SYSTEMS INTEGRATION AND ANALYSIS OF ADVANCED LIFE SUPPORT TECHNOLOGIES

A Thesis

by

GRACE A. NWORIE

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2006

Major Subject: Chemical Engineering

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Approved by:

Chair of Committee,	Mahmoud El-Halwagi
Committee Members,	Karen Butler-Purry
	Juergen Hahn
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ABSTRACT

Systems Integration and Analysis of Advanced Life Support Technologies.

(August 2006)

Grace A. Nworie, B.A., Austin College

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Extended missions to space have long been a goal of the National Aeronautics and Space Administration (NASA). Accomplishment of NASA's goal requires the development of systems and tools for sustaining human life for periods of several months to several years. This is the primary objective of NASA's Advanced Life Support (ALS) program. This work contributes directly to NASA efforts for ALS, particularly food production. The objective of this work is to develop a systematic methodology for analyzing and improving or modifying ALS technologies to increase their acceptability for implementation in long-duration space missions. By focusing primarily on the food production systems, it is an aim of this work to refine the procedure for developing and analyzing the ALS technologies. As a result of these efforts, researchers will have at their disposal, a powerful tool for establishing protocols for each technology as well as for modifying each technology to meet the standards for practical applications. To automate the developed methodology and associated calculations, a computer-aided tool has been developed. The following systematic procedures are interrelated and automatically integrated into the computer-aided tool:

- Process configuration, with particular emphasis given to food production (e.g., syrup and flour from sweet potato, starch from sweet potato, breakfast cereal from sweet potato);
- Modeling and analysis for mass and energy tracking and budgeting;
- Mass and energy integration
- Metrics evaluation (e.g., Equivalent System Mass (ESM)).

Modeling and analysis is achieved by developing material- and energy-budgeting models. Various forms of mass and energy are tracked through fundamental as well as semi-empirical models. Various system alternatives are synthesized and screened using ESM and other metrics. The results of mass, energy and ESM analyses collectively revealed the major consumers of time, equivalent mass, and energy, namely evaporation, condensation, dehydration, drying and extrusion. The targeted processes were subsequently targeted for modifications. In conclusion, this work provides a systematic methodology for transforming non-conventional problems into traditional engineering design problems, a significant contribution to ALS studies.

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NOMENCLATURE

ESM

M	Total mass of the system [kg]
V	Total pressurized volume of system [m^3]
V_{eq}	Mass equivalency factor for the pressurized volume infrastructure [kg/m^3]
P	Total power requirement of the system [kWe]
P_{eq}	Mass equivalency factor for the power generation infrastructure [kg/kWe]
C	Total cooling requirement of the system [kWth]
C_{eq}	Mass equivalency factor for the cooling infrastructure [kg/kWth]
CT	Total crewtime requirement of the system [CM-h/y]
D	Duration of the mission segment of interest [y]
CT_{eq}	Mass equivalency factor for the crewtime support [kg/CM-h]
kWe	kW electrical (for power equivalency)
kWth	kW thermal (for cooling equivalency)
M_i	Mass of subsystem i
$M_{v,i}$	Mass equivalency based on volume of subsystem i
V_i	Volume of subsystem i
$M_{p,i}$	Mass equivalency based on power requirement of subsystem i
P_i	Power requirement of subsystem i
$M_{c,i}$	Mass equivalency based on cooling requirement of subsystem i
C_i	Cooling requirement of subsystem i
$M_{CT,i}$	Mass equivalency based on crewtime for subsystem i
CT_i	Crewtime requirement for subsystem i
α_I	Fraction of time subsystem i is used
ESM_i	ESM of subsystem i
ESM_θ	Total ESM for a technology
θ	Technology (i.e. syrup, flour, cereal) or an alternative case
$\sum_{i=1}^{n} ESM_i$	Sum of ESM's of subsystems or total ESM for a technology

SYRUP

S1	Stream containing water
S2	Stream containing sweetpotato
S3	Reactor inlet stream
S4	Reactor outlet stream
S5	Stream containing water for filtration
S6	Stream containing filter cake
S7	Dilute syrup to deionization
S8	Dilute syrup to evaporation
S9	Dilute syrup from evaporation
S10	Stream containing syrup product
Q_1^{ADDED}	Heat added during the first reaction (CSTR1) in syrup production
$Q_2^{REMOVED}$	Heat removed in the second reaction (CSTR2) in syrup production
Q_3^{ADDED}	Heat added during the third reaction (CSTR3) in syrup production
Cp water	Heat capacity of water
Cp syrup	Heat capacity of syrup
Q_{S6}	Heat removed during filtration of syrup
Q_{S7}	Heat removed during deionization of syrup
Q_{S9}^{ADDED}	Heat added during evaporation due to water
Q_{S10}^{ADDED}	Heat added during evaporation due to syrup
$Q_{evaporator}^{added}$	Total heat added for the evaporator
$Q_{condenser}^{removed}$	Total heat removed for the condenser
$Q_{HI,1}^{ADDED}$	Heat added for heating dilute syrup from 25 to 80^{o}C
$Q_{HI,2}^{ADDED}$	Heat added for heating dilute syrup from 80 to 100^{o}C
$Q_{HI,3}^{REMOVED}$	Heat removed from water vapor at 100^{o}C
Q_{HI}	Total heat required for heat integration
$Q_{FC}^{REMOVED}$	Heat removed for freeze concentration
$V_{blender}$	Volume of blender
V_w	Volume of wall of equipment (i.e. blender)
$M_{water\&sweetpotato}$	Mass of water and sweetpotato
$V_{water\&sweetpotato}$	Volume of water and sweetpotato

$\rho_{water\&sweetpotato}$	Density of water and sweetpotato
$M_{blender}$	Mass of blender
$V_{support}$	Volume of support surrounding blender
$M_{v,blender}$	Mass equivalency based on volume for the blender
$P_{blender}$	Power requirement for the blender
$\alpha_{blender}$	Fraction of time in a cycle that blender is used
$M_{p, blender}$	Mass equivalency based on power for the blender
$M_{CT,blender}$	Mass equivalency based on crewtime for the blender
V_{cstr}	Volume of the reactor
Q_{CSTR1}	Heat added by first reaction
Q_{CSTR3}	Heat removed by third reaction
Q_{CSTR2}	Heat added by second reaction
α_{CSTR1}	Fraction of cycle time used by first reaction
α_{CSTR2}	Fraction of cycle time used by second reaction
C_{cstr3}	Cooling required of third reaction
$M_{c,cstr}$	Mass equivalency based on cooling for reactor
CT_{cstr}	Crewtime for the reactor
$M_{CT,cstr}$	Mass equivalency based on crewtime for the reactor
$M_{p,cstr}$	Mass equivalency based on power for the reactor
V_{centi}	Volume of the centrifugal filter
$M_{mixture}$	Mass of the syrup mixture
$\rho_{mixture}$	Density of the syrup mixture
ρ_{water}	Density of water
$V_{mixture}$	Volume of the mixture
M_{centi}	Mass equivalency based on mass of the centrifugal filter
$M_{v,centi}$	Mass equivalency based on volume of the centrifugal filter
$M_{p,centi}$	Mass equivalency based on power of the centrifugal filter
α_{centi}	Fraction of cycle time used by the centrifugal filter
CT_{centi}	Crewtime used by centrifugal filter
$M_{CT,centi}$	Mass equivalency based on crewtime for the centrifugal filter
V_{filter}	Volume of the vacuum filter

$M_{v, filter}$	Mass equivalency based on volume for the vacuum filter
$M_{p,filter}$	Mass equivalency based on power for the vacuum filter
α_{filter}	Fraction of cycle time used by the vacuum filter
CT_{filter}	Crewtime for the vacuum filter
$M_{CT,filter}$	Mass equivalency based on crewtime for the vacuum filter
V_{deion}	Volume of the deionizer
M_{deion}	Mass of the deionizer
$M_{v,deion}$	Mass equivalency based on volume for deionizer
$M_{p,deion}$	Mass equivalency based on power for deionizer
α_{deion}	Fraction o f cycle time used by the deionizer
CT_{deion}	Crewtime for the deionizer
V_{evap}	Volume of the evaporator
$M_{evap}=M_{cond}$	Mass of the condenser/evaporator
$M_{v,evap}$	Mass equivalency based on volume for the evaporator
$M_{p, evap}$	Mass equivalency based on power for the evaporator
CT_{evap}	Crewtime for the evaporator
$M_{CT,evap}$	Mass equivalency based on crewtime for the evaporator
$M_{v,cond}$	Mass equivalency based on volume for the condenser
C_{cond}	Cooling for the condenser
α_{cond}	Fraction of crewtime used for condensation
$M_{c,cond}$	Mass equivalency based on cooling for condenser
CT_{cond}	Crewtime for condenser
$M_{CT,cond}$	Mass equivalency based on crewtime for condenser
V_{freeze}	Volume of the freeze concentration device
M_{freeze}	Mass of the freeze concentration device
$M_{c,freeze}$	Mass equivalency based on cooling for freeze concentration
C_{freeze}	Cooling requirement for freeze concentration
α_{freeze}	Fraction of cycle time for freeze concentration
CT_{freeze}	Crewtime for freeze concentration
$M_{CT,freeze}$	Mass equivalency based on crewtime for freeze concentration
V_{TS}	Volume of thermal storage device

M_{water}	Mass of water
V_{water}	Volume of water
ρ_{water}	Density of water
M_{TS}	Mass of thermal storage device
$M_{v,TS}$	Mass equivalency based on volume for thermal storage
P_{pump}	Power required for pump
α_{TSpump}	Fraction of cycle time for thermal storage pump
$M_{p,pump}$	Mass equivalency based on power for pump
ESM_{TS}	ESM for thermal storage
ESM_{others}	ESM for equipment excluding evaporator, condenser and alternative technology
ESM_{BC}	Total ESM for the base case technology
ESM_{FC}	Total ESM for the freeze concentaration alternative technology
ESM_{HI}	Total ESM for the heat integration alternative technology
ESM_1	ESM for the blender
$ESM_{blender}$	ESM for the blender
ESM_2	ESM for the reactor
ESM_{cstr}	ESM for the reactor
ESM_3	ESM for the centrifugal filter
ESM_{centi}	ESM for the centrifugal filter
ESM_4	ESM for the vacuum filter
ESM_{filter}	ESM for the vacuum filter
ESM_5	ESM for the deionization column
ESM_{deion}	ESM for the deionization column
ESM_6	ESM for the evaporator/condenser
$ESM_{evap\&cond}$	ESM for the evaporator/condenser
FLOUR	
F0	Stream containing raw unpeeled sweetpotato
F1a	Stream containing fresh peeled sweetpotato
F1b	Stream containing sweetpotato peels
F1c	Stream containing lost sweetpotato

F2a	Stream containing sliced/shredded sweetpotato
F2b	Stream containing lost sweetpotato
F3	Stream containing water vapor
F4a	Stream containing dehydrated sweetpotato
F4b	Stream containing lost dehydrated sweetpotato
F5a	Stream containing blended sweetpotato
F5b	Stream containing lost blended sweetpotato
F6a	Stream containing milled sweetpotato (sifted sweetpotato flour)
F6b	Stream containing lost milled sweetpotato
F6c	Stream containing unsifted sweetpotato flour
F7a	Stream containing packaged sweetpotato
F8	Stream containing detergent
F9	Stream containing water
F10	Stream containing output from clean up 1
F11	Stream containing detergent
F12	Stream containing water
F13	Stream containing output from clean up 2
M0	Moisture Content in F1a
st	Starch Content in F1 and F2
ca	Carbohydrate Content in F1 and F2
su	Sugar Content in F1 and F2
ot	Other substances contained in F1 and F2
α	Ratio of streams F1a/ F0
β	Ratio of streams F2a/F1a
pl	Ratio of peels to unpeeled FP
γ	Moisture Content in F4-F7
δ	Fraction of dehydrated SP obtained F4a/F4total
ε	Blender Output ratio F5a/F4a
ζ	Ratio of flour obtained to dehydrator output F6a:F4a
η	Split ratio F5b:F6b
υ	Ratio of unsifted flour to total flour

ca4	Carbohydrate Content in F4-F7
p	Protein Content in F4-F7
f	Fat Content in F4-F7
a	Ash Content in F4-F7
n	Multiple of default primary input (user input/default input)
d	Detergent amount per 5000g input
w1	Water amount per 5000g input (for clean up 1)
w2	Water amount per 5000g input (for clean up 2)
ESM_1	ESM for the peeling process
ESM_{peel}	ESM for the peeling process
ESM_2	ESM for the slicer
ESM_{slicer}	ESM for the slicer
ESM_3	ESM for the dehydrator
$ESM_{dehydrator}$	ESM for the dehydrator
ESM_4	ESM for the blender
$ESM_{blender}$	ESM for the blender
ESM_5	ESM for the mill
ESM_{mill}	ESM for the mill
ESM_6	ESM for the packaging process
$ESM_{package}$	ESM for the packaging process
ESM_7	ESM for the first clean up process
$ESM_{cleanup1}$	ESM for the first clean up process
ESM_8	ESM for the second clean up process
$ESM_{cleanup2}$	ESM for the second clean up process
$V_{consumable}$	Volume of the working material
V_{peeler}	Volume of the mechanized/automated peeler
$M_{v,peeler}$	Mass equivalency of the automated peeler
$\rho_{stainless\ steel}$	Density of stainless steel
M_{peeler}	Mass of the automated peeler
P_{peeler}	Power required of the automated peeler
α_{peeler}	Fraction of cycle time utilized by the automated peeler

CT_{peeler}	Crewtime used by the automated peeler
ESM_{peeler}	ESM of the automated peeler
$M_{v,peeler}$	Mass equivalency based on volume of the automated peeler
$M_{p,peeler}$	Mass equivalency based on power of the automated peeler
$M_{c,peeler}$	Mass equivalency based on cooling of the automated peeler
$M_{CT,peeler}$	Mass equivalency based on crewtime of the automated peeler
$V_{consumable}$	Volume of working material
V_{slicer}	Volume of the slicer
$M_{v,slicer}$	Mass equivalency based on volume of slicer
M_{slicer}	Mass of the slicer
P_{slicer}	Power required of the slicer
α_{slicer}	Fraction of cycle time utilized by slicer
CT_{slicer}	Crewtime used by slicer
$M_{p,slicer}$	Mass equivalency based on power required of slicer
$M_{c,slicer}$	Mass equivalency based on cooling required of slicer
$M_{CT,slicer}$	Mass equivalency based on crewtime of slicer
$V_{dehydrator}$	Volume of the dehydrator
$M_{v,dehydrator}$	Mass equivalency based on volume of dehydrator
L_1	Length of outer dehydrator encasement
T_1	Thickness of dehydrator insulation
$V_{dehydrator, E}$	Exterior volume of dehydrator
$M_{dehydrator}$	Mass of the dehydrator
T_2	Temperature of stream entering the dehydrator
T_4	Temperature of material stream exiting the dehydrator
$Q_{dehydrator, A1}$	Heat energy generated by dehydrate based on alternative assessment
$M_{moist,SP}$	Mass of moist sweetpotato, F2a
H_v^{latent}	Latent heat of vaporization of the water in the sweetpotato and
M_{water}	Mass of water in sweetpotato entering the dehydrator = M0*F2a
$C_{p, moist SP}$	Specific heat capacity of moist sweetpotato
M =M0	Moisture content of F2a
$P_{dehydrator}$	Power utilized by dehydrator for base case

$P_{dehydrator, A1}$	Power required of dehydrator for alternative assessment $\alpha_{dehydrator}$
$M_{p,dehydrator}$	Mass equivalency based on power of dehydrator
$CT_{dehydrator}$	Crewtime used by dehydrator
$M_{v,dehydrator}$	Mass equivalency based on volume of dehydrator
$M_{c,dehydrator}$	Mass equivalency based on cooling required of dehydrator
$M_{CT,dehydrator}$	Mass equivalency based on crewtime of dehydrator
$M_{blender}$	Mass of blender
$V_{blender}$	Volume of blender
$M_{v,blender}$	Mass equivalency based on volume of blender
$P_{blender}$	Power required of blender
$\alpha_{blender}$	Fraction of crewtime utilized by blender process
$M_{p,blender}$	Mass equivalency based on power of blender
$CT_{blender}$	Crewtime used by blending process
$M_{c,blender}$	Mass equivalency based on cooling requirement of blender
$M_{CT,blender}$	Mass equivalency based on crewtime of blender
V_{mill}	Volume of mill
$M_{v,mill}$	Mass equivalency based on volume of mill
M_{mill}	Mass of mill
P_{mill}	Power required for mill
α_{mil}	Fraction of crewtime utilized by milling process
$M_{p,mill}$	Mass equivalency based on power requirement of mill
CT_{rmill}	Crewtime used by milling process
$M_{c,mill}$	Mass equivalency based on cooling requirement for mill
$M_{CT,mill}$	Mass equivalency based on crewtime for mill
$CT_{package}$	Crewtime used for packaging process
$M_{CT,package}$	Mass equivalency based on crewtime for packaging process
$CT_{cleanup1}$	Crewtime used for first clean up process
$M_{CT,cleanup1}$	Mass equivalency based on crewtime for first clean up process
$CT_{cleanup2}$	Crewtime used for second clean up process
$M_{CT,cleamup2}$	Mass equivalency based on crewtime for second clean up process
ESM_{A1}	ESM for combined alternative configuration of flour process

CEREAL

B0	Stream containing Ingredients w/o added water (g)
B0a	Stream containing sweetpotato flour (g)
B0b	Stream containing H_2O
B0c	Stream containing brown sugar
B0d	Stream containing baking soda
B0e	Stream containing maple syrup
B0f	Stream containing cinnamon
B1	Stream containing ingredients w/o water and sample
B1a	Stream containing sweetpotato flour
B1b	Stream containing H_2O
B1c	Stream containing brown sugar
B1d	Stream containing baking soda
B1e	Stream containing maple syrup
B1f	Stream containing cinnamon
B1g	Stream containing mixed ingredients in moisture analysis
B2	Stream containing water for formulation
B3	Stream containing formulation
B3a	Stream containing flour for formulation
B3b	Stream containing H_2O
B3c	Stream containing brown sugar
B3d	Stream containing baking soda
B3e	Stream containing maple syrup
B3f	Stream containing cinnamon
B4a	Stream containing packaged formulation
B4b	Stream containing loss from packaging formulation
B5a	Stream containing equilibrated formulation
B5b	Stream containing loss from equilibrate 1& 2
B6a	Stream containing extruded product
B6b	Stream containing lost extruded product (g)
B7	Stream containing discarded product

B8	Stream containing unknown (assumed to be water)
B9a	Stream containing broken extruded product pieces
B9b	Stream containing powder from broken pieces
B10a	Stream containing oven dried product
B10b	Stream containing lost oven dried product
B11	Stream containing lost H_2O from oven drying
B12a	Stream containing product in package 2
B12b	Stream containing lost product in packaging 2
B13	Stream containing detergent
B14	Stream containing water
B15	Stream containing output from clean up 1
B16	Stream containing detergent
B17	Stream containing water
B18	Stream containing output from clean up 2
$\theta 1$	Fraction of flour in ingredients
$\iota 1$	Fraction of water in ingredients
$\kappa 1$	Fraction of brown sugar in ingredients
$\lambda 1$	Fraction of baking soda in ingredients
$\mu 1$	Fraction of maple syrup in ingredients
$\nu 1$	Fraction of cinnamon in ingredients
$\theta 2$	Fraction of flour in formulation
$\iota 2$	Fraction of water in formulation
$\kappa 2$	Fraction of brown sugar in formulation
$\lambda 2$	Fraction of baking soda in formulation
$\mu 2$	Fraction of maple syrup in formulation
$\nu 2$	Fraction of cinnamon in formulation
ξ	Fraction lost from mixing ingredients
p	Fraction lost from package 1
q	Percent moisture in B0
l	Fraction of B4b lost as residue

m	Fraction of B4b used for moisture analysis
r	Fraction lost from equilibrate
τ	Moisture Content of B6a, B6b & B7
σ	Fraction lost from extruder
s	Fraction lost from extruder B6b
t	Fraction lost from extruder B7
u	Fraction lost from extruder B8
v	Fraction lost from pre-drying (B9b)
y	Percent moisture in stream from oven
z	Fraction lost from oven
w	Fraction of vapor lost from oven
x	Fraction lost from package 2
j	Fraction lost from vacuum sealer
n	Multiple of default primary input (user input/default input)
d	Detergent amount per 1214.3g input
w1	Water amount per 1214.3g input (for clean up 1)
w2	Water amount per 1214.3g input (for clean up 2)
ESM_{1}	ESM for manual mixing of ingredients before water is added
$ESM_{measureingredients}$	ESM for the process involving measuring ingredients
ESM_{2}	ESM for manual mixing of ingredients before water is added
$ESM_{mix\ manually}$	ESM for manual mixing of ingredients before water is added
ESM_{3}	A portion of the ESM for the mixer
ESM_{4}	ESM for manual mixing after water is added
$ESM_{addH2O\ \&\ mix}$	ESM for manual mixing after water is added
ESM_{5}	A portion of the mixer ESM due to electrically mixing after adding water
ESM_{mixer}	ESM for the mixer
ESM_{6}	ESM for the first cleanup step
$ESM_{package\ 1}$	ESM for the first packaging step
ESM_{7}	ESM for the first cleanup step

$ESM_{cleanup\ 1}$ ESM for the first cleanup step

ESM8 ESM for the first equilibrate step

$ESM_{equilibrate\ 1}$ ESM for the first equilibrate step

ESM_{9} ESM for the second equilibrate step

$ESM_{equilibrate\ 2}$ ESM for the second equilibrate step

ESM_{10} A portion of the ESM for the extruder due to preheating

ESM_{11} A portion of the ESM for the oven due to preheating

ESM_{12} A portion of the ESM for the extruder due to use for extrusion

ESM_{13} ESM for the preparations to dry the extruded product

$ESM_{drying\ prep}$ ESM for the preparations to dry the extruded product

ESM_{14} A portion of the ESM for the oven due to drying

ESM_{15} ESM for the second packaging step

$ESM_{package\ 2}$ ESM for the second packaging step

ESM_{16} ESM for the second cleanup step

$ESM_{cleanup2}$ ESM for the second cleanup step

$CT_{measureingredients}$ Crewtime for measuring ingredients

$M_{CTmeasureingredients}$ Mass equivalency based on crewtime for measuring ingredients

$CT_{mixmanually}$ Crewtime for mixing manually

$M_{CT,mi\ xmanually}$ Mass equivalency based on crewtime for mixing manually

$CT_{addH2O7mix}$ Crewtime for adding water and mixing manually

$M_{CT,addH2O\&mix}$ Mass equivalency based on crewtime for adding water and mixing manually

M_{mixer} Mass of the mixer

V_{mixer} Volume of the mixer

$M_{v,mixer}$ Mass equivalency based on volume of the mixer

P_{mixer} Power requirement for the mixer

α_{mixer} Fraction of cycle time utilized by the mixer

CT_{mixer} Crewtime for the mixer

$M_{p,mixer}$ Mass equivalency based on power requirement for mixer

$M_{c,mixer}$	Mass equivalency based on cooling requirement for mixer
$M_{CT,mixer}$	Mass equivalency based on crewtime requirement for mixer
$CT_{paclage1}$	Crewtime for first packaging process
$M_{CT,\ package1}$	Mass equivalency based on crewtime for first packaging process
$CT_{cleanup1}$	Crewtime for first clean up process
$M_{CT,\ clean\ up1}$	Mass equivalency based on crewtime for first clean up process
$CT_{equilibrate1}$	Crewtime for first equilibrate process
$M_{CT,\ equilibrate1}$	Mass equivalency based on crewtime for first equilibrate process
$CT_{equilibrate2}$	Crewtime for second equilibrate process
$M_{CT,equilibrate2}$	Mass equivalency based on crewtime for second equilibrate process
$M_{extruder}$	Mass of the extruder
$V_{extruder}$	Volume of the extruder
$M_{v,extruder}$	Mass equivalency based on volume of the extruder
$P_{extruder}$	Power required of the extruder
$\alpha_{extruder}$	Fraction of cycle time utilized by the extruder
$M_{p,extruder}$	Mass equivalency based on power requirement for the extruder
$CT_{extruder}$	Crewtime for the extruder
$M_{c,extruder}$	Mass equivalency based on cooling requirement for the extruder
$M_{CT,extruder}$	Mass equivalency based on crewtime for the extruder
$CT_{dryingprep}$	Crewtime for drying preparation
$M_{CT,drying\ prep}$	Mass equivalency based on crewtime for drying preparation
V_{oven}	Volume of the oven
$M_{v,oven}$	Mass equivalency based on volume of the oven
L_1	Length of inner encasement of the oven
L_2	Lenth of outer encasement of the oven
$\rho_{stainless\ steel}$	Density of stainless steel
$\rho_{fiber\ glass}$	Density of fiber glass
T_1	Thickness of stainless steel interior
T_2	Thickness of fiberglass interior
M_{oven}	Mass of oven
$M_{oven,S}$	Mass of stainless steel interior case

$M_{oven,F}$	Mass of fiberglass exterior case
$V_{oven,S}$	Volume of stainless steel interior case
$V_{oven,F}$	Volum of fiberglass exterior case
M=M0	Moisture content of material entering the oven
C_p	Specific heat capacity of working material (wet basis)
$C_{p,sp}$	Specific heat capacity of working material (dry basis)
x_w	Mass fraction of water
x_p	Mass fraction of protein
x_f	Mass fraction of fat
x_c	Mass fraction of carbohydrate
x_a	Mass fraction of ash
T_9	Temperature of cereal entering the drying oven
T_{10}	Temperature of cereal exiting the drying oven
$Q_{p,sp}$	Energy required for heating sweetpotato
M_{sp}	Mass of sweetpotato working material entering the oven
P_{sp}	Power required for heating sweetpotato
$C_{p,air}$	Specific heat capacity of air
ρ_{air}	Density of air
M_{air}	Mass of air
$Q_{p,air}$	Energy required for heating air
P_{air}	Power required for heating air
P_{oven}	Total power requirement for oven
α_{oven}	Fraction of cycle time utilized by oven
$M_{p,oven}$	Mass equivalency based on power requirement for oven
CT_{oven}	Crewtime required for oven
$M_{CT,oven}$	Mass equivalency based on crewtime for oven
$CT_{package}$	Crewtime for second packaging process
$M_{CT,package}$	Mass equivalency based on crewtime for second packaging process
$M_{CT,clean\ up\ 2}$	Mass equivalency based on crewtime for second cleanup process
ESM_{A1}	ESM for alternative utilizing sizing of the oven

1 INTRODUCTION

1.1. Review of ALS and CFESH

National Aeronautics and Space Administration (NASA) Advanced Life Support (ALS) has its origins as early as the 1950s when algae were used for oxygen regeneration in human life support research (Lawson, 2005). In the 1970s the focus shifted to long-term space missions such as missions to Mars or the Lunar surface. The ALS program developed from the need for a stable environment that provided for the sustainability of basic elements such as food, air and water and the impracticability of re-supply in such situations. The primary goal of NASA ALS is to develop systems that can support the lives of astronauts for the duration of extended missions. Tests and experiments are continuously being conducted at various NASA space centers as well as various research facilities at universities and other sites throughout the nation to determine the practicability of long-duration missions. NASA's ALS addresses a broad spectrum of systems pertaining to sustaining life in a controlled environment including but not limited to thermal control, solid waste, food systems, crop systems, water recovery and air revitalization.

