer areas for all effects. As more effects are added to the feed forward system, the operating temperature of the first and intermediate effects are raised to achieve equal areas. While steam use is decreased due to greater heat recovery, thiamin retention is also decreased due to longer residence times at higher operating temperatures. An operating pressure of 0.007 MPa (40°C saturation temperature) is on the low side for milk concentration. At this pressure, the use of a four effect feed forward evaporator will yield a product with unacceptably low thiamin retention. Both the two and three effect evaporator systems have effects which operate at temperatures above the typical 80°C, a temperature which is recommended to minimize product degradation. While thiamin retention is acceptable, other quality characteristics may not be within tolerable limits.

It should be noted that for the three effect systems that steam demand is no longer great enough for the evaporator condensate to be the sole heating source for the raw milk. To achieve a steam condensate mass flow rate to perform the heat exchanger duty, steam condensate from both the first evaporator effect and the spray dryer are combined at a point mix before entering the heat exchanger.

6. Process design results

Each of the five process design alternatives met the design specification of retaining a minimum 95% thia-

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Economic analysis results for whole milk powder process design alternatives

Alternative	Purchased equipment cost (\$k)	First year steam costs (\$k/y)	10-Year net present worth (\$M)
Ι	379.3	444.0	1.87
II	379.3	425.7	1.95
III	382.0	376.7	2.13
IV	405.2	253.6	2.45
V	425.4	210.8	2.47

min. Table 5 compares the purchased equipment costs, first year steam demand, and 10 yr net present value of the five alternatives. For each successive alternative, slightly larger heat exchangers or additional evaporator effects must be purchased.

The distribution of steam demand among the heat exchanger, evaporator, and spray dryer is shown in Fig. 5. Steam costs are highest for the first two alternatives where each piece of equipment uses the steam source as its heat transfer medium. For alternative II, the spray dryer steam demand is reduced from 3099 to 2569 kg/h, a 17% reduction compared to the base-line process design alternative (see Fig. 6). For alternatives III and IV, the heat exchanger is operated solely on steam condensate from the first or only evaporator effect. As evaporator effects are added to the process, steam demand drops. A drop of 44.4% in evaporator steam demand is achieved by adding the second effect; a total 59.3% reduction in steam demand is gained by adding the third effect.



Fig. 5. Whole milk powder process design alternative IV with a two effect feed forward evaporator.



Fig. 6. Steam demand by unit operation for each whole milk powder process design alternative.

Based on the study of these five alternative designs, it is evident that process alternative V best achieves the design goal of minimum steam use and maximum 10 yr net present worth. However, further analysis should be done to determine the degree to which high temperature evaporation may affect product quality.

7. Conclusions

FOODS-LIB and ECONANAL were used to study five different whole milk powder process design alternatives. The establishment of the base-line alternative and the subsequent development of the remaining four alternatives took on the order of one week for a usertrained in the use of the software. This does not include time for information gathering for data entry, such as locating the current cost of raw milk. Consider that the five best alternatives are presented here. In reality, an estimated 20–30 simulations were executed and analyzed to refine the alternatives. A significant time saving is achieved through the use of this tool.

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