Extended long term missions to outer space for periods of 120 days or more (Hanford, 2002) with minimal or no re-supply has long been a goal of NASA. In the mid 1980's researchers at Tuskegee University's Center for Food and Environmental Systems for Human (CFESH) Exploration of Space developed a nutrient film technique (NFT) for the hydroponic growth of sweetpotato (Bonsi et al., 1989; Hill et al., 1992), one of several target crops for ALS for extended space missions. Since the development of the NFT, researchers of CFESH have made great strides in the advancement and improvement of technologies relating to crop growth, food processing and waste management of the sweetpotato.

1.2. ALS and CFESH in This Study

Elements of NASA's ALS objectives that are addressed in the course of this study

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This thesis follows the style and format of Chemical Engineering Science.

are those pertaining to the crop production, food production and waste management systems. Of these elements, the food production system is of main focus. Being that the sweetpotato has long since gained acceptance as an ALS crop based on its nutritional value, versatility, acceptability and other criteria, CFESH researchers have pressed on with studies on its potential uses as a food source. Stable and successful long-term storage of sweetpotato roots is a challenge that researchers are currently tackling. In the meantime, more stable products such as starch, syrup, flour, and extruded products derived from the sweetpotato show immediate promise in regards to lengthened shelf life.

Systems integration of the crop growth, food processing, and waste management processes is the overall goal of the on-going research. The objective of this work is to report on the modeling, material and energy evaluation and integration, cost analysis and subsequent assessment of various sweetpotato food processing technologies. In order to evaluate the effectiveness of these processes, material and energy balances are utilized, heat integration is used to minimize energy loss, and equivalent systems mass (ESM), a form of NASA metrics (Levri et al., 2003) is employed for cost analysis. The key questions involved in the achievement of research objectives are:

- How do the technologies in question meet the goal of providing shelf-stable food choices for astronauts in long duration space missions?
- Can a systematic methodology for analyzing ALS technologies be developed?
- How does one decide what information about the process and data are essential for inclusion in the model?
- What is the process for developing equations for the appropriate calculations?
- How much space is in the ship?
- What should be the size of equipment?
- How much energy is required for each equipment/process?
- How will the issues of heat loss and gain be addressed?
- How can targets for improvement be identified?

- What are some ways that the technologies can be altered to be more efficient and reduce costs?
- How can computer technology be utilized to aid the analysis process for researchers?
- What are some of the benefits of the research here on earth?

In order to address these issues, it is necessary to understand the objectives of NASA ALS and to study existing food production systems developed by researchers at Tuskegee University. This thesis is inspired by the need to answer the aforementioned questions utilizing a systematic methodology that includes, modeling, material and energy balances, energy analysis and possibly integration, ESM cost analysis and subsequent energy and ESM analysis of pliable alternatives.

Section two provides a literature search treating on the topics of NASA Advanced Life Support (ALS), syrup processing, flour production, extrusion technology in food production processes, and Equivalent Systems Mass (ESM) and NASA cost analysis. Section three includes a formal statement of the problem of developing a systematic methodology for analyzing ALS technologies as well as that of creating a computer-aided tool for researchers of ALS technologies. Section four details the design approach, the methods of analysis. A case study of each of the pertinent methodologies is presented in the following three sections. Section five presents the case of the syrup technology, section six depicts the case of the flour technology, and section seven explores the case of the extruded product or breakfast cereal technology, all detailing the use of the proposed methodology. Section eight explains how a computer-aided module can be used to facilitate data analysis by providing a platform to run simulations, perform ESM calculations, integration, and sensitivity analyses. Finally, conclusions and recommendations are outlined in section nine.

2 LITERATURE REVIEW

2.1. Advanced Life Support (ALS) Studies

NASA's Advanced Life Support site online offers basic background information on ALS such as when the program was started and the objectives of the Systems Integration, Modeling and Analysis (SIMA) group within NASA. The goals of this thesis happen to require the application of analysis, modeling and integration, as do most ALS related studies, and are separate from the goals of NASA's SIMA and its goals. An overview of the different components of ALS can also be found on NASA's site (Lawson, 2005).

Morowitz, et al. (2005) addresses the subject of closure as a key scientific concept that has broadened from applications in classical thermodynamics to applications to ecological systems. Particularly interesting are the authors' treatment of closure as it applies to controlled environmental or closed ecological systems (class 2 or experimental closed ecological systems) such as those treated by NASA's ALS studies.

In 1997, the National Resource council published information on a collaborative project by the Committee on Advanced Technology for Human Support in Space, the Aeronautics and Space Engineering Board, the Commission on Engineering and Technical Systems, and the National Resource Council to make advancements in human space exploration primarily in the area of supporting human life (NRC, 1997). Some of the objectives of this project support those of ALS.

Tuskegee researchers exploring the possibilities of the sweetpotato for use in Controlled Ecological Life Support Systems (CELSS), made a tremendous impact by developing and implementing a nutrient film technique (NFT) for both short tem (<80 days) and full term (90 to 150 day) studies (Bonsi, et al., 1989). Development of the NFT greatly demonstrated the potential of the sweetpotato as a crop for CELSS use. As the sweetpotato was select by NASA as one of eight crops for CELSS, further studies on the sweetpotato were carried out. One such study focused on genotypic evaluation of four sweetpotato varieties to determine the most suitable types of sweetpotato for implementation (Mortley, et al. 1991). Another study (Trotman, et al. 1996) focused on the decomposition of organic substances (namely sweetpotato biomass) for recycle and reuse in crop production or in other feasible target systems in a CELSS. Trotman, et al. (1996) also identified potential challenges of degrading biomass in a CELSS including those regarding the generation a noxious fumes and the control of microbial processes. Other reports on the NFT developed by researchers at Tuskegee and on growing sweetpotato hydroponically can be found in the work by Hill et al. (1992).

Levri and Finn (2001) utilized the steady state assumption and the pinch method to determine the cost and savings associated with waste heat reuse for a Mars mission. Then, disregarding the steady state assumption in order to determine the scheduling challenges relating to waste heat reuse, researchers utilize the pinch method and other techniques to demonstrate the importance of scheduling hot and cold streams (Levri and Finn, 2001). Other researchers have tackled the issues that arise in regards to scheduling in an ALS study. El-Halwagi, et al (2003) investigated scheduling as it pertains to mass and mass integration. Namely the challenge was that of scheduling the biodegradation/composting of sweetpotato biomass from crop growth and harvest and other wastes, such as those from food processing systems in a CELSS. More details about this topic can be found in works by Williams (2002; El-Halwagi, 2003). The scheduling of batch processes is important to food production processes since they are often batch in nature. Kondili, et al. (1993) presents a method of batch process scheduling using state-task networks and mathematical formulations.

Garland, (1989) demonstrated a method for carrying out a mass balance for carbon dioxide from varying sources (i.e. plant production, and various bioreactors) in a CELSS. Levri and Perchonok (2004) presented a system-level analysis of food moisture content, pin-pointing water usage requirements from various systems including non-food systems (i.e. hygiene, atmosphere, and waste dryer) for a Mars Dual Lander Transit mission.

In the analysis of the food production technologies in the case studies of this thesis, it may be necessary to design alternative equipment. Mulloth et al. (2004) presented the mechanical design and thermal development of a model for a temperature swing adsorption compressor for air-revitalization systems in a closed-loop. The design scheme estimates key parameters such as mass, volume, temperature, pressure and average power. The machine was tested to obtain measured values for each parameter.

Experiments conducted in the Bioregenerative Planetary Life Support System Test Complex (BIO-Plex) allow for trade studies on systems such as the food systems for an early Mars mission (Levri et al., 2001). The trade study compares several different menu compositions as well as examines the mass fractions/mass compositions of essential nutrients.

Voit et al. (2005) conducted an ALS trade study on a system for processing tomatoes. The study addresses technology alternatives such as microfiltration, ultrafiltration and reverse osmosis (RO). The RO system was optimized and ESM values were obtained and compared.

A concise and informative work highlighting the importance of food production and food processing systems to ALS studies and long-duration missions in a closed environment was presented by Rappole et al. (1997). Czupalla et al. (2004) conducted an ALS trade study for an entire life support system for a Mars mission. The researchers considered several aspects of the mission including food, waste, water, atmosphere, and the crew members. ESM analysis was applied and integration was implemented to reduce ESM.

2.2. Syrup Processing

Woolfe (1992) explained the benefit of sweetpotato starch derived syrups as a substitute for more costly syrups derived from other food sources and sited the used of biological enzymes as a highly effective means for syrup production. More specifically, this author (Woolfe, 1992), states that sweetpotato starch can be used for the production of glucose by the action of amylase enzymes and even high fructose syrup by means of an isomerization reaction. Woolfe (1992) gives a brief description of a process for converting sweetpotato starch to glucose and fructose. In addition, sweetpotato starch can be utilized for making other sugars such as maltose. A process for maltose production is also summarized.

A reaction pathway for the conversion of sweetpotato to syrup is described in several sources (Whistler and Paschall, 1965; Whistler et al., 1984; Dziedzic and

Kearsley, 1984; Petersen, 1975). Starch is substance of focus in the sweetpotato since it is the starch that is acted on by the various agents, both biological and chemical. Starch is composed primarily of unbranched amylose (Fig. 2.1) and branched amylopectin (Fig. 2.2) (Biotechnologie B., 2002).

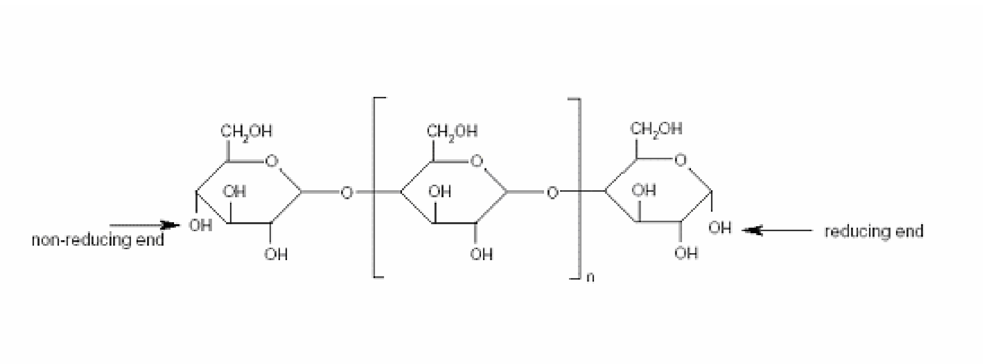

Fig. 2.1. General structure of amylose (Biotechnologie B., 2002).

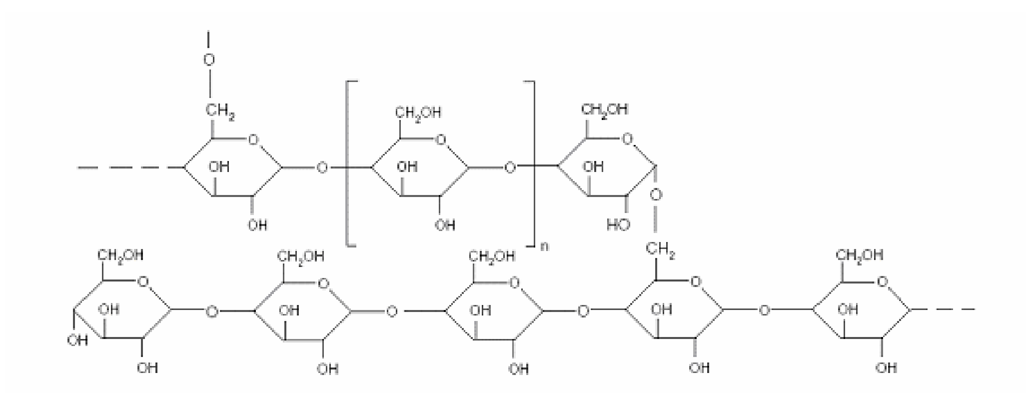

Fig. 2.2. General structure of amylopectin.

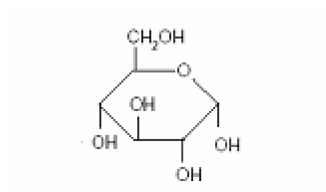

Fig. 2.3. Structure of glucose.

The main starch components are depolymerized to form simple sugars such as glucose (Fig. 2.3). The glucose can then be isomerized to fructose (Woolfe, 1992). Starch is first partially hydrolyzed via the process of liquefaction. Liquefaction takes place in two steps. The first is dextrinization where α–1,4 and α–1,6 dextrins are obtained from starch. The second is debranching, through which only α–1,4 dextrins are obtained. Saccharification, the formation of simple sugars from dextrins, occurs next. At the end of saccharification, mainly the simple sugar glucose is obtained. If a sweeter product is desired the glucose can then be isomerized to fructose. A schematic of this reaction pathway, including the relevant enzymes that act during each step is provided in figure 4 (Fullbrook, 1984; Petersen, 1975). The diagram also depicts undesirable reactions that are catalyzed by transglucosidase. A similar reaction pathway is presented in the work by Whistler and Paschall (1965) and is simplified in figure 2.4.

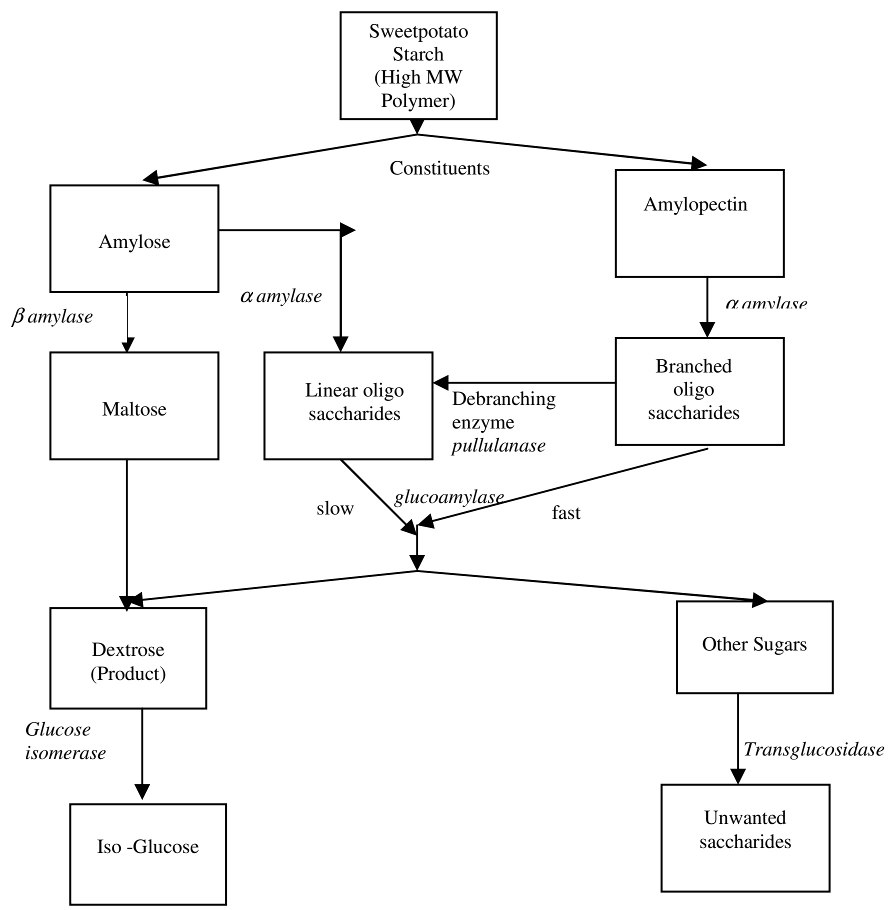

Fig. 2.4. Schematic representation of starch degradation (based on information from Fullbrook, 1984 and Petersen, 1975).

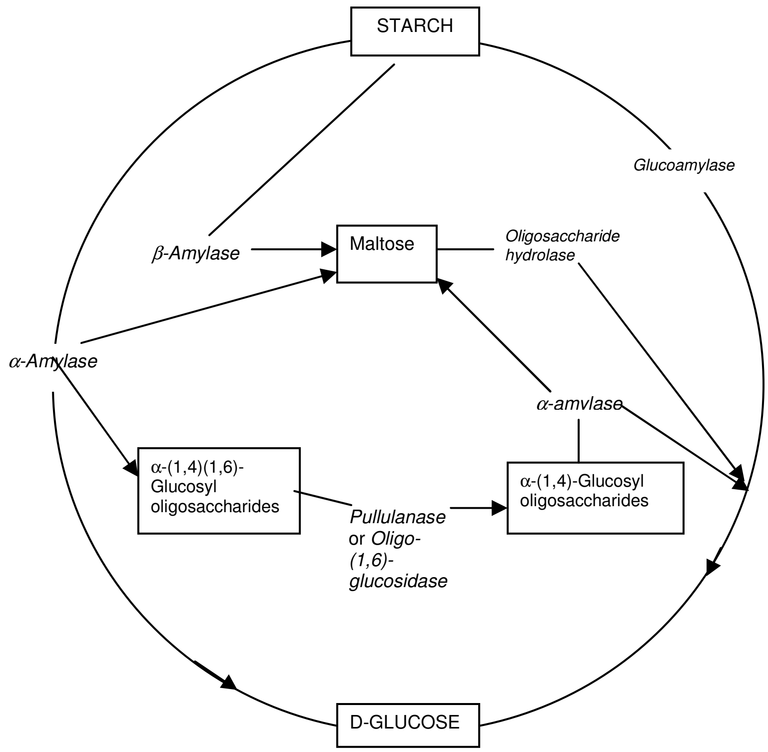

Fig. 2.5. Biochemical pathways for starch degradation to dextrose (Pazur, 1965).

In the pathway depicted in figure 2.5 (Pazur, 1965), α-amylase converts starch into maltose, D-glucose and branched a-D-glucosyl oligosaccharides containing α-1,4 and α-1,6 linkages. β-amylase is also capable of converting starch to maltose through another pathway. Maltose is broken down to D-glucose by oligosaccharide hydrolase. Pullulanse, or more specifically, oligo-1,6-glucosidase converts the branched glucosyl oligosaccharides to linear α-1,4 Glucosyloligosaccharides which are then converted to either maltose or D-glucose by α-amylase. Since glucoamylase can cleave 1,4 and 1,6 linkages, it is capable of converting starch directly to glucose, thus by passing other pathways.

During hydrolysis, other sugars and oligosaccharides may form, thus inhibiting the formation of the desired dextrose product and making it difficult to increase the glucose concentration. Transglucosidation/Transglucosylation has the ability to interfere with the formation of glucose and must be considered. Transglucosidase is the key enzyme behind transglucosidation. It is often present in glucoamylase enzyme preparations and its primary function is to drive the formation of other sugars from glucose, thus reducing the yield of dextrose. Several proposed methods for eliminating transglucosidase are listed by Petersen (1975).

Enzymes play a major role in the depolymerization reactions (Fullbrook, 1984). The four major enzyme groups for hydrolyzing starch are endo-amylases, exo-amylases, debranching enzymes and isomerases. Endo-amylases (α-amylases) cleave α-1,4 glycosidic bonds in amylose and amylopectin and related polysaccharides to yield α-oligosaccharides. Exo-amylases such as β-amylases and amyloglucosidase act on α-1,6 linkages in branched oligosaccharides of amylopectin. Exo-amylases act at slower reaction rates than for the endo-amylases that break α-1,4 linkages. Debranching enzymes such as pullulanase, hydrolyze α-1,6 linkages in amylopectin and act in the formation of maltose and maltotriose. Isomerases immobilize enzymes and primarily act on pentose sugars to convert them to a sugar isomer, such as in the conversion of glucose to form fructose (also called isoglucose). Detailed information about the various enzymes and their actions can be found in Fullbrook (1984) and Whistler et al. (1984).

Birch et al. (1970) gave descriptions of high and low dextrose equivalent syrups. A brief process description for starch hydrolysis by α– and β–amylase can be found in Hill et al. (1992). Bouwkamp (1985) also provided information on how syrup sucrose concentration affects sweetpotato that has been processed and packaged in addition to information on the amylose and amylopectin content of sweetpotato starch.

More information on the action of α– and β–amylase on starch can be found in the work by Radley (1953). Radley also provided detailed information about he structure and function of starch.

Silayo et al. (2003) provided the source for the syrup process configuration used in the syrup case study in section five. More details influencing the syrup process configuration can be found in the thesis by Miller (2003).

2.3. Producing Flour

Shaw and Booth (1983) provided information on some particular procedures used for dehydrating and milling potatoes and on obtaining starch from potatoes. Edmond and

Ammerman (1971) also provided information on dehydrating sweetpotatoes. Woolfe (1992) discussed dehydration and other drying methods used in developing countries to dry sweetpotatoes. An important finding by Woolfe (1992) that is to be noted is that the pressing of sweetpotatoes (to reduce the water content) greatly decreased the amount amylase. The decrease of amylase could affect further processing of the sweetpotato solids for other uses (i.e. extrusion). On the other hand, the juice from the pressed sweetpotato contain amylase may be used in other processes (i.e. syrup production). Pressing the sweetpotato a second time has been noted to extract up to 80% of the total amylase.

Sweetpotato flour has been used to process vermicelli pasta and the nutritive composition of the sweetpotato flour used in the vermicelli process was obtained (Hill et al., 1992). The nutritive value, the composition and the uses of potato flour were outlined by Talburt and Smith (1987). Salunkhe et al. (1991) also recorded some of the uses of potato flour. Information leading to the process configuration of the flour production was provided by Dansby (2002) and Dansby and Bovell-Benjamin (2003 (b)).

2.4. Extrusion Technology

Extrusion technology is one that has revolutionized the food production industry. Extrusion is the process of forcing a plastic or food material to flow through a restriction or die under a carefully chosen set of conditions in order to shape or form or dry an extruded product (Riaz, 2000). Single-screw and twin-screw extruders are the two main types of extruders, however, "new generation" extruders, patented in 1998 by Wenger Manufacturing Company offer a cost saving advantage over present single-screw and twin-screw technologies (Riaz, 2000). The compilation by Riaz (2000) offers a comprehensive overview of extrusion as it applies to food applications. In addition, it also presents a wealth of references and other resources about extrusion of foods.

An important portion of the work by Riaz (2000) is section seven, which describes the effects that extrusion has on foods both chemically and nutritionally. One notable chemical change is the possibility of manufacturing glucose by using extrusion to direct molecular degredation (Riaz, 2000). Additionally, the five general chemical and physicochemical changes that may result during the extrusion process and the major factors that influence those changes are outlined in the work. The factors influencing chemical and physicochemical changes are primarily barrel temperature, die geometry, extruder model, feed composition, feed moisture, feed particle size, feed rate, screw configuration, and screw speed and secondarily, product temperature, pressure, and specific mechanical energy. The main nutrients outlined by Riaz (2000) with respect to changes during extrusion are starch, dietary fiber, protein, lipids, vitamins, minerals and phytochmeicals. Food flavors can also be altered as a result of extrusion. A notable change to nutrients that can occur during extrusion includes the uptake of absorbable metals such as iron by food material from the extrusion equipment and ultimately by persons who consume the extruded foods.

Of particular importance is the section on ready-to-eat (RTE) breakfast cereal production (Riaz, 2000) and the benefits of extrusion cooking as opposed to traditional preparation methods. Direct expansion was identified as the simplest and most straight-forward method for producing RTE breakfast cereals (Riaz, 2000). Indirect expansion methods require several additional steps before and after drying (Fig. 2.6). Cereal grains such as wheat, oats, rice and bran are used most commonly although corn and other grains (i.e. exotic or ancient grains from Mexico or Central and South America) are used occasionally. In most cases these grains are processed into flour prior to use. Common methods for processing RTE breakfast cereals were described by Riaz (2000). An appendix outlining a method for performing material balance and energy calculations for extrusion technologies is also included.

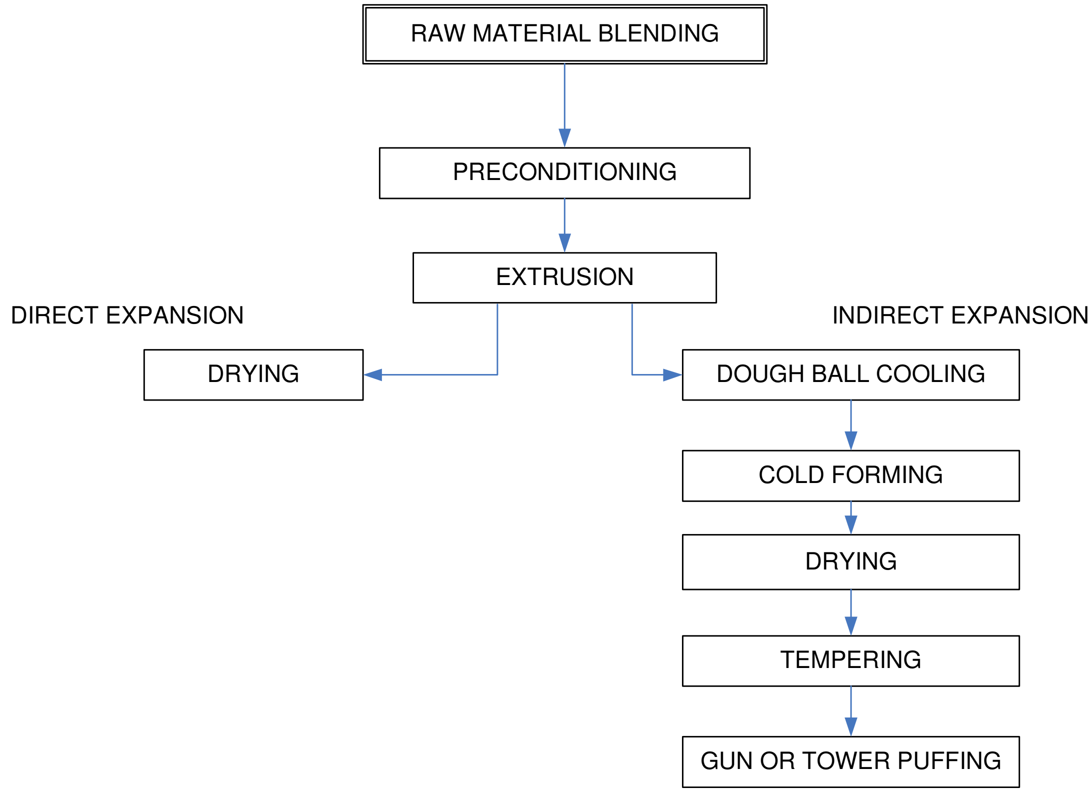

Fig. 2.6. Direct versus indirect expansion in RTE breakfast cereal extrusion (Riaz, 2000).

A work by Park (1991) provides detailed experimental results pertaining to the uses, settings and expected outcomes from modifying different variable for a single-screw extruder. In the case study presented in section seven of this work, the RTE breakfast cereal was made from sweetpotato flour rather than cereal grain flours. Researchers used a single-screw extruder rather than a twin-screw extruder and direct expansion methods were used.

In the work by Mercier and Cantarelli (1986), G. D. Kouthin presented information on the effects of extrusion on the nutrition content of food, the relevance and importance of extrusion cooked foods to developing countries. Also, Kouthin (Mercier and Cantarelli, 1986) briefly mentioned the use of flours of cereals for breakfast food products and explored extrusion cooking as a technology. Additional information about the modification of starches due to extrusion cooking and a comparison to changes to starch by drum-drying was given by Mercier and Cantarelli (1986).

Zuilichem et al. (Mercier and Cantarelli, 1986) examined the considerations for when designing single-screw extruders, namely having to do with the physical and chemical properties of raw materials. Quaglia and Paoletti (Mercier and Cantarelli, 1986) explored the possibilities and implications of utilizing extrusion cooking to exploit the local staple foods in developing countries.

Information on the selection of raw materials and extruders, in addition to considerations for operation temperatures were given by Guy (2001). Guy (2001) also examined the effects of extrusion on nutritional quality. Bouvier (Guy, 2001) explained the production of breakfast cereals and compared direct methods to a so-called pellet-to-flaking extrusion cooking process.

Dansby and Bovell-Benjamin (2003 (a)) summarized the procedures for extruding various RTE sweetpotato breakfast cereal products, the nutritive and physical property information as well as the evaluation results based on sampling by sixth graders. Dansby and Bovell-Benjamin (2003 (c)) also conducted sensory characterization of various RTE breakfast cereal products made from either sweetpotato flour (SPF), sweetpotato flour mixed with whole wheat bran (SPF/WWB) and whole wheat bran (WWB).

The main source of information for the preliminary process configuration for the breakfast cereal extrusion technology in the case study in section seven comes from the work by Dansby (2002). Through personal and electronic communication with Hill (2006), the process configurations were augmented based on data obtained from researchers of the Department of Food and Nutritional Sciences at Tuskegee University.

2.5. Equivalent Systems Mass (ESM) and NASA Cost Analysis

Ewert et al. (2001) presented a summary of the Equivalent System Mass predictions for the ship infrastructure and for key subsystems (air, biomass, food, thermal, waste, and water) that comprise the life support system for a Mars Dual Lander Mission. The predictions that were made were the result of the information collected by the SIMA element of NASA ALS.

The issue of using equivalent mass versus life cycle cost analysis for examining potential ALS technologies was explored by Jones (2003). The author discussed how ESM was more directed towards analysis of life support systems while Life Cycle Cost

(LCC) and Design, Development, Test and Engineering (DDT&E) cost had broader applications especially for calculating launch and operating cost. The ESM method, LCC method, DDT&E method and other methods of cost analysis were explored.

While the ESM guidelines document (Levri et al., 2003) was written as a detailed guide for researchers conducting ESM analyses, drafting the guidelines document led to the clarifying objectives document (Levri and Drysdale, 2003) as a supplement to the original guidelines. The points summarized by Levri and Drysdale (2003) are the key considerations for any ESM evaluation.

Fisher et al. (2003) explored the impacts of mission location on ESM and mission costs (in monetary terms) on ALS studies. Sample methods of evaluation for specific cases were presented (Fisher et al., 2003) including explanations of how location factors should be applied.

Similar information to that which is found in the ESM guideline document (Levri et al., 2003) was given in Levri et al. (2000). The theory and application of the ESM metric document (Levri et al., 2000) presents the ESM concept in its developmental stages. That is why it provided similar information to that which is found in the latter ESM guidelines document (Levri et al., 2003) but much updated information can be found in the latter document.

Hanford (2004) presented detailed figures, assumptions and guidelines for conducting ALS studies and developing ALS technologies. Key considerations in developing ALS technologies are the mission location and duration. Hanford (2004) also gives the technology metrics for the various missions. The work by Drysdale et al. (2002) is prior to the research and technology metric presented by Hanford (2004). The objectives and content of both documents are similar with the latter containing figures and slightly more current information.

For the ESM evaluation of ALS trade studies, the baseline values and assumptions document (BVAD) (Hanford., 2002) is a key source for equivalency factors and other key data for use in ESM analyses. The BVAD (Hanford, 2002) is also a source for certain values to be applied to ALS trade studies.

The ESM guideline document (Levri et al., 2003) clearly defines the definition of ESM and how ESM calculations should be carried out. Intended users for the ESM document are researchers, technology developers, managers and system analysts. The document (Levri et al., 2003) should be the primary guide for ESM computations but users of the document should look for the latest versions and updates such as the clarifying objectives document (Levri and Drysdale, 2003).

2.6. Process Integration

Several authors have published information about process integration as it applies to the chemical process industry (Dunn and El-Halwagi, 2003; Harmsen, 2004; (Hallele, 2001). El-Halwagi (1997) provided information on process integration tools with primary focus being on uses for pollution prevention. Detailed information on algebraic and analytical methods for process integration using direct recycle strategies, mass exchange networks, heat exchange networks, and mass, heat and property integration has recently been published by El-Halwagi (2006).

3 PROBLEM STATEMENT

3.1. Methodical Analysis of ALS Technologies

This research is aimed at assessing the applicability of food processing technologies of the sweetpotato, an ALS crop, for long term space missions. In particular, the technologies involving the derivation of syrup from sweetpotato and that of obtaining flour from fresh sweetpotato, and obtaining an extruded product from sweetpotato flour, are of primary concern. The goal is to conduct a systematic analysis of current technologies and to determine the extent to which they can be applied in extended missions in a controlled environment. As a result of the analyses, it will then be possible to address issues that will make the application of current technologies difficult in an ALS environment and suggest alternatives and additional technologies of increased feasibility.

In the systematic analysis of the pertinent technologies, several key problems must be addressed. The first is that researchers must decide which information about the process and data are essential in order to properly represent each system. In order to accomplish this it is important to extract information pertaining to mass flow of consumable materials, energy usage, factors arising in ESM analysis, equipment usage, process time, and other relevant information for use in the system analysis. In the process of extracting pertinent information from publications or data or other sources, it is necessary that researchers become proficient in identifying relevant versus irrelevant information.

The next problem is that of tracking material and energy flows for each process. In order to address this problem a procedure will be created for developing equations for the appropriate calculations. An important aspect of tracking material and energy flows is that of carefully noting what happens to intermediate streams, especially wherever losses occur. It will later be possible to ask questions as to why those losses occur and how they can be minimized or eliminated.

Other issues to be considered in this study are that a space vehicle has limited size, volume, and energy capacity and the time that the crew can devote to different operations is limited. ESM analysis addresses these issues and would require information on the types and number of equipment, the sizes of the equipment, the power and cooling information pertaining to each piece of equipment, the amount of time each equipment will be running, and the time that a crew-member of the space journey would be required to spend on each process, including operating and maintaining each piece of equipment.

The material and energy flows, energy analyses, and ESM analyses will be used to identify targets for improvement. Investigation of alternative equipment, procedures and technologies and modifications to existing technologies will be used to reach the specified targets.

3.2. Computer-Aided Analysis

In order to facilitate the process of analyzing various technologies and even the alternatives available within a certain technology and to make comparisons, computer technology will be utilized to ease the analysis process for researchers. The main problem is that of developing a computer-aided tool for analyzing and integrating food production systems for ALS that is able to address wide range of analytical concerns.

First of all, the computer-aided tool must be capable of depicting process flows, processing units, procedural steps, and overall configurations. The tool must also be useful for tracking the main species throughout the process, tracking energy usage by equipment, and tracking energy requirements of units and of certain reactions. In addition the tool should be capable of being utilized in conducting cost and sensitivity analyses, for example, by making it possible to explore the degree or extent to with certain changes to manipulated variables affect various aspects of the system performance and output. The computer-aided tool should also be useful for optimization and integration that will lead to mass and energy reduction, conservation of resources, increased or maximized product output.

Manipulated variables include the initial feed, desired output, reconfiguration of base case model, addition, removal or substitution of certain technologies, and in process mass and energy integration. Certain goals are desired to be achieved by implementing the tool. Those goals are the reduction of time in performing analysis calculations, increased ease of analysis, and a means of organizing and categorizing the types of analyses. Additionally the tool should provide for the systematic exploration of available optimization and integration options and the systematic generation of alternative optimization and integration options.

4 METHODS OF ANALYSIS

4.1. Overall Outline of Methods

The research focus is on developing appropriate methods for determining the usefulness and readiness of technologies for implementation in ALS systems. The hypothesis is that proper modeling and analysis of the food processing technologies will reveal the practicality of implementation of the technologies in question to long duration space missions and in controlled environments. The analyses will also lead to the development of replicable techniques and tools for modifying the technologies and for improving their readiness for space applications. The key elements to the research method are as follows:

- Modeling
- Mass and Energy Balances
- System Integration
- ESM (Cost Analysis/Metric Evaluation)
- Alternative Technologies

A necessary starting point is the development of a detailed and accurate model or process configuration of each of the ALS technologies to be investigated. The techniques are developed in the form of a hierarchical procedure composed of interacting stages that begins with a top-level semi-empirical model yielding a base-case configuration from experimental and literature data. Second each model is used to generate the appropriate material and energy balances. Based on the material and energy balances, the largest consumers of mass and energy are identified. These are designated as the targeted units and streams and are given priority in the rest of the analysis. Focus is given to the targeted units and streams to examine whether enough data are available for them. If there are insufficient data for these units and streams, then more data are gathered and/or incorporated into the semi-empirical model. If sufficient data are available, then the procedure moves to the system integration step.

Once the balances have been verified for accuracy for the specific system, system integration will be carried out where applicable, since the need for integration is system specific. System integration is primarily composed of mass and energy integration. The fields of mass and energy integration have received much attention from the chemical-engineering community with much success in theory and applications for the chemical process industry. Reviews and recent advances in the chemical-process industry can be found in recent literature (e.g., El-Halwagi, 2006; Harmsen, 2004; Dunn and El-Halwagi, 2003; Hallale, 2001). These advances in process integration are not directly applicable to ALS systems and must be revised for ALS applications.

Equivalent System Mass (Levri et al., 2003) will be the primary form of cost analysis or metric evaluation. Evaluation of the energy and cost analysis results will reveal whether or not there is a need to modify the system and report the changes for the sake of comparison. Modifications to the original system setup will be presented in the form of alternative technologies that will be tied to the original system in question. Figure 4.1 is a schematic representation of the developed hierarchical approach. Although there are several steps, the approach can be categorized into three main tasks:

1. ***Process Configuration and Key Modeling Equations:***
    a. Develop a process configuration for a food product (e.g., syrup from sweetpotato).
    b. Determine various forms of mass and energy inputs, outputs, and intermediate flows.
    c. Synthesize several alterative configurations for the food processing component.
    d. Document the rationale for each process configuration, the operating principles, and the potential advantages and disadvantages.
    e. Develop basic equations for material and energy balances
2. ***Performance Targets and Integration:***
    a. Refine and validate models using experimental data
    b. Define default values and assumptions for use when specific data are absent
    c. Incorporate the gathered data into the modeling equations to develop mass- and energy- tracking equations
    d. Use mass- and energy-targeting techniques to identify performance benchmarks.

e. Conduct mass and energy integration

3. Evaluation of Metrics

a. Track of overall mass and energy (input, output, and propagation)

b. Select or develop rational definitions for performance metrics in terms of energy used, mass consumed, and waste discharged. The metrics will be defined per process as well as for the overall subsystems. Equivalent System Mass (ESM) is the metric that will be used and is described in more detail in section 4.5.

4.2. Modeling

Overcoming the challenge of system modeling begins with a thorough understanding of the system itself. This process begins by first studying the system and understanding what is taking place. Studying a process for the purpose of developing a model of the system begins by extracting pertinent information for available experimental data and literature. It is then necessary to develop a template, a basic representation of the system in question that can be modified and applied to other systems. In this case, the model takes the form of a mass flow diagram with labeled streams (Fig. 4.1).

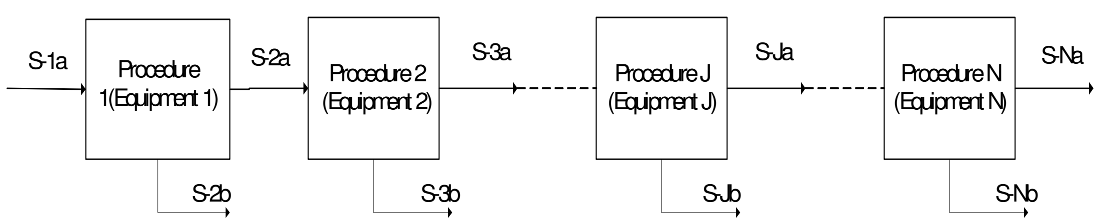

Fig. 4.1. General mass flow diagram.

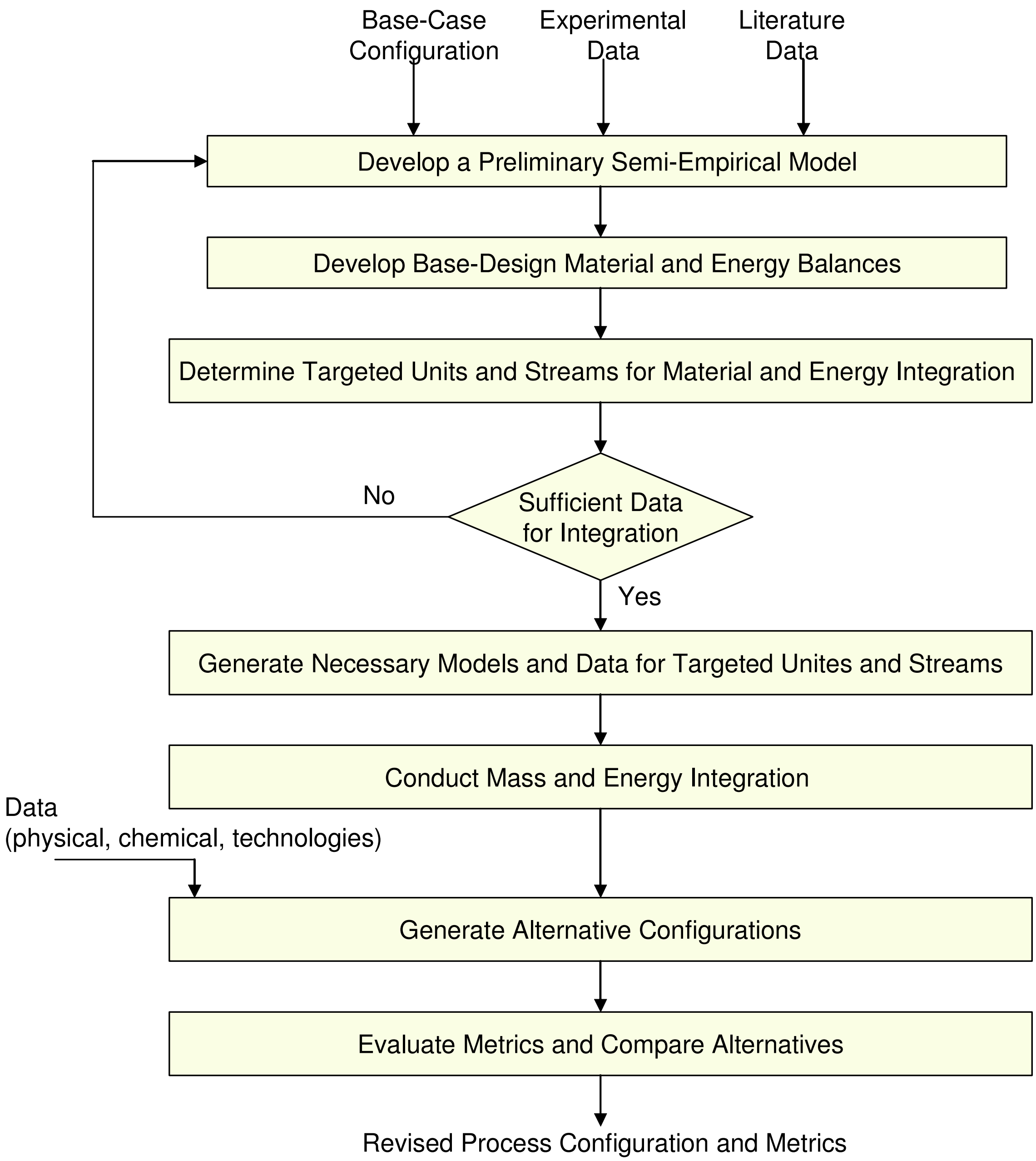

Fig. 4.2. Overall approach.

The streams exiting from a process or equipment and not feeding into an adjacent process are labeled with the same number but a different lowercase letter of the alphabet to denote that they are associated with one another but one portion is retained while the other portion (or portions) is (are) inevitably lost to the waste system or to the surroundings (i.e. in the case of water vapor). The streams exiting directly from the right side of the equipment and entering into the adjacent step that is further to the right are streams containing retained working material. In some cases, these streams may not be labeled with a lowercase letter. However, lowercase letters may be used to denote the individual components of the stream composition in cases where the composition is complex.

Deciding on which information should be used to construct a model requires a thorough understanding of the system in question. In order to gain the appropriate level of understanding, it may be necessary to conduct an investigation into an outside discipline. Through system modeling it will be possible to keep track of inputs and outputs of a given process and within a given process and identify how they are related to other processes (i.e. where they enter and leave other processes). By first identifying inputs and outputs, it will be possible to subsequently assign numerical values to each input and output stream utilizing quantitative information from data in the texts (Silayo et al, 2003; Dansby, 2002). The software used for the modeling are Microsoft Visio and Microsoft Word.

4.3. Material and Energy Balances

Once a system has been modeled using a mass flow diagram, it will then be possible to carry out material balance calculations in order to derive equations and ultimately obtain numerical values. It will be necessary to denote certain values in the material balance as primary inputs and secondary inputs. Primary inputs are user defined inputs such as the main input stream(s) (for forward calculations) or the main output stream(s) (for backward calculations), if an overall balance on the system were to be conducted. Secondary inputs are generally information obtained from the data or scientific study that place constraints on certain streams. Secondary inputs may or may not be user defined and usually depend on the ratios of streams, the moisture content of streams, stream composition, system constrains or other specifications for a specific stream or streams. Primary and secondary inputs are given variable names. Where available, temperature data and equipment information will be utilized to calculate the energy requirements for each process or equipment.

After designating primary and secondary inputs, it is then possible to develop equations for each stream by performing a sequential, individual material balance over each procedure or equipment, as depicted by an individual box in the figure above. The stream names from the labeled flow diagram as well as the variable names for the primary and secondary inputs are used to develop equations that will be utilized to quantify each stream. For example, an equation for Procedure 1/Equipment 1 might look like: S1 = S2a + S2b. Streams S2a and/ or S2b may have a specified ratio in relation to S1 (i.e. S2a = y * S1) from data or system constraints. By substituting (y *S1) for S2a, S2b can be found to be: S2b = S1 – y * S1 = S1 * (1-y). This method is carried out for other procedures/equipment unit an equation is obtained for each stream. The mass flow diagram of the model is represented in Excel and the primary and secondary inputs as well as the developed equations are entered in the appropriate cells (see figure or Appendix). The software used for this portion are Microsoft Word and Excel.

4.4. System Integration

Integration techniques will involve both functional (qualitative) and quantitative integration. As an example of the qualitative and quantitative aspects of integration consider a food production system that requires a separate heating step and cooling step. A qualitative analysis for the purpose of integration would involve first of all identifying that the two steps can be combined and then a verbal or written description of the recommended method to carryout the integration (heat exchanger, thermal storage, etc.) Quantitative analysis refers to the numerical calculations that would be needed to implement the functional (qualitative) integration (i.e. determining temperatures, heat exchange networks, pinch diagrams, etc.). Integration techniques will follow the systematic procedures detailed by El-Halwagi (1997). Microsoft Excel is used for this analysis.

4.5. Equivalent Systems Mass (Cost Analysis/Metric Evaluation)

In this work ESM is used for evaluation of the equipment required for the processes proposed by researchers at Tuskegee University for converting sweetpotato to syrup, flour or to an extruded breakfast cereal product.

ESM is used in this study since it is accepted as NASA's primary metric for ALS trade studies. ESM is particularly useful for the comparison of several configurations of alternatives for the purpose of determining the most probable and desirable alternative for a given mission of a certain destination and duration. The mass, volume, power, cooling and crewtime requirements drive the analysis (Levri et al., 2003). Equivalency factors for volume, power, cooling, and crewtime (Hanford, 2004) are used to account for the infrastructure costs and to relate the different parameters in terms of a common mass equivalency. The general ESM formula (Levri et al., 2003) is given below.

$$ESM = M+(V*V_{EQ}) +(P*P_{EQ})+(C*C_{EQ})+(CT*D*CT_{EQ}) \quad (4.1)$$

M = the total mass of the system [kg],

V = the total pressurized volume of system [m^3],

V_{eq} = the mass equivalency factor for the pressurized volume infrastructure [kg/m^3],

P = the total power requirement of the system [kWe],

P_{eq} = the mass equivalency factor for the power generation infrastructure [kg/kWe],

C = the total cooling requirement of the system [kWth],

C_{eq} = the mass equivalency factor for the cooling infrastructure [kg/kWth],

CT = the total crewtime requirement of the system [CM-h/y],

D= the duration of the mission segment of interest [y],

CTeq = the mass equivalency factor for the crewtime support [kg/CM-h],

where kWe = kW electrical and kWth = kW thermal. The volume parameter (V) may have both initial and time-dependent components.

The mass equivalency factors, Veq, Peq, Ceq, and CTeq are used to convert the non-mass parameters, V, P, C and CT, to mass equivalencies. Equivalency factors are determined by computing the ratio of the unit mass of infrastructure required per unit of resource. An example of an equivalency factor calculation is given in the ESM guidelines document (Levri, et al, 2003).

Some assumptions pertaining to the use of ESM calculations in this work are:

1. The quantities of working materials in the system are not taken into account. In reality, the throughput of the system would be different at different configurations.
2. Equivalency factors obtained from the ALS Baseline Values and Assumptions Document (BVAD) (Hanford, 2002) for a Mars surface mission are applied to each of the sub-systems under study.
3. The individual components of equation 4.1 are assumed to be independent of each other.

Calculations in this work are based on a version of the general ESM equation (4.1) that has been modified based on the actual food technology process configurations. The equivalency factors and duration constants used in calculating ESM are shown in Table 4.1.

Table 4.1
Equivalency factors (Levri, et. al., 2003)

Equivalency Factors and Duration		
Mass	1	**kg/kg**
Volume	215.5	**kg/m^3**
Power	237	**kg/kWe**
Cooling	60	**kg/kWth**
Crew Time	1.14	**kg/CM-h**
Duration	**0.49**	**y**

The following definitions and equations apply to the study.

M_i=Mass of subsystem i

$M_{v,i}=V_i*V_{eq}$= mass equivalency based on volume of subsystem i

$M_{p,i}= \alpha_i * P_i * P_{eq}$ = mass equivalency based on power requirement of subsystem i

$M_{c,i}=\alpha_i * C_i * C_{eq}$ = mass equivalency based on cooling requirement of subsystem i

$M_{CT,i}=CT_i*D*CT_{eq}$ = mass equivalency based on crewtime for subsystem i

α_i=fraction of time subystem i is used

$$ESM_i=M_i+(V_i*V_{eq})+(\alpha_i * P_i * P_{eq})+(\alpha_i * C_i * C_{eq})+(CT_i*D*CTeq) \quad (4.2)$$

$$ESM_i= M_i+M_{v,i}+M_{p,i}+M_{c,i}+M_{CT,i} \quad (4.3)$$

$$ESM_\theta=\sum_{i=1}^{n} ESM_i = \text{Total ESM} \quad (4.4)$$

Where θ = syrup (SY), flour(FL), cereal (BC), or an alternative case(Ai)

Where i = 1 – N and N = number of cases

Equation 4.2 is used to calculate the equivalent system mass of each subsystem (i.e. each procedural step or each equipment in the process) while equation 4.4 is utilized in the calculation of the total equivalent system mass of the base case technology (consisting of all subsystems) and each alternative configuration. So the theta (θ) above symbolizes one of the food process technologies or an alternative technology. Equation 4.3 is equivalent to equation 4.2. Microsoft Word and Excel are used to carryout ESM analyses.

4.6. Analysis of Alternatives

Proposal and development of alternative steps in the procedure, alternative equipment for usage and/or alternative implementation of current or new equipment will depend on the results of the integration/energy analysis and the cost analysis. Portions of the process configuration presenting the greatest ESM cost, energy usage or integration opportunities will be targeted for alternative analysis. The least costly and most feasible alternatives will be implemented. Criteria that will be used to determine least costly include the options with the lowest ESM values and the least energy demands. Microsoft Word and Excel are the software used for analyzing alternatives.

5 CASE STUDY I: SYRUP TECHNOLOGY

5.1. Model

For the sweetpotato to syrup technology, the process configuration is that developed by researchers (Silayo, et. al., 2003) of CFESH at Tuskegee University. A schematic representation of the system is shown in figure 5.1.

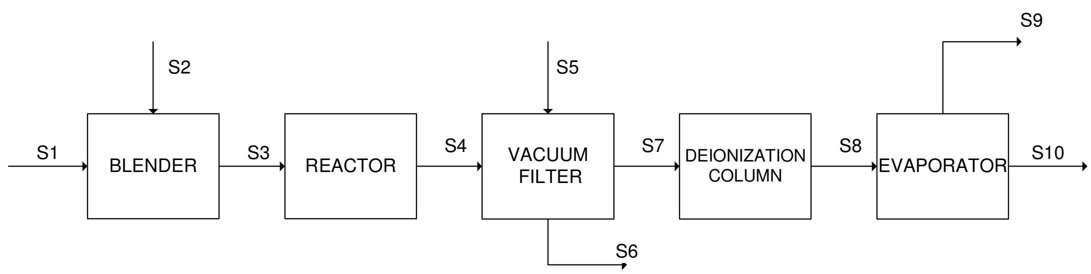

Fig. 5.1. Experimental process for converting starch into glucose syrup (Silayo, et. al., 2003).

As depicted in figure 5.1, water (S1) is to be combined with peeled and pelletized sweetpotato (S2) in a 2 to 1 ratio (600g of water to 300g of sweetpotato for this case). The sweetpotato and water are processed in a blender to form slurry which is then sent to a reactor. Three reaction steps are performed in series within the reactor in order to generate a high yield of product. For the purpose of initiating the conversion of starch to glucose, the slurry is first heated to 85 ºC for approximately 30 minutes. The conversion achieved from the first reaction step is approximately 32.5%. Second, the reaction mixture is cooled to 50 ºC and a sodium hydroxide solution is used to adjust to a pH of 6.9. Diastase of malt enzyme is then added to hydrolyze the starch in the mixture. After hydrolysis, the reaction is allowed to proceed for approximately 3 hours. By the end of the second reaction phase, conversion of 43.6% is achieved. Finally, the reaction is heated to 60 ºC and a hydrochloric acid solution is used to bring the pH down to 4.5. During this third reaction phase, the Dextrozyme C enzyme is added and the reaction is allowed to proceed for approximately 24hours. Approximately 78.1% conversion is attained at the end of all three reaction phases. The conversions were calculated based on the formation of dextrose ($C_6H_{12}O_6$) and the given sugar concentrations at the end of each reaction phase. A constant volume (900 ml for the base case) was assumed for the entire reaction.

Upon completion of the reaction phases, the unreacted materials and the products formed from the reaction were sent to a vacuum filtration unit for the removal of liquid. The filter cake was then rinsed with water and vacuum filtered again in order to recover more products. Although researchers tried several filtration methods and filtration stabilizers, only the vacuum filtration method was considered in this analysis because the highest amount of product was recovered using vacuum filtration. Total time for filtration of the base case was approximately 1 hour. Next, the liquid product from the vacuum filtration process was sent to a deionization column. Time for the deionization process is estimated at 1 hour. In order to concentrate the syrup product, an evaporation and condensation procedure was used to remove excess water in order to obtain the desired glucose syrup product (approximately 150ml in the base case) with a dextrose equivalent concentration of 310mg/ml. The total time for evaporation/condensation is 3 hours with 2 hours for evaporation and 1 hour for condensation.

5.2. Material and Energy Balance

The typical composition of a sweetpotato is shown in figure 5.2. The key components in the sweetpotato are starch (14%) and water (70%). This composition data (Woolfe, 1992) is utilized to carryout the component material balance of streams containing the sweetpotato working material. Other compounds, sugars and non-starch carbohydrates are also present in the sweetpotato.

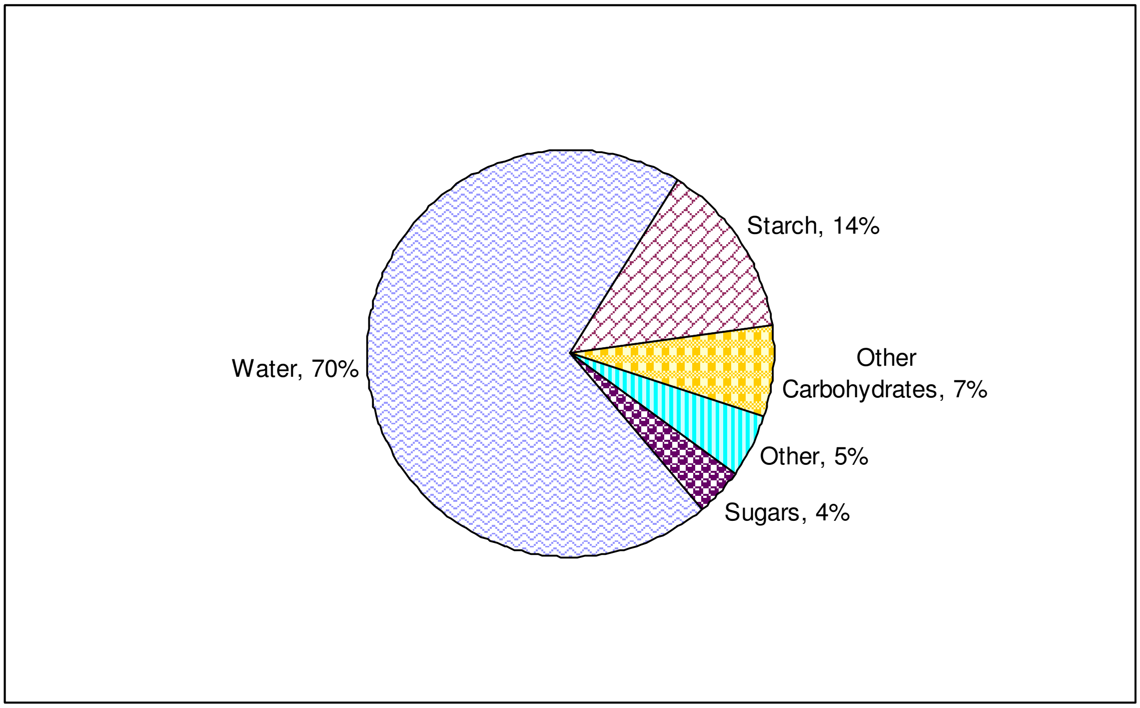

Fig. 5.2. Composition by weight of sweetpotato (Woolfe, 1992).

By applying the methodology in section 4.5 and utilizing the data provided by Silayo et al. (2003) and other sources mentioned in section 2.2, a material balance was calculated for the syrup technology. Sample calculations are provided in Appendix A.

In the forward calculation direction, primary inputs are water (S1) and peeled and pelletized sweetpotato (S2). The secondary input is the stream containing water for the vacuum filtration. In the reverse calculation direction, the primary input is the desired amount of syrup (S10). Researchers should provide all primary inputs for the process in order to begin the calculations. In the Excel spreadsheet, once the primary inputs are provided or modified, all other stream calculations will reflect the changes in the primary input. If the secondary input is not provided, calculations will be performed using default values stored in the spreadsheet. Table 5.1 summarizes the results obtained from the material balance calculations. All the values in the table are in units of grams. Sample material balance calculations can be found in Appendix A.

Table 5.1
Material balance for syrup production

Stream	Water (g)	Starch (g)	Carb (g)	Sugars (g)	Others (g)	Total (g)
S1-water	600	0	0	0	0	600
S2-sweetpotato	210	42	21	12	15	300
S3-reactor inlet	810	42	21	12	15	900
S4-reactor outlet	807	9	21	48	15	900
S5-water for filtration	40	0	0	0	0	40
S6-filter cake	42	9	21	3	15	90
S7-dilute syrup to deionization	805	0	0	45	0	850
S8-dilute syrup to evaporation	805	0	0	45	0	850
S9-dilute syrup from evaporation	780	0	0	0	0	780
S10-syrup product	25	0	0	45	0	70

Energy calculations were performed for the blender, the three reaction phases and the evaporator/condenser. Table 5.2 summarizes the energy data and the energy calculations can be found in Appendix A.

Table 5.2
Energy results for syrup production

Equipment/Process	Energy (kJ)
Blender	84
Reactor - Phase 1	227
Reactor - Phase 2	126
Reactor – Phase 3	36
Filtration	44
Deionization	33
Evaporator	2022
Condenser	2008
Total	**4503**

5.3. System Integration

Using information from the energy balance for processes requiring heating and cooling, it is possible to separately categorize the process heating and cooling requirements as depicted in Tables 5.3 and 5.4 below. Once again, sample energy calculations can be found in Appendix A. Evaporation and condensation required for syrup concentration place the greatest demands on the syrup production process. A time-based chart is useful for visualization of the scheduling demands relating to heat addition and removal. The Gantt chart in Figure 5.3 illustrates the demands on heating and cooling over time.

Table 5.3
Syrup production process heating requirements

Process Step	**Temperature range (°C)**	**mass(kg)**	**Δ H (kJ)**
CSTR1	25-85	0.9	227
Preheating of CSTR3	50-60	0.9	36
Vaporization (for syrup concentration)	25-200		2022
		Total	*2285*

Table 5.4
Syrup production process cooling requirements

Process Step	**Temperature range (°C)**	**mass(kg)**	***-Δ H(kJ)***
Precooling of CSTR2	85-50	0.9	*126*
Filtration	50-40	.807	*44*
Deionization	40-25	.805	*33*
Condensation and subcooling from 100 °C Of vapor from syrup concentration	100-25	0.64	*2008*
		Total	***2134***

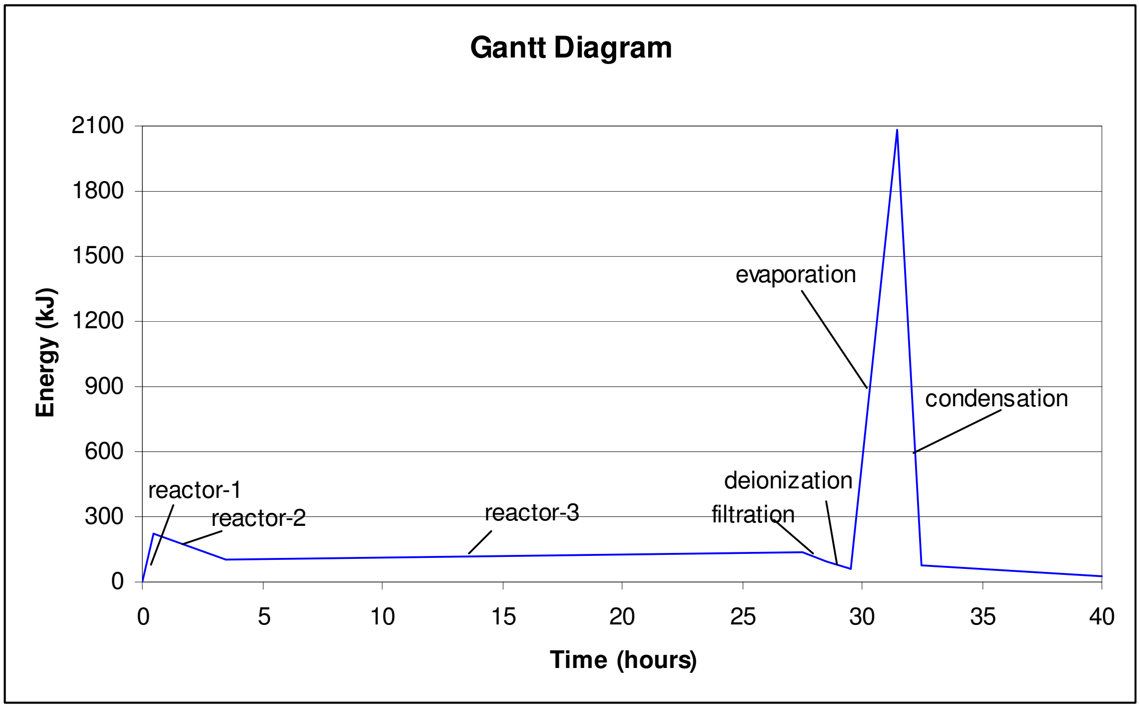

Fig. 5.3. Gantt diagram for thermal energy.

Based on the energy analysis results, targets can be identified for heat integration. The heating and cooling tasks associated with evaporation and condensation will be integrated. Further details of how the integration should be implemented will be explored. One option is to use a thermal-storage system which operates intermittently to provide heat during evaporation and release it during condensation. Water can be used as the thermal storage fluid since it would enable reuse for mass integration purposes. Figures 5.4a and 5.4b are a schematic representation of the proposed system.

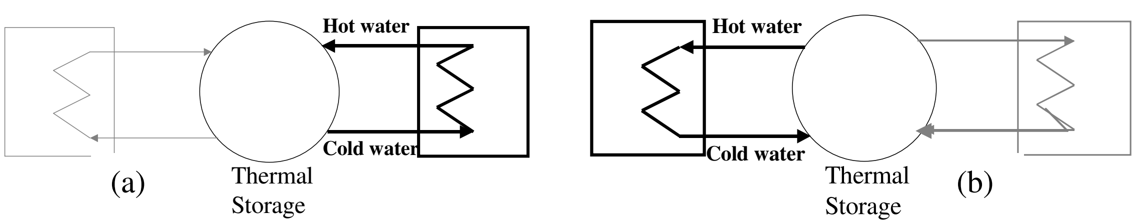

Fig. 5.4. (a)The heat storage phase and (b) The heat release phase.

Another integration option for thermal energy reduction is the use of an intermediate “energy wheel” that is capable of heat capture and released in accordance with system scheduling demands. Such a system is depicted in Figure 5.5. Calculations for this energy cascade system show heating and cooling utility reductions of 190kJ each. Detailed calculations for the energy cascade can be found in Appendix A. Through the energy integration process targets for minimum heating and cooling utilities can be identified, scheduling plans for heat integration can be drafted, heat exchangers can be sized and designed for operation and water usage for heating and reuse in mass integration can be planned.

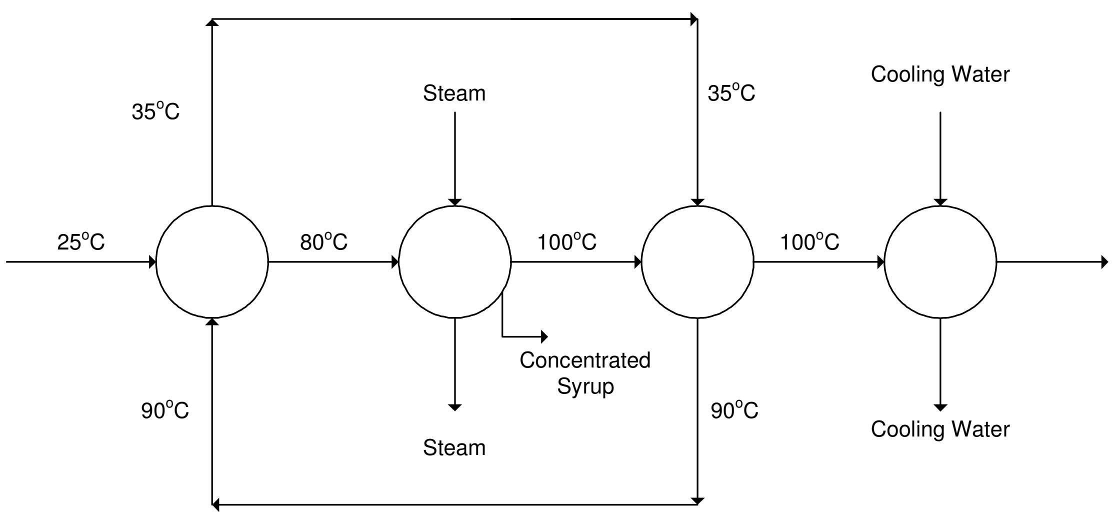

Fig. 5.5. Energy cascade for scheduling heat capture and release.

In regards to mass integration, the main consumable fresh resource that can be targeted is water. Water is a valuable resource in a controlled ecological environment. The syrup production system has two key processes, creating a slurry (S1) and filtration (S5), that require water and in which fresh water is currently being used. In order to reduce the water consumption, it is possible that less water can be used in liquefaction of the fresh sweet potato. It may be possible to reduce the water input ration to a ratio closer to that of the stoichiometric demands (1:1). The greatest considerations in reducing the initial water demand is that the water requirement should be sufficient for liquefaction while maintain a level of water which sustains the enzymatic activity level for the sweetpotato to glucose reactions. Since enzymes function well within a certain temperature range and pH and the amount of water present may affect the enzyme function, it will be necessary to determine the optimum amount of water needed for the enzyme catalyzed processes.

Another option for the mass integration of water will be either to recycle the water obtained from the filtration process or use recycled water in the liquefaction and filtration processes. In developing water recycle and reuse strategies for these two steps, the main challenge will be to prevent the accumulation of impurities and non-process elements.

5.4. ESM

The overall ESM results of the base case of the syrup production configuration described in section 5.1, are 18.78kg as shown in Table 5.5. The greatest ESM contributor was the evaporation/condensation process and equipment. Equipment contributing most to ESM will be targeted for alternative analysis. All processes will be targeted for automation to decrease crew time requirements. Special attention will be given to processes making the greatest contribution to ESM crew time. Detailed ESM calculations an be found in Appendix A.

Table 5.5
Base case ESM results for syrup production

Procedure/Equipment	**ESM (kg)**
Blender	2.147
CSTR	5.032
Centrifugal Filter	1.26
Vacuum Filter	1.12
Deionization Column	1.30
Evaporation/Condensation	7.29
Total	**18.15**

5.5. Analysis of Alternatives

The syrup concentration step is the most energy intensive step in the entire syrup production process. As a result, alternatives have been proposed for improving energy and mass utilization for the syrup concentration portion. The alternatives to the base case are heat-integrated evaporation, vacuum evaporation, vapor-compression with evaporation, reverse osmosis (RO), freeze concentration (FC), membrane distillation and gel dehydration. Heat integration has already been explored in the systems integration section (5.3). In the remainder of this section, the remaining alternatives will be explored.

Vacuum Evaporation can be used in order to reduce the heat duty of the evaporator. As the vacuum increases, the boiling point of the syrup decreases, thereby reducing the heat duty of evaporation.

Another method for improving the efficiency of the evaporator is to use vapor compression in order to evaporate the syrup. First enough heat must be provided to the unit to effect evaporation. Once the vapor is released, it is compressed in order to elevate its temperature and increase its heating duty. The compressed steam is then used to induce evaporation.

Reverse osmosis involves the use of a semi-permeable membrane to separate substances with a large molecular size difference, in this case water and glucose. The pressure-driven membrane process selectively allows water to pass through the membrane leaving the concentrated syrup behind. The retentate (concentrated syrup) is the stream retained at the high-pressure side and the stream transported to the low-pressure side is called the permeate (water). Reverse osmosis has the advantages of near ambient operating temperatures thus minimizing the excessive use of heating and cooling associated with evaporation and condensation (particularly latent heats) and of providing clean water which can be reused. Also, due to its modular nature, reverse osmosis provides a flexible way to be operated on-demand for syrup concentration or other purposes if needed. The RO process is depicted in figure 5.6.

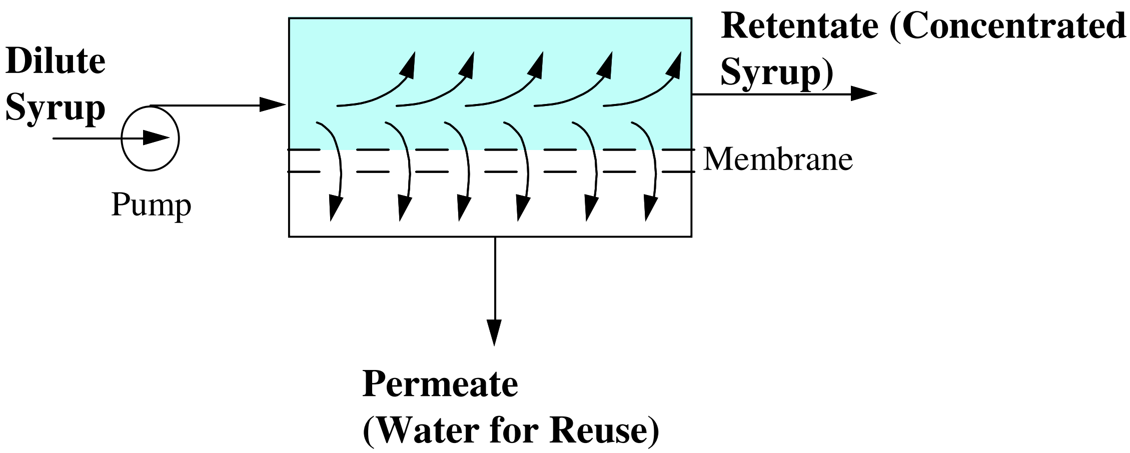

Fig. 5.6. Reverse osmosis.

Preliminary calculations indicate that less than 50 kJ of electric energy is needed to run the reverse osmosis system. The system cannot reach a sugar concentration of 65% without major operational problems (fouling, biological growth, concentration polarization), however, and should be followed by another syrup concentration step (e.g., evaporation). Preliminary calculations indicate an energy savings of about 25% of the membrane-evaporation (RO-evaporation) system compared to evaporation alone.

The main operating principle of freeze concentration is to pass the dilute syrup over a refrigerated heat transfer surface (e.g., pipe with refrigerant). Water condenses out of the syrup in the form of ice crystals which form over the cold surface leaving behind concentrated syrup. The system should be stopped frequently and the ice crystals melted to prevent their accumulation and the water from the ice crystals should be collected for reuse. A depiction of the freeze concentration process can be found in figure 5.7.

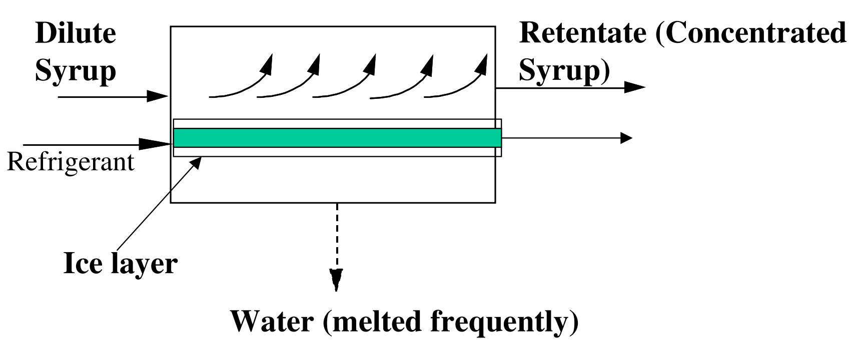

Fig. 5.7. Freeze concentration.

Preliminary calculations for the energy requirements of freeze concentration have been performed and can be found in Appendix A. The initial results indicate that freeze concentration is a promising alternative. Its thermodynamic requirements are 346 kJ of cooling. This is significantly less than the evaporation system and should be further investigated using tailored experiments and detailed simulation.

Membrane distillation is a combination of vapor-liquid separation as well as membrane permeation. Heat is provided and a semi-permeable membrane is used to facilitate the permeation of water. The result is a net reduction in heat duty of the system.

In gel dehydration, a selective gel is used to adsorb water, leaving behind concentrated syrup. The gel swells upon hydration. Next, the gel is regenerated by mechanical compression (squeezing) and the water can be reused.

Of the aforementioned alternatives, the four most feasible and promising were selected. These alternatives are the base case evaporation, heat integrated evaporation, membrane separation (RO) coupled with evaporation and freeze concentration. The thermodynamic results for the four syrup concentration alternatives can be seen in Figure 5.8. While freeze concentration appears to be the most promising technology (Table 5.6), additional experimental and simulation studies are needed to refine the results.

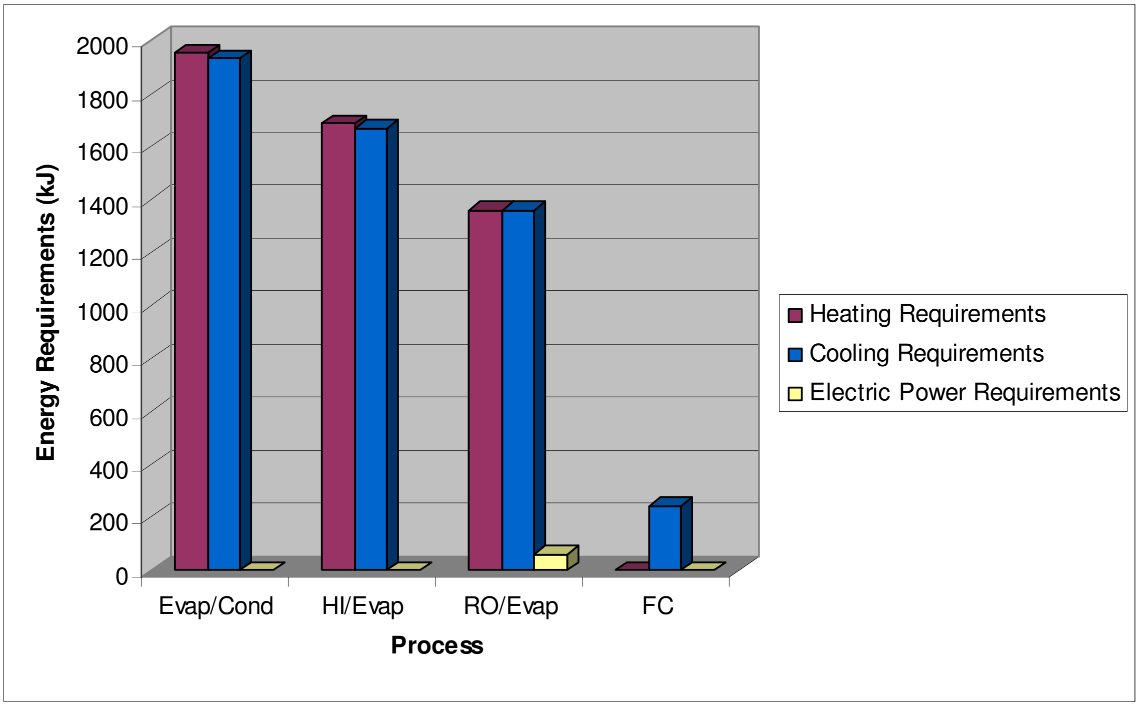

Fig. 5.8. Analysis of energy requirements of various alternatives (where Evap/Cond is evaporation/condensation, HI/Evap is heat integration with evaporation, RO/Evap is membrane reverse osmosis with evaporation, and FC is freeze concentration).

Table 5.6
ESM alternatives for syrup production

Alternative	ESM (kg)
Evaporation/Condensation	7.29
Heat Integrated Evaporation/Condensation	10.23
Reverse Osmosis/Evaporation	9.21
Freeze Concentration	2.15

6 CASE STUDY II: FLOUR TECHNOLOGY

6.1. Model

The process configuration for the sweetpotato to flour system is largely based on the work of Dansby (2002). A model and material balance equations were developed based on the information provided by Dansby (2002). As the current system configuration utilized by researchers in Tuskegee differs slightly from the configuration available in the literature (Dansby, 2002), the model and material balance equations were subject to change pending receipt of data. The system configuration by Dansby (2002) has been modified based on experimental data receive from Tuskegee CFESH researchers in April 2006. The following is a description of the process.

The process began by obtaining and weighing a mass of fresh sweetpotato that will be processed. This particular study began with 5000 grams of fresh unpeeled sweetpotato. Next, the sweetpotatoes were peeled with a hand held peeler. Some amounts of edible sweetpotato were inevitable last with the peels in the peeling process. The peels were weighed and an amount of loss was attributed to the peels and other losses. After the peeling process, the potatoes were fed according to the equipment capabilities into a Hobart food slicer. Using the appropriate equipment and technique, the slicer was opened to extract as much hidden sweetpotato material as possible from the equipment chamber. Some mass losses are assumed to inevitably occur with each transfer process. The shredded sweetpotato pieces were then spread out on the different trays of a Cabela's food dehydrator.

After 12 hours, the dried sweetpotato slices were removed from the dehydration and the slices from each tray or rack were poured into one pan. Using a blender, the shredded sweetpotatoes were blended accordingly until the entire working mass reached the proper consistency for use as feed into the hopper of the mill.

Sufficient amounts of blended sweetpotato were poured from the blender into the feed hopper of the mill with appropriate timing and a long handled rigid device to aid the blended granules as they passed through the hopper. As the flour was milled, it fell into a component of the mill designed to catch the product. Flour from the catch tray was poured into a suitable packaging container. Flour that was not sifted as product was counted with the losses because even though it could be captured, the quality was not suitable for further processing. The storage container used to package the flour was weighed prior to being filled with flour. After being filled with flour it was weighed again and the mass of flour was determined. Since some flour was lost in the milling and transfer process, losses were categorized as lost milled sweetpotato and unsifted flour.

Two “clean up” procedures are associated with the flour production process. Clean up first takes place after loading the dehydrator and the next clean up occurs after packaging the final flour product. Lost sweetpotato from the associated processes, fresh water and detergent are fed to the “clean up” steps. The material flow diagrams generated from this model are shown in Figures 6.1 and 6.2.

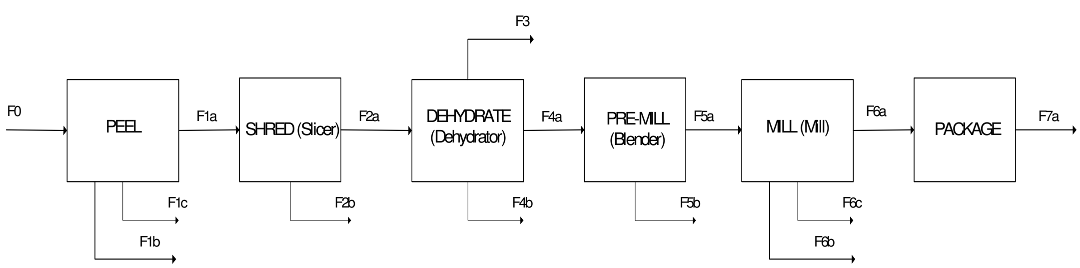

Fig. 6.1. Process configuration for the sweetpotato to flour technology.

Fig. 6.2. Process configuration for the clean up steps associated with flour technology.

6.2. Material and Energy Balance

Using equations developed by applying the techniques outlined in section 4.3, it was possible to generate a material balance over each process and equipment in order to obtain numerical quantities reflective of the data. The data was used to generate equations and default values for secondary inputs and both the equations and secondary inputs were stored in an Excel spreadsheet. Compositions of the working material at the start of the process and after the dehydration may vary depending on the type of sweetpotato used. Researchers should obtain composition data for the raw unpeeled sweetpotato and for the dehydrated sweetpotato before further processing the working material. A summary of the data obtained from the material balance is shown in Table 6.1 below. Detailed material balance calculations can be found in Appendix B.

The results from the energy calculations (Table 6.2) for the flour production reveal that the dehydrator uses a disproportionately large amount of energy in comparison to the other equipment. As a result, the dehydrator is made a preliminary target for energy reduction and integration. ESM analysis will further reveal equipment and process targets for the reduction of equivalent mass.

6.3. System Integration

Functional (qualitative) integration opportunities have been identified for the flour production process in terms of mass integration. A main goal will be to reduce losses by suggesting alternatives after ESM analysis. Where losses cannot be avoided, the lost mass of working materials from flour production will be utilized in the waste production and processing system. As mentioned in the introduction, a nutrient film technique is used to grow sweetpotato. In the work by Williams (2002), there is a description of using an Oxymax composter to obtain nutrients from sweetpotato biomass. The lost sweetpotato mass from the flour production process can be used in the composter for nutrient harvesting. The major loss of water is in the dehydration process. Pressing the wet based working material by squeezing the water out before drying it may lead to loss of nutrients or alter the nutrient content of the resulting dry base working material. It would be (thermodynamically) infeasible to capture the water vapor in the dehydration step. Another target for functional integration will be to use recycled water from other clean up steps.

Table 6.1
Material balance for flour production

Mass Balance								
Stream	**Description**	**H_2O (g)**	**Starch (g)**	**Carb (g)**	**Sugars (g)**	**Others (g)**	**Peels (g)**	**Total**
F0	raw unpeeled SP (g)	3848.20	587.91	293.96	167.97	101.95		5000.00
F1a	fresh peeled SP (g)	3485.70	532.53	266.27	152.15	92.35		4529.00
F1b	SP peels (g)						460.3	460.30
F1c	lost SP (g)	8.24	1.26	0.63	0.36	0.22		10.70
F2a	sliced/shredded SP (g)	3451.30	527.27	263.64	150.65	91.44		4484.30
F2b	lost sliced SP (g)	34.40	5.26	2.63	1.50	0.91		44.70
F3	H_2O vapor (g)	3428.90	0.00	0.00	0.00	0.00		3428.90
		H_2O (g)	Carb (g)	Protein (g)	Fat (g)	Ash (g)	Detergent (g)	Total
F4a	dehydrated SP (g)	21.92	944.22	8.33	9.37	49.16		1033.00
F4b	lost dehydrated SP (g)	0.48	20.47	0.18	0.20	1.07		22.40
F5a	blended SP (g)	21.81	939.66	8.29	9.32	48.92		1028.01
F5b	lost blended SP (g)	0.11	4.56	0.04	0.05	0.24		4.98
F6a	milled SP (sifted SP flour) (g)	20.25	872.28	7.69	8.66	45.42		954.30
F6b	lost milled SP (g)	0.56	24.14	0.21	0.24	1.26		26.41
F6c	unsifted SP flour (g)	1.00	43.24	0.38	0.43	2.25		47.30
F7a	packaged SP (g)	20.25	872.28	7.69	8.66	45.42		954.30
F8	detergent (g)	0.00	-	-	-	-	1.7	1.70
F9	water (g)	12.00	-	-	-	-	-	12.00
F10	output from clean up 1 (g)	12.00	-	-	-	-	1.7	13.70
F11	detergent (g)	0.00	-	-	-	-	1.7	1.70
F12	water (g)	12.40	-	-	-	-	-	12.40
F13	output from clean up 2 (g)	12.40	-	-	-	-	1.7	14.10

Table 6.2
Energy results for flour production

Equipment	**Energy (kJ)**
Slicer	102.948
Dehydrator	69,120
Blender	91.2
Mill	492

6.4. ESM

The overall ESM result of the base case, the flour production configuration described in section 6.1, is 1355.4 kg as shown in Table 6.3. The greatest ESM contributors are the dehydrator, mill, and slicer for the equipment, and clean up 2, for the crew time (Fig. 6.3). Equipment contributing most to ESM will be targeted for alternative analysis. All processes will be targeted for automation to decrease crew time requirements. Special attention will be given to the second clean up process since it contributes the most to ESM crew time. Sample ESM calculations can be found in Appendix B.

Table 6.3
Base case ESM results for flour production

Procedure/Equipment	**ESM (kg)**
Peel	131.7
Shred/Slicer	158.3
Dehydrate/Dehydrator	485.8
Pre-mill/Blender	68.6
Mill/Mill	188.1
Package	15.6
Clean Up 1	116.7
Clean Up 2	190.6
Total	**1355.4**

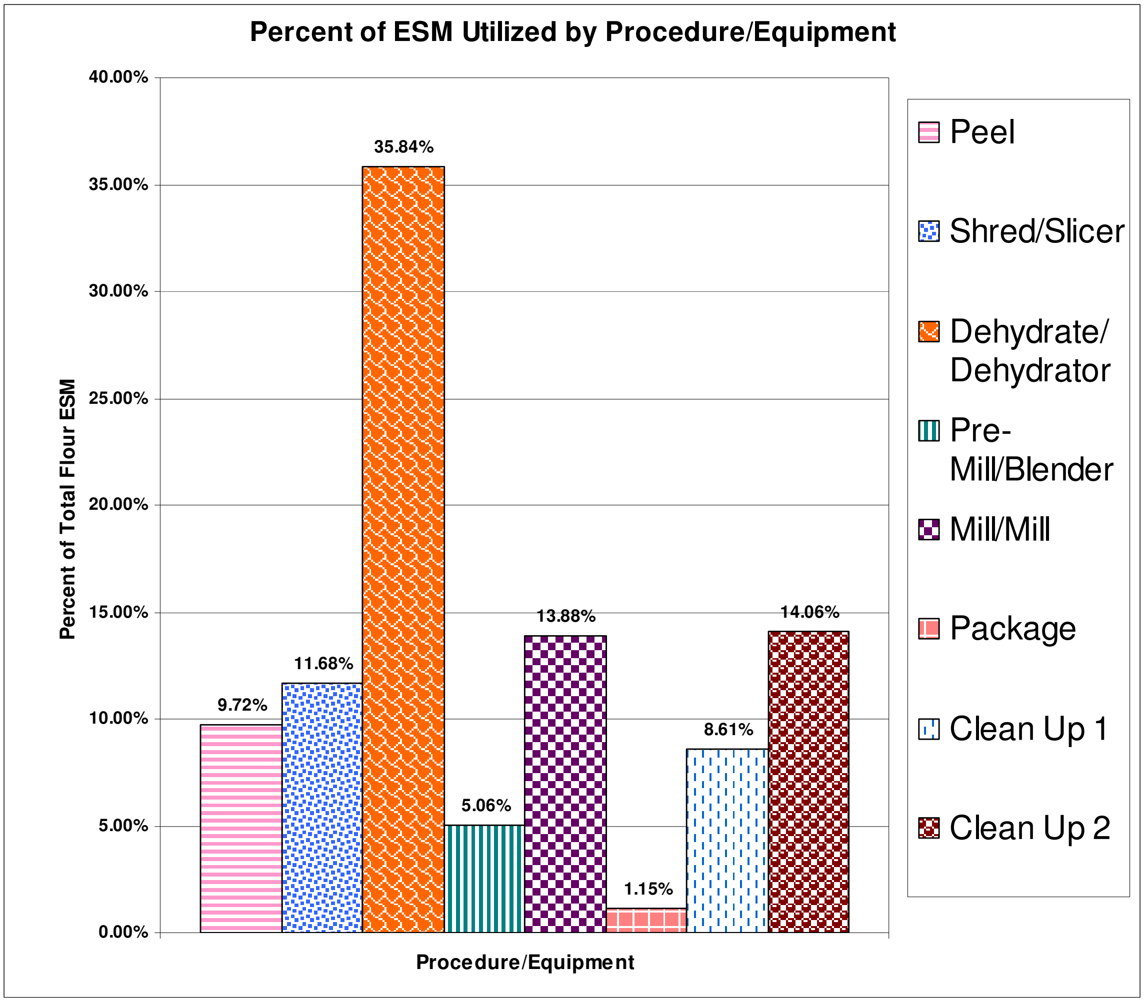

Fig. 6.3 Percent ESM utilization of flour processes and equipment.

6.5. Analysis of Alternatives

Based on the ESM analysis of the base case, the equipment targets for alternative analysis are the dehydrator, mill and slicer. For crew time reductions, a mechanized and automated alternative will be sought for the peeler. A major goal for all equipment will be to size and specially design equipment based on the maximum amount of working material that will be processed in each cycle in order to reduce mass and volume requirements. After studying the power, mass, volume, and crew time requirements of the specified equipment targets, an alternative has been generated to specifically address the key variables of ESM requiring the most equivalent mass demand. Table 6.4. is a summary of the ESM for the base case and the alternative equipment.

Table 6.4
Equipment alternatives for flour production

Equipment	ESM (kg)
Base Case	1355.38
Automated Peeler	1154.29
Sized Dehydrator	1038.66
Sized Mill	1257.57
Sized Slicer	1290.79
Alternative Peeler, Dehydrator, Mill and Slicer	837.27

Although each individual equipment change causes a reduction in total ESM, the greatest decrease in ESM occurs when all the various equipment alternatives are combined. In order to further reduce the total ESM alternatives should be sought for the clean up processes. The combinatorial effect of replacing the stated equipment with viable alternatives results in an estimated total ESM savings of 38.2%.

7 CASE STUDY III: BREAKFAST CEREAL TECHNOLOGY

7.1. Model

The process configuration for the sweetpotato flour to breakfast cereal system is largely based on the work of Dansby (2002). A model and material balance equations were developed based on the information provided by Dansby (2002). As the current system configuration utilized by researchers in Tuskegee differs slightly from the configuration available in the literature (Dansby, 2002), the model and material balance equations were subject to change pending receipt of data. The system configuration by Dansby (2002) has been modified based on experimental data receive from Tuskegee CFESH researchers in April 2006. The following is a description of the process.

For the formulation, the protocol states that syrup, baking powder, cinnamon, and brown sugar should be combined with sweetpotato flour. This combination should be mixed by hand and then with an electronic mixer, in this case, a Kitchen Aid mixer. The formulation should then be tested for moisture. The desired moisture level is approximately ten percent (10%) for the sweetpotato cereal formulation. A small portion of the mixed ingredients will be lost in this step as it will be used as a sample for moisture analysis. By using only the minimum required amount for moisture analysis, the loss in this step can be kept to a minimum. Water should then be added accordingly to bring the moisture content to the appropriate level. Again, the formulation should be mixed with an electronic mixer. Since the final composition of the working materials is dependent on the moisture content and the amount of water that will be added, the percentages of each of the ingredients will not be readily known. Repeated trials and experience have allowed researchers to approximate the values given by Dansby (2002) while allowing for modifications that improve the quality and quantity of the final product. The formulation will then be packaged and allowed to equilibrate first to 4 degrees Celsius for 12 hours and then to ambient temperature. The extruder should be preheated for approximately 26.6 minutes in preparation for its use.

Next, the equilibrated mixture should be fed into the extruder through the feed hopper. Extruder temperatures vary at different sections of the extruder. The expansion ratio of the exiting product should be tested as soon as product exits the extruder. After the extrusion process, the moisture content of the working material as wells as it physical properties, would have changed. The extruded material should be tested for moisture content after extrusion. As a result of the extrusion process, certain losses are expected. Since the extrusion process here is a cooking process and occurs at high temperatures, losses in the form of water vapor are usual. Some working material may remain trapped within the equipment while some extruded product may not be of desirable quality. All of these factors contribute to the total losses of extruded product. Prior to the drying process, the drying oven must be preheated to 80 degrees Celsius. The extruded product is collected into an oven acceptable container.

In the drying process, the extruded product is placed in the oven for approximately 25 minutes. Once again the moisture content may be slightly altered by the drying process. All losses in the drying process are assumed to be those due to loss of water vapor. Finally, the dried extruded product is packaged. During the transfer of the extruded product into the package, some product mass may be lost. Figures 7.1 and 7.2 are the flow diagrams of the breakfast cereal process configuration.

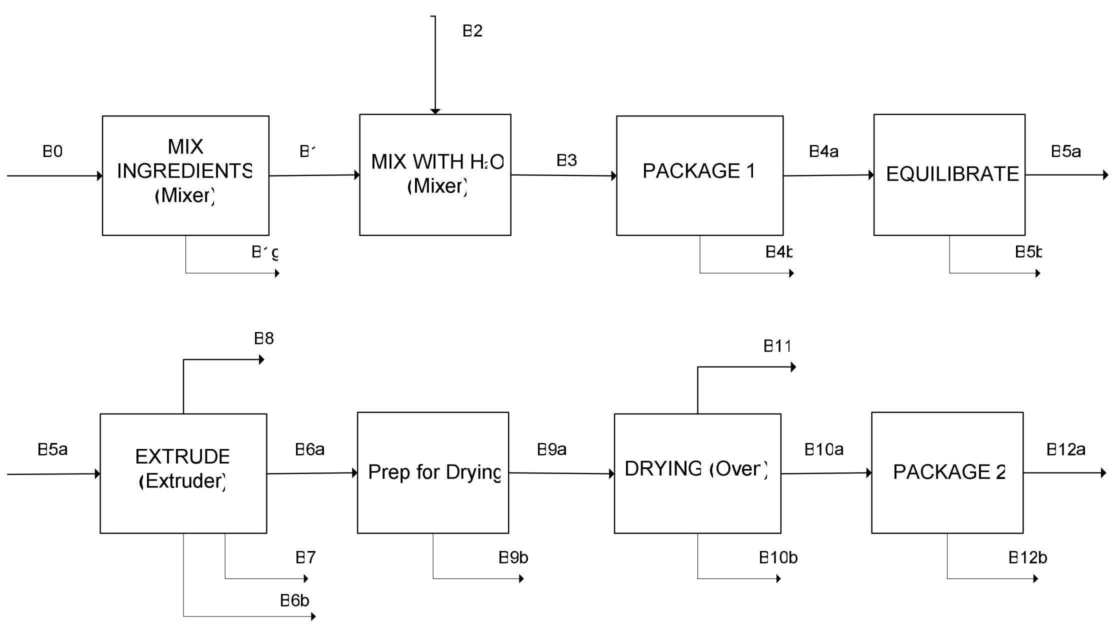

Fig. 7.1. Process configuration for the sweetpotato flour to cereal technology.

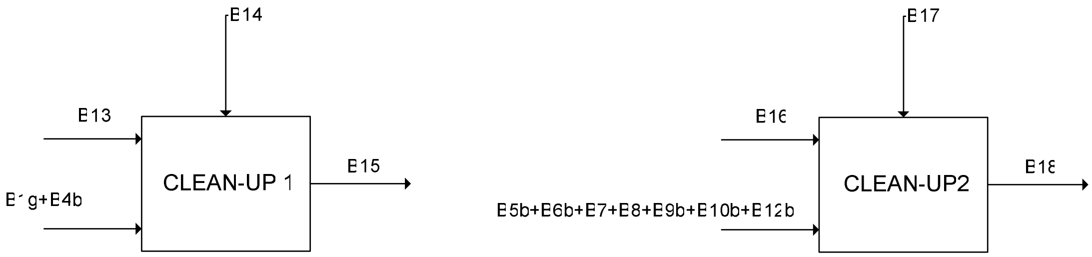

Fig. 7.2. Process configuration for the clean up steps associated with cereal technology.

7.2. Material and Energy Balance

Using equations developed by applying the techniques outlined in section 4.3, it was possible to generate a material balance over each process and equipment in order to obtain numerical quantities reflective of the data. The data was used to generate equations and default values for secondary inputs and both the equations and secondary inputs were stored in an Excel spreadsheet. The composition of the ingredients can be readily determined for the ingredients that are mixed initially without water. Researchers should obtain composition data for the formulation after the addition of water to achieve ten percent (10%) moisture. This composition data for the ingredient mixture without added water and for the moist formulation, if it can be obtained, should be used as secondary inputs. Other data that should be attained and utilized as secondary inputs are the moisture contents for the streams believed to contain water that exit the extruder and the oven. Energy calculations reveal that for the cereal production technology, the extruder and oven utilized the most energy (Table 7.1). The extruder and oven will those be noted as the greatest energy consuming equipment in regards to this technology. Further analysis via ESM will reveal both equipment and process that require the greatest cost in NASA terms. A summary of the data obtained from the material balance is shown in Table 7.2 below. Detailed material balance calculations can be found in Appendix C.

Table 7.1
Energy results for cereal production

Equipment	Energy (kJ)
Mixer	388.8
Extruder	11,682.36
Oven	9,900

Table7.2
Material balance for cereal technology

Mass Balance								
Stream	**Description**	**H_2O(g)**	**Carb (g)**	**Protein (g)**	**Fat (g)**	**Ash (g)**		**Total (g)**
B0a	sweetpotato flour (g)	26.00	913.00	9.00	8.00	44.00		1000.00
Stream	Description	H_2O (g)	SP (g)	Brown Sugar (g)	Bkg Soda (g)	Mple Syrp (g)	Cinnamon (g)	Total (g)
B0	Ingredients w/o added water (g)	0.00	1000.00	142.90	14.30	42.80	14.30	1214.30
B0b	H_2O (g)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B0c	brown sugar (g)	0	0.00	142.90	0.00	0.00	0.00	142.90
B0d	baking soda (g)	0	0.00	0.00	14.30	0.00	0.00	14.30
B0e	maple syrup (g)	0	0.00	0.00	0.00	42.80	0.00	42.80
B0f	cinnamon (g)	0	0.00	0.00	0.00	0.00	14.30	14.30
B1	Ingredients w/o water and sample (g)	0.00	995.80	142.30	14.24	42.62	14.24	1209.20
B1a	sweetpotato flour (g)	0	995.80	0.00	0.00	0.00	0.00	995.80
B1b	H2O (g)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
B1c	brown sugar (g)	0	0.00	142.30	0.00	0.00	0.00	142.30
B1d	baking soda (g)	0	0.00	0.00	14.24	0.00	0.00	14.24
B1e	maple syrup (g)	0	0.00	0.00	0.00	42.62	0.00	42.62
B1f	cinnamon (g)	0	0.00	0.00	0.00	0.00	14.24	14.24
B1g	mixed ingredients in moisture analysis (g)	3.96	0.29	0.57	0.06	0.17	0.06	5.10
B2	water for formulation (g)	72.1	0.00	0.00	0.00	0.00	0.00	72.10
B3	formulation (g)	72.10	995.80	142.30	14.24	42.62	14.24	1281.30
B3a	flour for formulation (g)	25.89	909.17	8.96	7.97	43.82		995.80
B3b	H2O (g)	72.10	0.00	0.00	0.00	0.00	0.00	72.10
B3c	brown sugar (g)	0	0.00	142.30	0.00	0.00	0.00	142.30
B3d	baking soda (g)	0	0.00	0.00	14.24	0.00	0.00	14.24
B3e	maple syrup (g)	0	0.00	0.00	0.00	42.62	0.00	42.62
B3f	cinnamon (g)	0	0.00	0.00	0.00	0.00	14.24	14.24
B4a	packaged formulation (g)	70.37	971.86	138.88	13.90	41.60	13.90	1250.50
B4b	loss from packaging formulation (g)	1.73	23.94	3.42	0.34	1.02	0.34	30.80
B5a	equilibrated formulation (g)	70.37	971.86	138.88	13.90	41.60	13.90	1250.50
B5b	loss from equilibrate 1& 2 (g)	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Stream	Description	H_2O(g)	Carb (g)	Protein (g)	Fat (g)	Ash (g)		Total
B6a	extruded product (g)	56.24	944.83	100.11	10.80	12.82		1124.80
B6b	lost extruded product (g)	1.08	18.14	1.92	0.21	0.25		21.60
B7	discarded product (g)	2.51	42.17	4.47	0.48	0.57		50.20
B8	unknown (assumed to be water) (g)	2.70	45.28	4.80	0.52	0.61		53.90
B9a	broken extruded product pieces (g)	56.24	944.83	100.11	10.80	12.82		1124.80
B9b	powder from broken pieces (g)	0.00	0.00	0.00	0.00	0.00		0.00
B10a	oven dried product (g)	31.47	914.00	96.57	10.42	32.55		1085.00
B10b	lost oven dried product (g)	0.00	0.00	0.00	0.00	0.00		0.00
B11	lost H2O from oven drying (g)	39.80	0.00	0.00	0.00	0.00		39.80
B12a	product in package 2 (g)	31.06	902.13	95.31	10.28	32.13		1070.90
B12b	lost product in packaging 2 (g)	0.41	11.88	1.25	0.14	0.42		14.10
B13	detergent (g)	0.00	-	-	-	-	1.7	1.70
B14	water (g)	1787.50	-	-	-	-	-	1787.50
B15	output from clean up 1 (g)	1787.50	-	-	-	-	1.7	1789.20
B16	detergent (g)	0.00	-	-	-	-	1.7	1.70
B17	water (g)	7.60	-	-	-	-	-	7.60
B18	output from clean up 2 (g)	7.60	-	-	-	-	1.7	9.30

7.3. System Integration

Functional (qualitative) integration opportunities have been identified for the flour production process in terms of mass integration. A main goal will be to reduce losses by suggesting alternatives after ESM analysis. Where losses cannot be avoided, the lost mass of working materials from flour production will be utilized in the waste production and processing system. As mentioned in the introduction, a nutrient film technique is used to grow sweetpotato. In the work by Williams (2002), there is a description of the use of an Oxymax composter to obtain nutrients from sweetpotato biomass. The lost sweetpotato mass from the flour production process can be used in the composter for nutrient harvesting. The major loss of water is in the dehydration process. Pressing the wet based working material by squeezing the water out before drying it may lead to loss of nutrients or alter the nutrient content of the resulting dry base working material. It would be (thermodynamically) infeasible to capture the water vapor in the dehydration step. Another target for functional integration will be to use recycled water from other clean up steps.

7.4. ESM

The overall ESM result of the base case, the cereal production configuration described in section 7.1, is 1476.6kg as shown in Table 7.3. The greatest ESM contributors are the extruder and the oven, for the equipment, and clean up 2, for crew time (Fig. 7.3). Equipment contributing most to ESM will be targeted for alternative analysis. All processes will be targeted for automation to decrease crew time requirements. Special attention will be given to the second clean up process since it makes the greatest contribution to ESM crew time. Sample ESM calculations can be found in Appendix C.

Table 7.3
Base case ESM results for cereal production

Procedure/Equipment	**ESM (kg)**
Measure Ingredients	52.8
Mix Manually	42.2
AddWater&Mix	23.8
Mixer	32.1
Package1	18.4
CleanUp1	64.0
Equilibrate1	4.8
Equilibrate2	0.0
Extruder	453.6
Drying Prep	24.2
Oven	512.1
Package2	13.1
CleanUp2	235.5
Total	**1476.6**

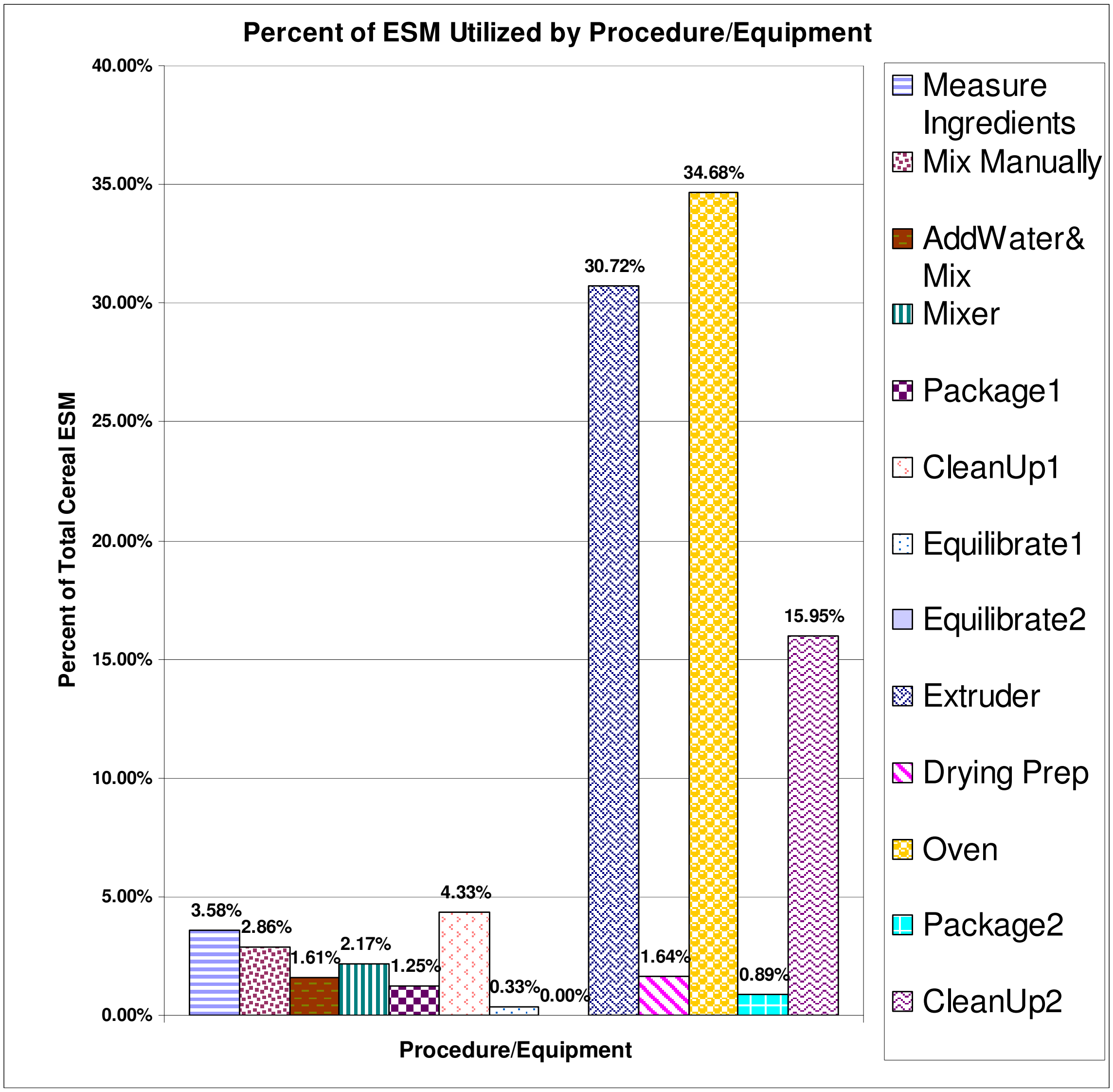

Fig. 7.3. Percent ESM utilization of cereal processes and equipment.

7.5. Analysis of Alternatives

Based on the ESM analysis of the base case, the equipment targets for alternative analysis are the extruder and the oven. A major goal for all equipment will be to size and specially design equipment based on the maximum amount of working material that will be processed in each cycle in order to reduce mass and volume requirements. After studying the power, mass, volume, and crew time requirements of the specified equipment targets, an alternative has been generated to size the oven for in terms of mass, volume and power. Mass and volume will be used to size the oven based on the amount of working material and the oven will be sized in terms of power based on the temperature changes that occur upon material entering and leaving the oven. Table 7.4 summarizes the ESM for the sized oven alternative in comparison to the base case configuration for the cereal technology.

Table 7.4
ESM alternative for cereal production

Equipment	**ESM (kg)**
Base Case	1476.6
Sized Oven	980.61

Since many factors must be taken into consideration in designing an extruder, it is beyond the scope of this work to make even preliminary attempts at sizing an extruder. The oven, however, was sized resulting in an ESM savings of 33.6%. ESM calculations for the oven can be found in Appendix C.

8 COMPUTER-AIDED ANALYSIS OF FOOD PRODUCTION TECHNOLOGIES

8.1. Objective

The objective of the computer-aided tool is to address the issues and concerns in the problem statement, section 3.2 by automating the modeling, analysis, integration and metrics evaluation for use by researchers. The preceding sections of this work address the areas of developing a systematic methodology and providing examples of how the methodology is applied. This section describes how a computer automated application facilitates the usage and employment of the methods.

8.2. Layout

By presenting data taken from an Excel spreadsheet in a separate Visual Basic user screen, the computer-aided tool allows the user to focus primarily on the process simulation at hand without drawing focus back to the individual equations. In the Visual Basic module there will be interactive mass flow diagrams of each process configuration. By selecting a stream label using the mouse, the user is able to view tables containing mass balance information pertaining to that stream. Results of energy analyses, ESM analyses, sensitivity analyses and other calculations will be accessible and viewable in the form of tables, charts and graphs. Figure 8.1 is a snapshot of the active tool analysis screen for the syrup technology.

In addition to performing mass balance analysis through the Excel files accessed by the program, users will also be able to perform ESM analyses, sensitivity analyses and integration analyses. Currently the module/Excel system is able to perform integration within a certain technology (i.e. heat integration for the syrup technology). In the near future, as the tool is further developed, it will also be useful for utilization for systems integration analyses of the various ALS technologies.

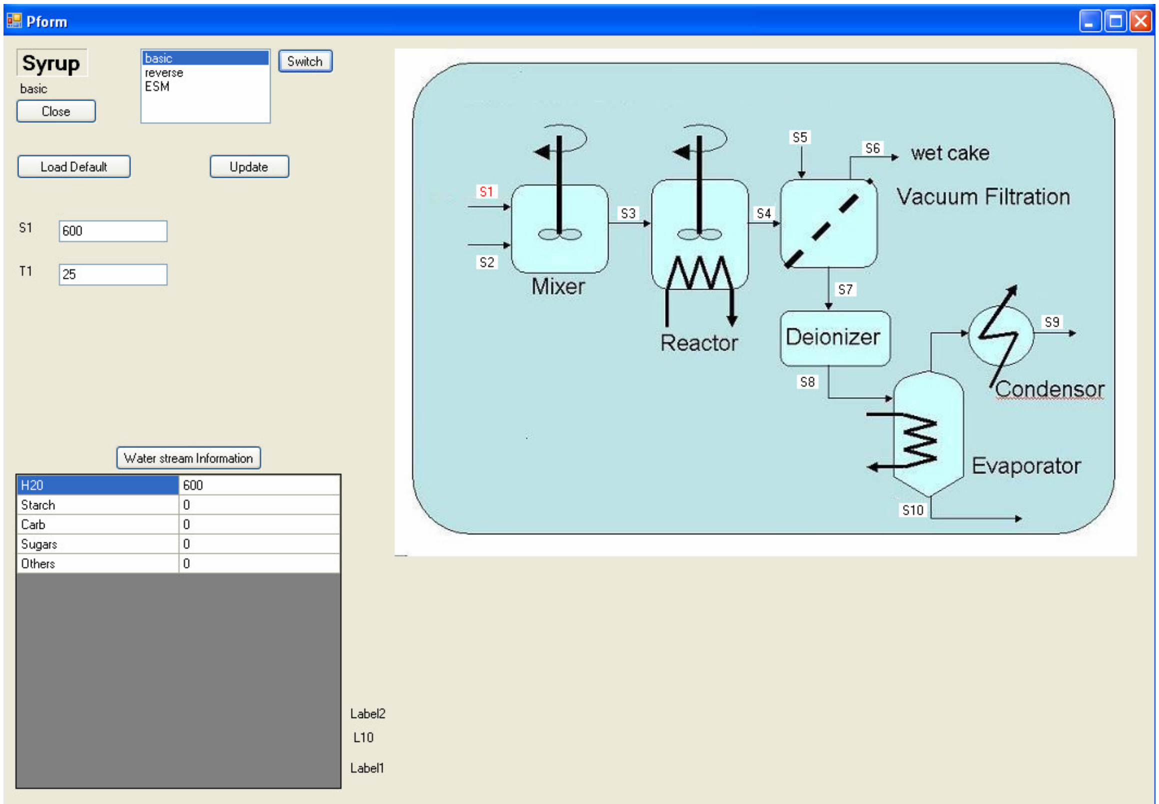

Fig. 8.1. Computer-aided tool active analysis screen for syrup technology.

The tool module begins with an opening page containing a menu with several key items. The first is the "Tool Overview." By selecting this item the viewer will be able to view general information about the tool, a description of the purpose of the tool, the tools main objects, the authors/creators of the tool and the date when the tool was created. The next menu item will be the "Run an Analysis" bar. This menu item allows the user to begin an analysis from scratch with only the preloaded default values. "Run an Analysis" is the key portion of the tool. It enables the user to choose a technology to assess from the different technologies available. Another menu item is the "Modify an Existing Process" button. As the title suggests, it allows users to open a saved run and make changes to it. This is important if a user must end an analysis without completing it since the user will be able to return to the analysis and begin from where they last ended. There is also a menu item that allows users to "Add a New Process." In its current state the tool only allows users to make work with the syrup, flour and cereal technologies (only food production technologies). As was mentioned in the introduction, there are other systems in ALS, including the crop production and waste management systems.

Within each ALS system, there resides the possibility of the development of several other technologies. The “Add a New Process” menu item would address the issue of the addition of other food technologies besides the three being explored in this work in addition to other ALS technologies being developed. These menu items subject to modifications as the computer-aided tool is still in developmental stages. Figure 8.2 shows a sample module opening page.

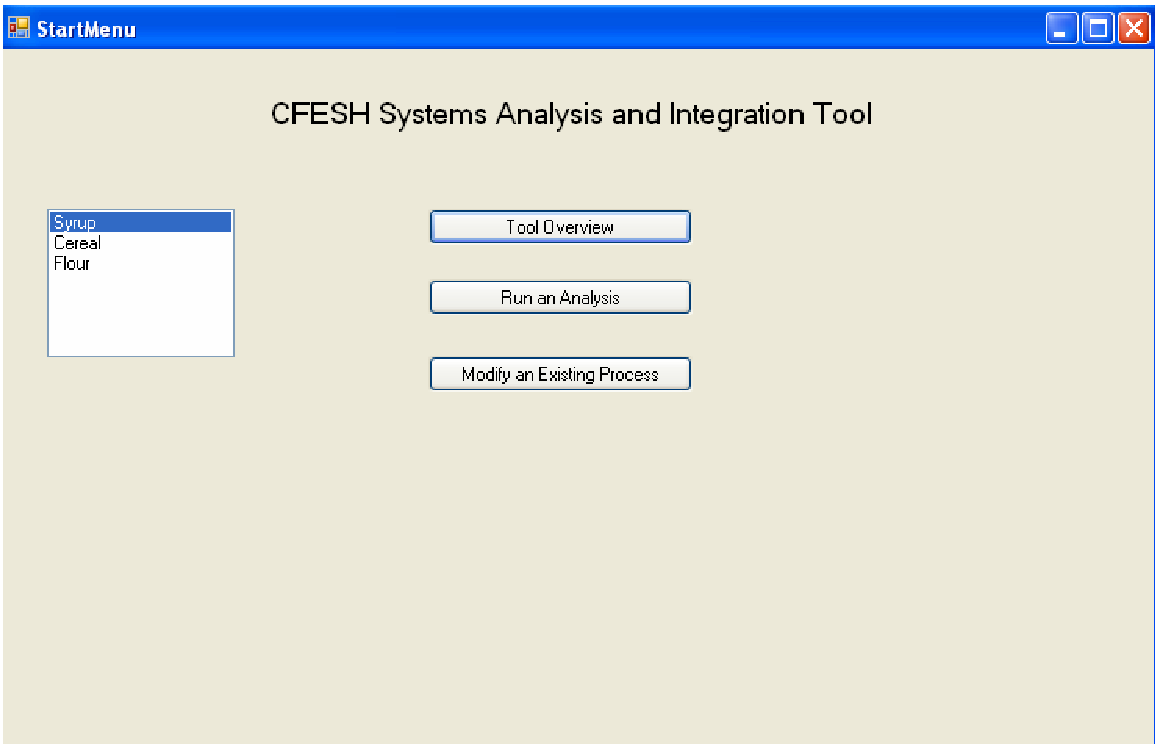

Fig. 8.2. Computer-aided analysis tool start page.

8.3. Information for the User

There are key features of the computer tool that should be made clear to the user. One key feature is that to begin an analysis, primary inputs in the form of variable fields are required. Although default primary input values are stored in the program’s memory, the user should enter primary inputs that are specific to the case being analyzed. Based on the primary input(s) alone, the user will be able to obtain simulation results. For more case specific results, there will also be optional secondary inputs that the user can access with the appropriate fields or buttons. As with the primary inputs, there will also be stored default values for the secondary inputs, but the user will have the option to enter other secondary input values.

Another key feature is the ability to perform a simulation in a forward or reverse mode. For the forward mode, the primary inputs are the major feed streams. The purpose of the forward mode is to predict the output and intermediate streams. In the reverse mode, the primary input is the desired output in terms of quality and quantity (i.e. stream composition and stream mass). The purpose of the reverse mode is to predict the required amount of starting materials needed as well as intermediate streams. Additional features include informative text that may appear when accessed in the proper manner (click of a button or roll over text with a mouse arrow).

This computer-aided tool will help provide insight to system developers and researchers in some important areas. The first is that it will signal developers and researchers as to the additional information that must be collected and experiments that should be conducted in order to carryout the ALS study on the technologies to the level of detail necessary. In addition it will become clear as to the format and specifications required in order to report protocols and present data and results. Finally, it will be possible to determine which system components contribute the most to ESM and require the greatest mass and energy.

9 CONCLUSIONS AND RECOMMENDATIONS

9.1. Conclusions

Material balance calculations revealed details pertaining to the material flows in the syrup, flour and cereal production technologies, enabling the tracking of key streams containing working materials, water and waste. Energy analyses revealed that the major energy consumers were the evaporation/condensation processes for the syrup technology, the dehydration process for the flour technology and the extruder and oven for the cereal technology. ESM results confirmed the findings of the energy calculations. In addition ESM analyses also reveal the major consumers of crew time, namely clean up processes. Analysis of ESM alternatives reveals freeze concentration to be a more cost-efficient alternative to evaporation/condensation of the syrup. Also ESM alternatives involving sizing or designing equipment based on the actual working materials that will be processed during each cycle revealed significant cost savings for the flour and cereal technologies.

This work provided a hierarchical framework for system analysis and budgeting of energy and mass for food production in planetary habitation. First, the mass and energy budgeting and tracking were developed for the system with the result of identifying key consumers for mass and energy. Then, process integration strategies were developed. Performance was assessed by calculating ESM, the metric which is used to screen alternatives. The developed approach was automated by developing a Visual Basic computer-aided tool. The tool operates in forward mode for analysis of mass and energy when the inputs are provided. It also operates in reverse mode for predicting feed stocks when the quantity and quality of products are given. The usefulness of the tool was demonstrated by addressing a case study on sweet potato-to-syrup process. The tool also provides feedback to the system developers and analyzers on:

- What additional data need to be collected or experiments to be conducted?
- Format and specifications needed for reporting protocols, data, and results
- Which components are the largest contributors to ESM? What research is needed to reduce the ESM at specific components with specific strategies?

The tool can be used for design purposes as well as for on-line operation. It is being developed in a flexible way that enables future modifications and updates. Once an analysis is conducted and a unit or a process is identified as a major contributor to ESM, additional development can be undertaken to analyze alternative units or processes that reduce ESM.

9.2. Recommendations and Future work

This work can form the basis for broader research. This study only addresses one portion of the entire ALS systems; namely food production. Additional research can involve the integration of the food, crop, and waste systems of ALS, all of which include the human component. Integrating any two of these systems would require a great deal of work, calculations, and collaboration with NASA and CFESH researchers. Further statistical analysis of data would help in the generation of more equations. Development of specialized mathematical models would greatly impact further advancement in the analysis of data and in the progress of the computer-aided tool.

The computer-aided tool can be expanded to apply to new processes or other ALS system technologies (i.e. technologies within waste production and crop production). Development of new processes for addition into the computer tool should follow the methodology outlined in this work. Finally, mass and energy integration techniques can be incorporated in the tool with the objective of automating system integration calculations.

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APPENDIX A : SYRUP PRODUCTION CALCULATIONS

Appendix A presents a sample of the calculations utilized in analyzing the syrup technology. In section A.1 there is a summary of the mass balance calculations. In section A.2 there are the energy calculations. Section A.3 presents the calculations for the base case heat integration. For the freeze crystallization alternative, sample calculations are presented in section A.4. Section A.5 contains sample ESM calculations for the base case and the alternatives.

A.1Sample Mass Balance Calculations

Blender

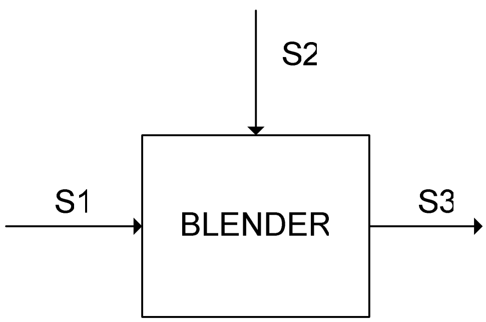

Fig. A.1. Mass balance on the blender

Primary Inputs: S1, S2
S1+S2=S3

Reactor – Overall

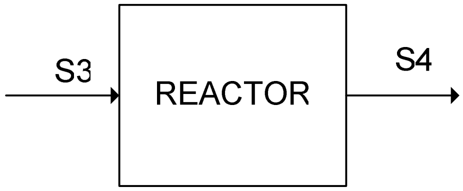

Fig. A.2. Mass balance on the reactor.

S3=S4

42 g starch * 0.781 = 33 g + 3 g H_2O (consumed in rxn) = 36 g sugars

Total sugars = 36 g (from hydrolysis) + 12 g (initial) = 48 g sugars

H_2O consumed = 33 g * 18 H_2O/180 glucose = 3 g H_2O

Vacuum Filter

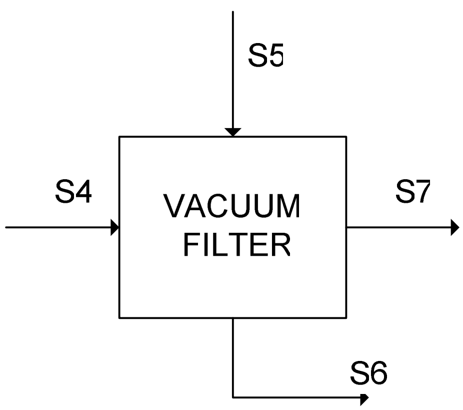

Fig. A.3. Mass balance on the vacuum filter.

S4+S5=S6+S7

Assumptions:
1. Only sugars and water pass through filter
2. The percentage of sugars recovered in the filtrate

$$\frac{77.6}{82.2} \times 100\ \% = 94.4\ \%$$ (from Figure 2, p. 13)

3. Five percent of the water stays with the cake

Deionization

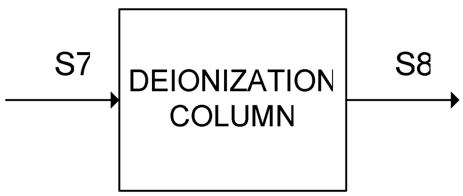

Fig. A.4. Mass balance on the deionization column.

S7=S8

Evaporator

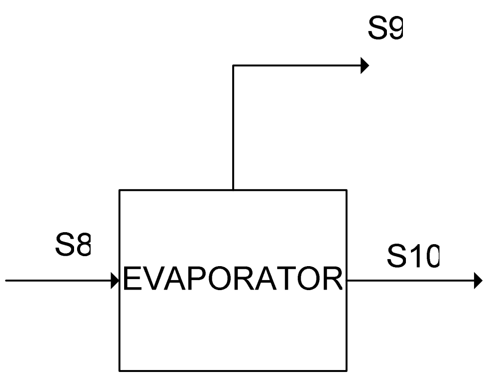

Fig. A.5. Mass balance on the evaporator.

S8=S9+S10

The syrup content is taken as 65% sugars and 45% water (Grace). The remaining water that does not form part of the syrup is completely evaporated.

A.2 Energy Calculations

The latent heat of vaporization λ_v = 2257 kJ/kg

The latent heat of fusion, λ_f = 333 kJ/kg

Blender

5 min * 0.375 hp * 0.75 kJ/s*hp * 60 s/min = 84 kJ

CSTR

The CSTR energy balance was divided into 3 sections to describe the 3 separate reaction zones:

CSTR1 : Inlet Stream = S3 , T_{S3} = 25 °C
Outlet Stream = S3a , T_{S3a} = 85 °C

In CSTR1, the feed stream is heated to 85 °C for 30 minutes then held at that temperature for 3 hours.

CSTR2 : Inlet Stream = S3a , T_{S3a} = 85°C
Outlet Stream = S3b , T_{S3b} = 50 °C

In CSTR2, the stream is precooled to 50 °C for 30 minutes then held at that temperature for 3 hours.

CSTR3 : Inlet Stream = S3b , T_{S3b} = 50°C
Outlet Stream = S3c , T_{S3c} = 60 °C

After CSTR2, the stream is preheated to from 50 °C to 60 °C in a time period of 30 minutes. Once 60 °C has been reached, CSTR3 will be kept at this temperature for 24 hours.

CSTR1

Cp_{avg} = 4.0 kJ/kg*°C

ΔH_{rxn} = 126 kJ/mole of starch reacted

n = moles reacted = 14 g starch / 162(g/mol) = 0.09 moles reacted

$Q_1^{added} = M*Cp*(T_{S3a} - T_{S3}) + n * \Delta H_{rxn}$

Q_1^{added} = 0.9 kg * 4.0 kJ/kg*°C * (85 °C – 25 °C) + 0.09 moles * 126 kJ/mole

Q_1^{added} = 216 kJ + 11 kJ = 227 kJ

The majority of the total heat is due to the sensible heat of the water so

ΔH_{rxn} << sensible heat

CSTR2

$Q_2^{removed} = M*Cp*(T_{S3b} - T_{S3a})$

$Q_2^{removed}$ = 0.9 kg * 4.0 kJ/kg*°C * (50 °C – 85 °C) = 126 kJ

CSTR3

$Q_3^{added} = M*Cp*(T_{S3c} - T_{S3b})$

Q_3^{added} = 0.9 kg * 4.0 kJ/kg*°C * (60 °C – 50 °C) = 36 kJ

Filtration and Ionization – further clarification is needed for analysis

However, temperature information is as follows:

T_{S7} = 40 °C

T_{S8} = 25 °C

$Q_{S6} = M*Cp*(T_{S7} - T_{S6})$

Q_{S6} = 0.805 kg * 2.7 kJ/kg*°C * (40 °C – 60 °C) = -44 kJ

$Q_{S7} = M*Cp*(T_{S7} - T_{S8})$

Q_{S7} = 0.805kg * 2.7 kJ/kg*°C * (25 °C – 40 °C) = -33 kJ

Evaporator

Cp_{water} = 4.18 kJ/kg*°C

Cp_{syrup} = 2.7 kJ/kg*°C

For Stream S9

$Q_{S9}^{added} = M*(Cp*(T_{S9} - T_{S8}) + \lambda_v$

Q_{S9}^{added} = 0.781 kg * [4.18 kJ/kg*°C * (100 °C – 25 °C) + 2257 kJ/kg]

Q_{S9}^{added} = 244.84 kJ + 1762.72 kJ

Q_{S9}^{added} = 2007.56 kJ

For Stream S10

$Q_{S10}^{added} = M*Cp*(T_{S10} - T_{S8})$

Q_{S10}^{added} = 0.069 kg syrup * 2.7 kJ/kg*°C * (100 °C – 25 °C)

Q_{S10}^{added} = 13.97 kJ

The total Q^{added} for the evaporator system is the sum of the two heats in streams S9 & S10

Total $Q^{added} = Q_{evaporator}^{added} = Q_{S9}^{added} + Q_{S10}^{added}$ = 2021.53 kJ

It should be noted that the majority of the heat added is due to the latent heat of evaporation of water.

Condenser

Only water is being condensed, going from 100 °C to 25 °C. This value is equal to the heat required for evaporation in Stream S7

$Q_{condenser}^{removed}$ = 2007.56 kJ

A.3 Base Case Heat Integration

Energy Cascade ("Energy Wheel") Calculations
Heat added for heating dilute syrup from 25 °C to 80 °C

$Q_{HI,1}^{added}$ = 0.781 kg * 4.18 kJ/kg*°C * (80 °C – 25 °C) +

0.069 kg * 2.7 kJ/kg*°C * (80 °C – 25 °C)

$Q_{HI,1}^{added}$ = 189.65 kJ

Heat added for heating dilute syrup from 80 °C to 100 °C (includes sensible and latent heats)

$Q_{HI,2}^{added}$ = 0.781 kg * [4.18 kJ/kg*°C * (100 °C – 80 °C) + 2257 kJ/kg] +

0.069 kg * 2.7 kJ/kg*°C * (100 °C – 80 °C)

$Q_{HI,2}^{added}$ = 65.29 kJ + 1762.72 kJ + 3.73

$Q_{HI,2}^{added}$ = 1831.74 kJ

Amount of heat removed from water vapor at 100 °C

$Q_{HI,3}^{removed}$ = 0.825 * 4.18 kJ/kg*°C * (90 °C – 35 °C)

$Q_{HI,3}^{removed}$ = 189.65 kJ

Amount of heat necessary to condense remaining vapor (latent heat only)

Q_{HI} = 2007.56 kJ – 189.65 kJ = 1817.96 kJ

A.4 Freeze Crystallization

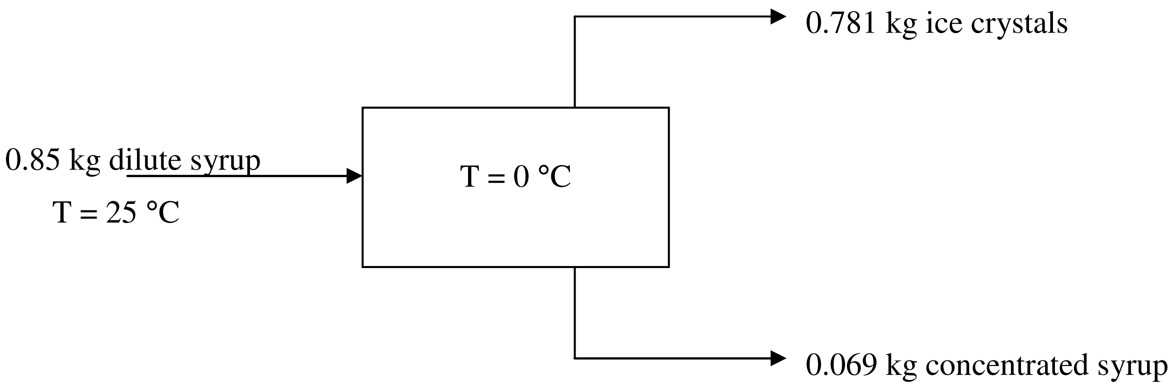

Fig. A.6. Mass balance on the freeze crystallizer.

$$Q_{FC}^{removed} = 0.781\ [4.18\ \text{kJ/kg*°C} * (25\ \text{°C} - 0\ \text{°C}) + 333\ \text{kJ/kg}]$$

$$+ 0.069\ \text{kg} * 2.7\ \text{kJ/kg*°C} * (25\ \text{°C} - 0\ \text{°C})$$

$$Q_{FC}^{removed} = 341.69\ \text{kJ} + 4.66 = 346.35\ \text{kJ}$$

A.5 Syrup ESM

Assumptions

1. The quantities of working materials in the system are not taken into account. In reality, the throughput of the system would be different at different configurations.

2. The equivalence factors obtained from the ALS Baseline Values and Assumptions Document (BVAD) (Hanford, 2002) are assumed to be applicable to the sub-system under study.

3. The individual components of equation 4.1 are assumed to be independent of each other.

4. The only difference accounted for between the ESM calculations for the different alternatives was in terms of heating and cooling requirements.

5. The same mass equivalence factor is assumed for all equipment.

6. The time required for one cycle of the batch process is 36 hours.

7. The individual equipment masses were assumed to be (kg)

Blender	0.648
CSTR	0.780
Centrifugal Filter	0.677
Vacuum Filter	0.528
De Ionization Column	0.600
Evaporator/Condenser	0.600

8. The individual equipment volumes were assumed to be (m^3)

Blender	.0010
CSTR	.0015
Centrifugal Filter	.0001
Vacuum Filter	.0001
De Ionization Column	.0006
Evaporator/Condenser	.0012

9. The power requirements for individual equipment were assumed to be (kWe)

Blender	0.28

CSTR	0.146
Centrifugal Filter	1
Vacuum Filter	0
De Ionization Column	0
Evaporator/Condenser	1.12

10. The cooling requirements for the individual equipment were assumed to be (kWth)

Blender	0
CSTR	0.07
Centrifugal Filter	0
Vacuum Filter	0
De Ionization Column	0
Evaporator/Condenser	1.12

11. The annual crew time associated with the operation of the individual equipment were assumed to be (CM-h)

Blender	2.025
CSTR	6.075
Centrifugal Filter	1.012
Vacuum Filter	1.012
De Ionization Column	1.012
Evaporator/Condenser	3.24

Calculations

1.) <u>BLENDER</u>

Mass

Assume the blender is composed of a hollow cylinder with a shell of thickness (T) and a diameter from the center to inner shell (D) (See Fig. A.7).

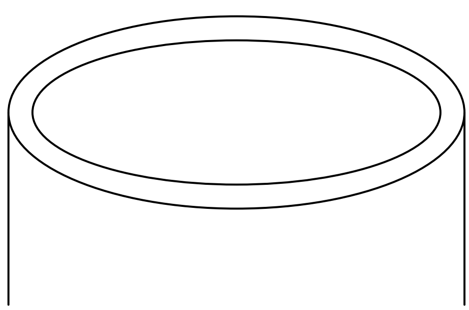

Fig. A.7. Depiction of the cylindrical shape used to calculate blender volume.

$$V_{blender} = \frac{\pi}{4}\left[(D+T)^2 - D^2\right]L$$

$$V_{blender} = \frac{\pi}{4}\left(2DT + T^2\right)L$$

$$V_w = \frac{\pi}{4}D^2 L$$

$$\frac{V_{blender}}{V_w} = \frac{2DT + T^2}{D^2}(assume T^2 negligible)$$

$$\frac{V_{blender}}{V_w} \approx \frac{2T}{D}$$

say T = 0.1D => $\frac{V_b}{V_w} = 0.2$ *(+ 10% for motor and other components)*

$$\frac{V_{blender}}{V_w} = 0.3 \, (with\ motor)$$

Mass and volume of water and sweetpotato going into blender

$$M_{water\&sweetpotato} = 900g$$

$$V_{water\&sweetpotato} \cong 900mL$$

$$\rho_{water\&sweetpotato} \approx \rho_{water} \approx 1\frac{g}{mL}$$

$V_{blender} = 0.3 * 900mL = 270mL = 0.27L$

(glass or Al): $\rho \approx 2.4$ *kg/lit*

$M_{blender} = 0.27L*2.4kg/lit$

$= 0.648kg$

$= 648g$

Volume

Assume the volume of the enclosure around the blender is slightly larger than the contents it must hold.

$$V_{support} = 1L$$

$$V_{eq} = 215\frac{kg}{m^3}$$

$$M_{v,blender} = V * V_{eq} = .215kg = 215g$$

Power

$$P_{blender} = 0.375hp * 0.746\frac{kW}{hp}$$

$$P_{blender} = 0.28kW$$

P_{eq}= 237kW

$$\alpha_{blender} = \frac{5\min}{36hr * 60\frac{\min}{hr}} = 0.0023$$

$$M_{p,blender} = \alpha_{blender} * P_{blender} * P_{eq} = 0.154kg = 154g$$

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{36\frac{hrs}{cycle}} = 243\frac{cycles}{yr}$$

Crewtime for blender per cycle =0.5 min/cycle

$$CT = Crewtime / year = \frac{243\frac{cycles}{yr} * 0.5\frac{\min}{cycle}}{60\frac{\min}{hr}} = 2.025\frac{CM - hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM - hr}$$

$D = 0.49\ yr$

$$\mathrm{M}_{\mathrm{CT,\ blender}} = CT * D * CT_{eq} = 2.0\frac{CM - hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM - hr} = 1.13kg$$

ESM_1=$ESM_{blender}$= $M_{blender}$+$M_{v,blender}$+$M_{p,blender}$+$M_{c,blender}$+$M_{CT,blender}$

ESM_1=$ESM_{blender}$= 648g+215g+154g+0g+1130g=2147g=2.147kg

2.) <u>CSTR</u>

Mass *(perform calculations similar to that for a blender except for a 1.3L cylindrical Pyrex jar with a submerged propeller stirrer)*

$$V_{cstr} = \frac{\pi}{4}\left[(D+T)^2 - D^2\right]L$$

$$V_{cstr} = \frac{\pi}{4}\left(2DT + T^2\right)L$$

$$V_w = \frac{\pi}{4}D^2 L$$

$$\frac{V_{cstr}}{V_w} = \frac{2DT + T^2}{D^2} (assume T^2 negligible)$$

$$\frac{V_{cstr}}{V_w} \approx \frac{2T}{D}$$

say T = 0.1D => $\frac{V_{cstr}}{V_w} = 0.2$ *(no motor but add 5% for stirrer)*

$\frac{V_{cstr}}{V_w} = 0.25$ *(with stirrer)*

V_w=0.9L (rxn mixture)+0.4L (excess)=1.3L

V_{cstr} = 0.25 1300mL =325mL =0.325L*

(glass or Al): ρ ≈ 2.4 kg/L

*M_{cstr} = 0.325L*2.4kg/L*

= 0.780kg

= 780g

Volume

$$V_{\sup port} = 1.5L$$

$$V_{eq} = 215\frac{kg}{m^3}$$

$$M_{v,cstr} = V * V_{eq} = .323g = 323g$$

Power

The same CSTR was used for 3 processes. Process 1 and 3 involve power usage.

Q_{CSTR1} 227kJ

Q_{CSTR3} 36kJ

$$Q_{cstr1} = \frac{227kJ}{30\min * 60\frac{s}{\min}} = 0.126kW$$

$$Q_{cstr3} = \frac{36kJ}{30\min * 60\frac{s}{\min}} = 0.020kW$$

$$P_{eq} = 237\frac{kg}{kW}$$

$$\alpha_{cstr} = \frac{30\min}{36hr*60\frac{\min}{hr}} =.0139$$

$$\alpha_{cstr1}*P*P_{eq} = 0.0139*0.126*237 = 0.415kg = 415g$$

$$\alpha_{cstr2}*P*P_{eq} = 0.0139*0.02*237 = 0.066kg = 66g$$

$$M_{p,cstr} = 415g + 66g = 481g$$

Cooling

$$C_{eq} = 60\frac{kg}{kW_{th}}$$

$$C_{cstr3} = \frac{126kW}{30\min*60\frac{s}{\min}} = 0.07kW$$

$$M_{c,cstr} = \alpha_{cstr}*C_{cstr3}*C_{eq} = 0.0139*0.07*60 = 0.058kg = 58g$$

Crew Time

$$\textit{Number of cycles per year} = \frac{365\frac{days}{yr}*24\frac{hrs}{day}}{36\frac{hrs}{cycle}} = 243\frac{cycles}{yr}$$

$$\textit{Crewtime for CSTR per cycle} = \frac{30\min*1month*1day*36hrs}{month*30days*24hrs*1cycle} = 1.5\frac{\min}{cycle}$$

C = Crewtime per yr

$$CT_{cstr} = Crewtime/year = \frac{243\frac{cycles}{yr}*1.5\frac{\min}{cycle}}{60\frac{\min}{h}} = 6.075\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$$\mathrm{M}_{\mathrm{CT,\,cstr}} = CT_{cstr}*D*CT_{eq} = 6.075\frac{CM-hr}{yr}*0.49yr*1.14\frac{kg}{CM-hr} = 3.39kg = 3390g$$

$ESM_2 = ESM_{cstr} = M_{cstr*}M_{v,cstr}*M_{p,cstr}*M_{c,cstr*}M_{CT,cstr}$

$ESM_2 = ESM_{cstr} = 780g + 323g + 481g + 58g + 3390g = 5032g = 5.032kg$

3.) <u>CENTRIFUGAL FILTER</u>

Mass *(perform calculations similar to that for a blender)*

$$V_{centi} = \frac{\pi}{12}\left[(D+T)^2 - D^2\right]L$$

$$V_{cent} = \frac{\pi}{12}\left(2DT + T^2\right)L$$

$$V_w = \frac{\pi}{12}D^2 L$$

$$\frac{V_{centi}}{V_w} = \frac{2DT + T^2}{D^2}(assume T^2 negligible)$$

$$\frac{V_{centi}}{V_w} \approx \frac{2T}{D}$$

say T = 0.1D => $\frac{V_{centi}}{V_w} = 0.2$ *(add 10% for filter paper and motor)*

$$\frac{V_{centi}}{V_w} = 0.30 \text{ (with motor)}$$

$$M_{mixture} = 940g$$

$$\rho_{mixture} \approx \rho_{water} \approx 1\frac{g}{mL}$$

$$V_{mixture} = 940mL$$

Assume volume of the evaporator is 1L

V_{centi} = 0.25 940mL =282mL =0.282L*
(glass or Al): $\rho \approx$ 2.4 kg/lit
*M_{centi} = 0.282L*2.4kg/lit*
= 0.677kg
= 677g

Volume

100mL fed to filter in intervals every 10min until 940mL are fed

$$V = 100mL = 0.1L = 1.0x10^{-4} m^3$$

$$V_{eq} = 215\frac{k}{m^3}$$

$$M_{v,centi} = V * V_{eq} = 0.0215kg = 21.5g$$

Power

None

$$M_{P,centi} = \alpha_{cemti} * P * P_{eq} = 0kg = 0g$$

Cooling

None

Crew Time

$$\text{Number of cycles per year} = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{36\frac{hrs}{cycle}} = 243\frac{cycles}{yr}$$

$$\text{Crewtime for evaporator per cycle} = \frac{10\min * 1month * 1day * 36hrs}{month * 30days * 24hrs * 1cycle} = 0.5\frac{\min}{cycle}$$

$$CT_{centi} = Crewtime / year = \frac{243\frac{cycles}{yr} * 0.5\frac{\min}{cycle}}{60\frac{\min}{h}} = 1.012\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

$D = 0.49\ yr$

$$M_{CT,centi} = CT_{centi} * D * CT_{eq} = 1.012\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 0.566g = 566g$$

$ESM_3 = ESM_{centi} = M_{centi} * M_{v,centi} * M_{p,centi} * M_{c,centi} * M_{CT,centi}$

$ESM_3 = ESM_{centi} = 677g + 21.5g + 0g + 0g + 566g = 1264.5g = 1.26kg$

4.) <u>VACUUM FILTER</u>

Mass *(perform calculations similar to that for a blender)*

$$V_{filter} = \frac{\pi}{4}\left[(D+T)^2 - D^2\right]L$$

$$V_{filter} = \frac{\pi}{4}\left(2DT + T^2\right)L$$

$$V_w = \frac{\pi}{4}D^2 L$$

$$\frac{V_{filter}}{V_w} = \frac{2DT + T^2}{D^2} (assume T^2 negligible)$$

$$\frac{V_{filter}}{V_w} \approx \frac{2T}{D}$$

say T = 0.1D => $\frac{V_{filter}}{V_w} = 0.2$ *(add 2% for filter paper)*

$$\frac{V_{filter}}{V_w} = 0.22 \textit{ (with paper)}$$

$$M_{mixture} = 940g$$

$$\rho_{mixture} \approx \rho_{water} \approx 1\frac{g}{mL}$$

$$V_{mixture} = 940mL$$

Assume volume of the evaporator is 1L

V_{filter} = 0.22 1000mL =220mL =0.22L*

(glass or Al): ρ ≈ 2.4 kg/lit

*M_{filter} = 0.2L*2.4kg/lit*

= 0.528kg

= 528g

Volume

100mL fed to filter in intervals every 10min until 940mL are fed

$$V = 0.1L = 1.0x104m^3$$

$$V_{eq} = 215\frac{kg}{m^3}$$

$$M_{v,filter} = V * V_{eq} = 0.0215kg = 21.5g$$

Power

None

$$M_{P,filter} = \alpha_{filter} * P * P_{eq} = 0kg = 0g$$

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{36\frac{hrs}{cycle}} = 243\frac{cycles}{yr}$$

$$Crewtime\ for\ evaporator\ per\ cycle = \frac{10\min * 1month * 1day * 36hrs}{month * 30days * 24hrs * 1cycle} = 0.5\frac{\min}{cycle}$$

$$CT_{filter} = Crewtime / year = \frac{243\frac{cycles}{yr} * 0.5\frac{\min}{cycle}}{60\frac{\min}{h}} = 1.012\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

$D = 0.49\ yr$

$$M_{CT,filter} = CT_{filter} * D * CT_{eq} = 1.012\frac{CM-hr}{yr} * 0.49yr * 1.14\frac{kg}{CM-hr} = 0.566g = 566g$$

$ESM_4 = ESM_{filter} = M_{filter} * M_{v,filter} * M_{p,filter} * M_{c,filter} * M_{CT,filter}$

$ESM_4 = ESM_{filter} = 528g + 21.5g + 0g + 0g + 566g = 1115.5g = 1.12kg$

5.) <u>DEIONIZATION COLUMN</u>

Mass

$$V_{deion} = \frac{\pi}{4} D^2 L$$

$$D = 6cm$$

$$L = 22cm$$

$$V_{deion} = \frac{\pi}{4}\left(\frac{6cm * 1m}{100cm}\right)^2 L$$

$$V_{deion} = 0.000622m^3 = 0.6L$$

V_{deion} = 0.25 1000mL =250mL =0.25L*
(glass or Al): ρ ≈ 2.4 kg/lit
*M_{deion} = 0.25L*2.4kg/lit*
= 0.6kg
= 600g

Volume

$$V_{deion} = \frac{\pi}{4} D^2 L$$

$$D = 6cm$$

$$L = 22cm$$

$$V_{deion} = \frac{\pi}{4}\left(\frac{6cm * 1m}{100cm}\right)^2 L$$

$$V_{deion} = 0.000622m^3 = 0.6L$$

$$V_{eq} = 215\frac{kg}{m^3}$$

$$M_{v,deion} = V * V_{eq} = 0.0006m^3 * 215\frac{kg}{m^3} = 0.129kg = 129g$$

Power

None

$$M_{P,deion} = \alpha_{deion} * P * P_{eq} = 0kg = 0g$$

Cooling

None

Crew Time

$$\textit{Number of cycles per year} = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{36\frac{hrs}{cycle}} = 243\frac{cycles}{yr}$$

$$Crewtime\ for\ evaporator\ per\ cycle = \frac{10\min * 1month * 1day * 36hrs}{month * 30days * 24hrs * 1cycle} = 0.5\frac{\min}{cycle}$$

$$CT_{deion} = Crewtime / year = \frac{243\frac{cycles}{yr} * 0.5\frac{\min}{cycle}}{60\frac{\min}{h}} = 1.012\frac{CM - hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM - hr}$$

$D = 0.49\ yr$

$$M_{CT,deion} = CT_{deion} * D * CT_{eq} = 1.012\frac{CM - hr}{yr} * 0.49yr * 1.14\frac{kg}{CM - hr} = 0.566g = 566g$$

$ESM_5 = ESM_{deion} = M_{deion} * M_{v,deion} * M_{p,deion} * M_{c,deion} * M_{CT,deion}$

$ESM_5 = ESM_{deion} = 600g + 129g + 0g + 0g + 566g = 1295g = 1.30kg$

6.) <u>EVAPORATION/CONDENSATION</u>

<u>EVAPORATION</u>

Mass *(perform calculations similar to that for a blender)*

$$V_{evap} = \frac{\pi}{4}\left[(D+T)^2 - D^2\right]L$$

$$V_{evap} = \frac{\pi}{4}\left(2DT + T^2\right)L$$

$$V_w = \frac{\pi}{4}D^2 L$$

$$\frac{V_{evap}}{V_w} = \frac{2DT+T^2}{D^2} (assume T^2 negligible)$$

$$\frac{V_{evap}}{V_w} \approx \frac{2T}{D}$$

say T = 0.1D => $\frac{V_{evap}}{V_w} = 0.2$ *(add 5% for heat coil)*

$\frac{V_{evap}}{V_w} = 0.25$ *(with coil)*

$$M_{mixture} = 850g$$

$$\rho_{mixture} \approx \rho_{water} \approx 1\frac{g}{mL}$$

$$V_{mixture} = 850mL$$

Assume volume of the evaporator is 1L

V_{evap} *= 0.25* 1000mL =250mL =0.25L*

(glass or Al): $\rho \approx$ *2.4 kg/lit*

M_{evap} *= 0.25L*2.4kg/lit*

= 0.6kg

= 600g

Volume

$$V = 1.2L = 1.2x10^{-3}m^3$$

$$V_{eq} = 215\frac{kg}{m^3}$$

$$M_{v,evap} = V * V_{eq} = 0.258kg = 258g$$

Power

2021.53kJ

$$Q = 2021.53kJ$$

$$P = \frac{2021.53kJ}{30\min * 60\frac{s}{\min}} = 1.12kW$$

$$P_{eq} = 237\frac{kg}{kW}$$

$$\alpha_{evap} = \frac{30\min}{36hr * 60\frac{\min}{hr}} = 0.0139$$

$$M_{P,evap} = \alpha_{evap} * P * P_{eq} = 3.69kg = 3690g$$

Cooling

None

Crew Time

$$\text{Number of cycles per year} = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{36\frac{hrs}{cycle}} = 243\frac{cycles}{yr}$$

$$\text{Crewtime for evaporator per cycle} = \frac{10\min * 1month * 1day * 36hrs}{month * 30days * 24hrs * 1cycle} = 0.5\frac{\min}{cycle}$$

$$CT_{evap} = Crewtime / year = \frac{243\frac{cycles}{yr} * 0.5\frac{\min}{cycle}}{60\frac{\min}{h}} = 2.025\frac{CM - hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM - hr}$$

$$D = 0.49\ yr$$

$$M_{CT,evap} = CT_{evap} * D * CT_{eq} = 2.025\frac{CM - hr}{yr} * 0.49yr * 1.14\frac{kg}{CM - hr} = 1.13kg = 1130g$$

CONDENSATION

Mass (same as for evaporator)

$M_{cond}=M_{evap} = 0.6kg= 600g$

Volume (same as for evaporator)

$$V = 1.2L = 1.2x10^{-3} m^3$$

$$V_{eq} = 215\frac{kg}{m^3}$$

$$M_{v,cond} = V * V_{eq} = 0.258kg = 258g$$

Power

None

Cooling

$Q=2007.56kJ$

$$C_{cond} = \frac{2007.56kJ}{30\min * 60\frac{s}{\min}} = 1.12kW$$

$$C_{eq} = 60\frac{kg}{kW}$$

$$\alpha_{cond} = \frac{30\min * 1.12kW}{36hr * 60\frac{\min}{hr} * 1.12kW} =.0139$$

$$M_{c,cond} = \alpha_{cond} * C_{cond} * C_{eq} = 0.0139 * 1.12 * 60 = 0.934kg$$

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{36\frac{hrs}{cycle}} = 243\frac{cycles}{yr}$$

$$Crewtime\ for\ blender\ per\ cycle = \frac{6\min * 1month * 1day * 36hrs}{month * 30days * 24hrs * 1cycle} = 0.3\frac{\min}{cycle}$$

$$CT_{cond} = Crewtime / year = \frac{243\frac{cycles}{yr} * 0.3\frac{\min}{cycle}}{60\frac{\min}{hr}} = 1.215\frac{CM - hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM - hr}$$

$D = 0.49\ yr$

$$M_{CT,cond} = CT_{cond} * D * CT_{eq} = 1.215\frac{CM - hr}{yr} * 0.49yr * 1.14\frac{kg}{CM - hr} = 0.679kg = 1697g$$

Evaporation and condensation are performed by the same piece of equipment.

$ESM_6=ESM_{evap\&cond}= M_{evap\ (OR\ cond)}+M_{v,evap\ (OR\ cond)}+M_{p,evap}+M_{c,cond}+M_{CT,evap}+M_{CT,cond}$

$ESM_6=ESM_{evap\&cond}= 600g+258g+3690g+934g+1130g+679g=7291g=7.291kg$

7.) FREEZECONDENSATION

Mass (calculations similar to those for evaporator)

$$V_{freeze} = \frac{\pi}{4}\left[(D+T)^2 - D^2\right]L$$

$$V_{freeze} = \frac{\pi}{4}\left(2DT + T^2\right)L$$

$$V_w = \frac{\pi}{4}D^2 L$$

$$\frac{V_{freeze}}{V_w} = \frac{2DT + T^2}{D^2} (assume T^2 negligible)$$

$$\frac{V_{freeze}}{V_w} \approx \frac{2T}{D}$$

say T = 0.1D => $\frac{V_{freeze}}{V_w} = 0.2$ *(add 5% refrigerant)*

$$\frac{V_{freeze}}{V_w} = 0.25 \text{ (with coil)}$$

$$M_{mixture} = 850g$$

$$\rho_{mixture} \approx \rho_{water} \approx 1\frac{g}{mL}$$

$$V_{mixture} = 850mL$$

Assume volume of the evaporator is 1L

V_{freeze} *= 0.25* 1000mL =250mL =0.25L*

(glass or Al): $\rho \approx$ *2.4 kg/lit*

M_{freeze} *= 0.25L*2.4kg/lit*

= 0.6kg

= 600g

Volume

$$V_{freeze} = 1.2L = 1.2x10^{-3}m^3$$

$$V_{eq} = 215\frac{kg}{m^3}$$

$$M_{c,freeze} = V_{freeze} * V_{eq} = 0.258kg = 258g$$

Power

None

Cooling

Q=346kJ

$$C_{freeze} = \frac{346kJ}{120\min * 60\frac{s}{\min}} = 0.0481kW$$

$$C_{eq} = 60\frac{kg}{kW}$$

$$\alpha_{freeze} = \frac{120\min * 1.12kW}{36hr * 60\frac{\min}{hr} * 1.12kW} = 0.056$$

$$M_{c,freeze} = \alpha_{freeze} * C_{freeze} * C_{eq} = 0.056 * 0.0481 * 60 = 0.164kg = 164g$$

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{36\frac{hrs}{cycle}} = 243\frac{cycles}{yr}$$

$$Crewtime\ for\ blender\ per\ cycle = \frac{10\min * 1month * 1day * 36hrs}{month * 30days * 24hrs * 1cycle} = 0.5\frac{\min}{cycle}$$

$$CT_{freeze} = Crewtime / year = \frac{243\frac{cycles}{yr} * 0.5\frac{\min}{cycle}}{60\frac{\min}{h}} = 2.025\frac{CM - hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM - hr}$$

$D = 0.49\ yr$

$$M_{CT,freeze} = CT_{freeze} * D * CT_{eq} = 2.025\frac{CM - hr}{yr} * 0.49yr * 1.14\frac{kg}{CM - hr} = 1.13kg = 1130g$$

$ESM_7 = ESM_{freeze} = M_{freeze} + M_{v,freeze} + M_{p,freeze} + M_{c,freze} + M_{CT,freeze}$

$ESM_7 = ESM_{freeze} = 600g + 258g + 0g + 164g + 1130g = 2152g = 2.152kg$

8.) HEAT INTEGRATED EVAPORATION
Thermal Storage ESM

Mass of Cylinder

$$V_{TS} = \frac{\pi}{4}\left[(D+T)^2 - D^2\right]L$$

$$V_{TS} = \frac{\pi}{4}\left(2DT + T^2\right)L$$

$$V_w = \frac{\pi}{4}D^2 L$$

$$\frac{V_{TS}}{V_w} = \frac{2DT + T^2}{D^2}(assume T^2 negligible)$$

$$\frac{V_{TS}}{V_w} \approx \frac{2T}{D}$$

say T = 0.1D => $\frac{V_b}{V_w} = 0.2$

Mass and volume of water going into Thermal Storage

$$M_{water} = 825g$$

$$V_{water} \cong 825mL$$

$$\rho_{water} \approx 1\frac{g}{mL}$$

*V = 0.2 * 825mL =165mL =0.165L*
(glass or aluminum): $\rho \approx$ *2.4 kg/lit*
M_{TS} *= 0.165L*2.4kg/lit*
= 0.396kg
= 396g

Volume

$$V_{\sup port} = 1L$$

$$V_{eq} = 215\frac{kg}{m^3}$$

$$M_{v,TS} = V * V_{eq} = .215kg = 215g$$

Power (only for pump, there is no heating term)

P_{pump}*=0.105 kW*
P_{eq}*= 237kW*

$$\alpha_{TSpump} = \frac{30\min}{36hr * 60\frac{\min}{hr}} = 0.014$$

$$M_{p,pump} = \alpha_{pump} * P_{pump} * P_{eq} = 0.348kg = 348g$$

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{36\frac{hrs}{cycle}} = 243\frac{cycles}{yr}$$

Crewtime for blender per cycle =0.5 min/cycle

$$CT = Crewtime/year = \frac{243\frac{cycles}{yr} * 0.5\frac{\min}{cycle}}{60\frac{\min}{hr}} = 2.025\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$$CT * D * CT_{eq} = 2.0\frac{CM-hr}{yr} * 0.49yr * 1.14\frac{kg}{CM-hr} = 1.13kg$$

$$ESM_{TS} = M_{TS} + M_{v,TS} + M_{p,pump} + M_{c,TS} + M_{CT,TS}$$

$$ESM_{TS} = 396g + 215g + 348g + 0g + 1130g = 2089g = 2.089kg$$

The power and cooling values in the original evaporation and condensation ESM values will decrease as a result of the cooling and heating supplied by the thermal storage unit. Thus, a new ESM for the evaporation and condensation will be calculated to capture the impact.

Evaporation

Power

2021.53kJ – 189.65 kJ = 1831.88 kJ

$$Q = 1831.88kJ$$

$$P = \frac{1831.88kJ}{30\min * 60\frac{s}{\min}} = 1.02kW$$

$$P_{eq} = 237\frac{kg}{kW}$$

$$\alpha_{evap} = \frac{30\min}{36hr * 60\frac{\min}{hr}} = 0.0139$$

$$M_{P,evap} = \alpha_{evap} * P * P_{eq} = 3.36kg = 3360g$$

Condensation

Cooling

Q=2007.56kJ – 189.65kJ = 1817.91 kJ

$$C_{cond} = \frac{1817.91kJ}{30\min * 60\frac{s}{\min}} = 1.01kW$$

$$C_{eq} = 60\frac{kg}{kW}$$

$$\alpha_{cond} = \frac{30\min * 1.01kW}{36hr * 60\frac{\min}{hr} * 1.01kW} =.0139$$

$$M_{c,cond} = \alpha_{cond} * C_{cond} * C_{eq} = 0.0139 * 1.01 * 60 = 0.842kg$$

$$ESM_{evap\&cond} = M_{evap\ (OR\ cond)} + M_{v,evap\ (OR\ cond)} + M_{p,evap} + M_{c,cond} + M_{CT,evap} + M_{CT,cond}$$

$$ESM_{evap\&cond} = 600g+258g+3360g+842g+1130g+679g=6869g=6.869\ kg$$

The original $ESM_{evap\&cond}$ was 7.291 kg, which is higher than the new $ESM_{evap\&cond}$ calculated above. It would appear that since the new $ESM_{evap\&cond}$ value is lower, that this would indeed be a more attractive opportunity. However, we must now include the ESM for the thermal storage system. Thus, with all other values remaining unchanged (ESM's for the blender, CSTR's, etc), the impact of the thermal storage will be as follows

(a) ESM_{others} + $ESM_{evap\&cond}$ = 7.291 kg

(b) ESM_{others} + $ESM_{evap\&cond}$ + ESM_{TS} = ESM_{others} + 6869g + 3360g = 10229g = 10.23kg

Subtracting (a) from (b), we obtain a delta of +2.939, showing that our overall ESM has increased, which is not an improvement over the original case and thus, is not an attractive option.

<u>TOTAL ESM</u>

Base Case

$$ESM_{BC} = \sum_{i=1}^{6} ESM_i = ESM_1+ESM_2+ESM_3+ESM_4+ESM_5+ESM_6$$

$$ESM_{BC} = (2.147+5.032+1.26+1.12+1.30+7.29)kg=18.15kg$$

Freeze Concentration

$$ESM_{FC} = \sum_{i=1}^{5} ESM_i + ESM_7 = (2.147+5.032+1.26+1.12+1.30)kg+2.152kg$$

$$=10.859kg+2.152kg=13.011kg=13.01kg$$

Heat Integrated Evaporation

$$ESM_{HI} = \sum_{i=1}^{5} ESM_i + ESM_{TS} = 10.859kg+10.23kg=21.089kg$$

Summary and Observations

The values of ESM for different alternatives are tabulated in Table A.1.

Table A.1
ESM for different syrup technology alternatives

Summary of calculations		
Configuration #	**Description**	**ESM (kg)**
0	Base Case	18.2
1	Heat Integrated Evaporation	20.2
2	Freeze Concentration	13.3

Observations:

1. Although in heat integration has the potential to reduce energy requirement, in terms of ESM the cost of adding thermal storage equipment reduces the potential benefits of heat integration. Freeze concentration
2. Freeze concentration has lower cost that the base case in terms of ESM.
3. The greatest penalty in terms of ESM is that of crew-time.
4. Automation of the entire system or at least portions of the system would greatly reduce crew-time costs.

APPENDIX B : FLOUR PRODUCTION CALCULATIONS

Appendix B contains sample calculations for the flour production technology. Section B.1 contains material balance calculations for the forward direction while section B.2 contains material balance calculations for the reverse direction. The material balances were calculated utilizing data provided from Tuskegee University on February 14, 2006. Section B.3 contains base case flour production ESM calculations while section B.4 contains ESM calculations for alternatives to the base case configuration.

B.1 Material Balance Calculations (Forward Direction)

Table B.1
Primary input for flour production (forward)

Flour Production		
Primary Input	**Symbol**	**Value**
Unpeeled Sweetpotato	F0	5000

Table B.2
Secondary inputs for flour production

Flour Production			
Secondary Inputs (Flour)	**Symbol**	**Default Value for this case**	**Default value**
Moisture Content in F1a	M0	0.7696	0.7
Starch Content in F1 and F2	St	0.1176	0.14
Carbohydrate Content in F1 and F2	Ca	0.0588	0.07
Sugar Content in F1 and F2	Su	0.0336	0.04
Other substances contained in F1 and F2	Ot	0.0204	0.05
Ratio of streams F1a/ F0	α	0.9058	0.9058
Ratio of streams F2a/F1a	β	0.9901	0.9901
Ratio of peels to unpeeled FP	Pl	0.0921	0.0921
Fraction of dehydrated SP obtained F4a/F4total	δ	0.9058	0.9058
Blender Output ratio F5a/F4a	ε	0.9901	0.9901
Ratio of flour obtained to dehydrator output F6a:F4a	ζ	0.0921	0.0921
Split ratio F5b:F6b	η	0.9058	0.9058
Ratio of unsifted flour to total flour	υ	0.047229156	0.047229156
Moisture Content in F4-F7	γ	0.0212	0.029
Carbohydrate Content in F4-F7	ca4	0.9141	0.907
Protein Content in F4-F7	P	0.0081	0.008
Fat Content in F4-F7	F	0.0091	0.009
Ash Content in F4-F7	A	0.0476	0.047
multiple of default primary input (user input/default input)	N	1	1
Detergent amount per 5000g input	D	1.7	1.7
water amount per 5000g input (for clean up 1)	w1	12	12
water amount per 5000g input (for clean up 2)	w2	12.4	12.4

Flour Production

Assumption: Moisture content in F0, F1a and F2a&b is the same.

1.) Peel

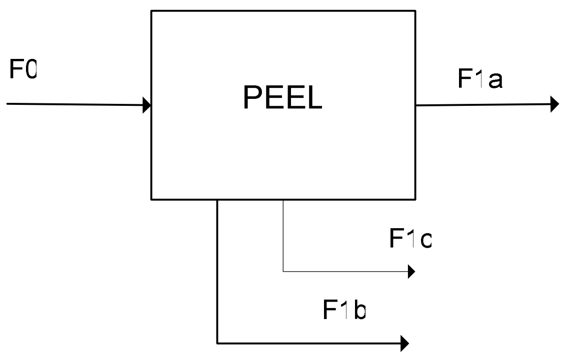

Fig. B.1. Mass balance for peeling process.

Overall Balance

F0 = F1a + F1b +F1c

i.) F0 = raw unpeeled SP

ii.) F1a = α * F0; α = 4529/5000

F1b = peels pl = 460.3/5000

F1c = other losses

F1b + F1c = total losses

F0 = F1a + (F1b + F1c)

F1b + F1c = (1-α)F0 = F0-F1a

iii.) F1b = pl * F0

iv.) F1c = F0 – F1a – F1b

2.) Shred

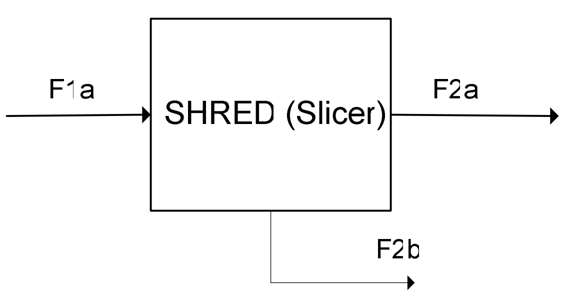

Fig. B.2. Mass balance for shredding process.

Overall Balance
F1a = F2a +F2b
i.) F2a = β * F1a; β = 4484.3/4529
ii.) F2b = (1-β)F1a = F1a-F2a

3.) Dehydrate

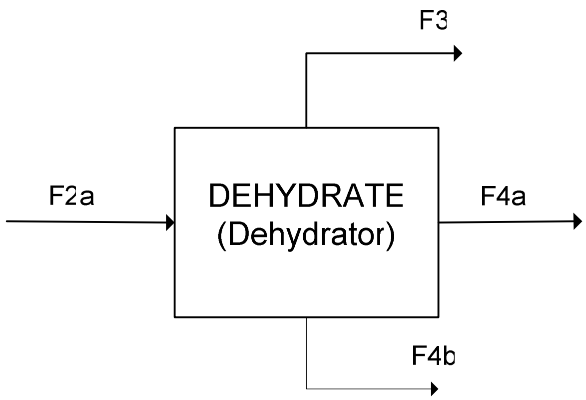

Fig. B.3. Mass balance for dehydration process.

Overall Balance
F2a = F3 + F4a + F4b
Water in F2a = β * M0 * F1a = M0 * F2a
Percent Moisture in F4a = γ; γ = 0.029
δ = fraction of dehydrated SP obtained in dehydration
δ = F4a/(F4a+F4b); δ = 1033/1055.4
Note-need to obtain F4a+F4b below in order to obtain δ
Fractional loss = (1-δ)
(1-δ) = F4b/(F4a+F4b)
(1-δ)F4b + (1-δ)F4a = F4b
F4b= (1-δ)F4a/ (1-(1-δ))
Dry Bone
(F4a+F4b) (1-γ) = (1-M0) F2a
i.) (F4a+F4b) = (1-M0)F2a/(1-γ)
Water Balance
γ(F4a+F4b) + F3 = β * M0 * F1a
ii.) F3 = (β * M0 * F1a) - γ(F4a+F4b)
iii.) F4b = (1-δ)(F4a+F4b)
iv.) F4a = (F4a + F4b) – F4b
If γ differs from above default value, then use data and γ = M0 * F2a – F3/(F4a+F4b)

4.) Pre-mill

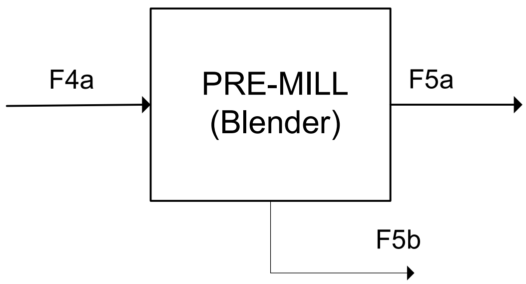

Fig. B.4. Mass balance for the pre-milling process.

Overall Balance
F4a = F5a +F5b
Assumption: F5a and F5b have the same moisture content as F4a

5.) Mill

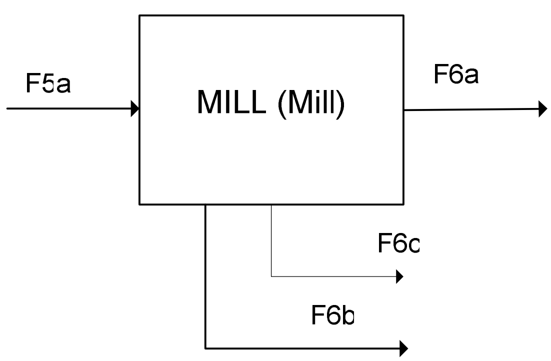

Fig. B.5. Mass balance for the milling process.

Overall Balance
F5a = F6a + F6b + F6c
Must use 4.) and 5.) together to solve for variables in 4.) and 5.)
Flour obtained to dehydrator output ζ = F6a/F4a; ζ = 954.3/1033
i.) F6a = F4a * ζ
υ = F6c/(F6a+F6c) υ = 47.3/1001.5
ii.) F6c = υ F6a/(1- υ)
F5a = F6a + F6b + F6c

F5a = F4a – F5b
F4a – F5b = F6a + F6b + F6c
F4a – F6a = F5b +F6b + F6c
Split ratio- η = F5b/F6b; η = 5/26.5 = 0.1887
F4a – F4a * ζ = ηF6b + F6b + F6c
F4a – F4a * ζ = (η + 1)F6b + F6c
iii.) F6b = ((F4a – F4a * ζ) – F6c) / (η + 1)
iv.) F5a = F6a + F6b + F6c
v.) F5b = F4a – F6a – F6b – F6c

6.) Package

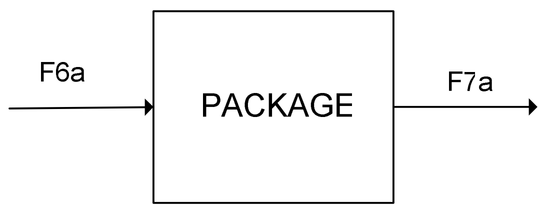

Fig. B.6. Mass balance for the packaging process.

Overall Balance
F6a =F7a

7.) Clean Up 1

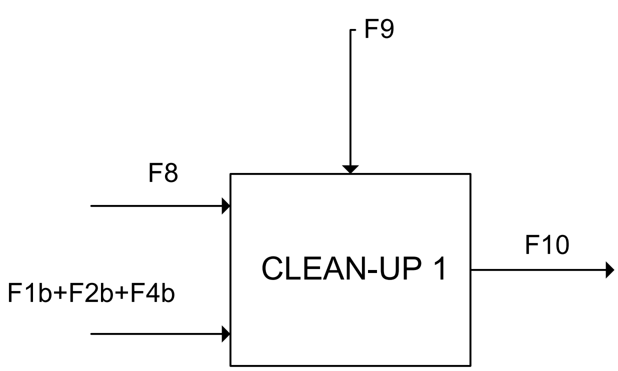

Fig. B.7. Mass balance for the first clean up process.

Overall Balance
F10 = F8 + F9 + F1b + F2b + F4b
F8 = n * d n = 5000/5000=1
F9 = n * w1 w1 = 12.0
F10 = n (d + w1)
d = 1.7

8.) Clean Up 2

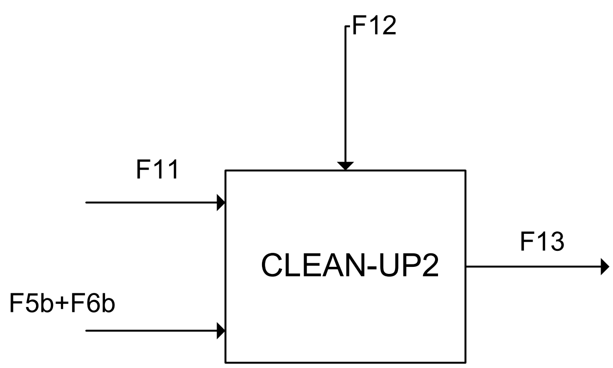

Fig. B.8. Mass balance for the second clean up process.

Overall Balance
F13 = F11 + F12 + F5b + F6b
F11 = n * d
F12 = n * w2 w2 = 12.4
F13 = n (d + w2)

<u>Secondary Inputs</u>
M0 = total losses from dehydrator/input to dehydrator = 3451.3/4484.3 = 0.7696
st = Starch content in F1 = (0.7/ M0) * 0.14 – (M0 – 0.7) * 0.14
ca = Carb. content in F1 = (0.7/ M0) * 0.07 – (M0 – 0.7) * 0.07
su = Sugar content in F1 = (0.7/ M0) * 0.04 – (M0 – 0.7) * 0.08
ot = Other substances inF1 = 1 – st – ca – su
γ = moisture content in F4-F7 = Equation in 4.) above
ca4 = carbohydrate content in F4- F7 = 0.907 + (0.029 - γ) * 0.907
p = protein content in F4- F7 = 0.008 + (0.029 - γ) * 0.008
f = fat content in F4- F7 = 0.009 + (0.029 - γ) * 0.009

a = ash content in F4- F7 = 1- γ - ca4 – p – f

B.2 Material Balance Calculations (Backward Direction)

Table B.3
Primary input for flour production (reverse)

Flour Production		
Primary Input	**Symbol**	**Value**
Flour Produced	F7a	954.3

The secondary input for flour production for the calculations in the reverse direction are the same as for the calculation in the forward direction (see Table B.2).

Flour Production

9.) Package (See Fig. B.6)

Overall Balance

F6a =F7a

10.) Mill (See Fig. B.5)

Overall Balance

F5a = F6a + F6b + F6c

Must use 2.) and 3.) together to solve for variables in 2.) and 3.)

Flour obtained to dehydrator output ζ = F6a/F4a; ζ = 954.3/1033

i.) υ = F6c/(F6a+F6c) υ = 47.3/1001.5

ii.) F6c = υ F6a/(1- υ)

iii.) (F6a + F6c) = F6c/ υ

iv.) (F5a-F6b) = (F6a + F6c)

11.) Pre-mill (See Fig. B.4)

Overall Balance

F4a = F5a +F5b

i.) F6a = F4a * ζ → so F4a = F6a/ζ

Split ratio- η = F5b/F6b → F6b = F5b/η η = 5/26.5 = 0.1887

Use 2.iv.) with 3.i.) and split ratio to solve for F5b

(F5a –F6b) = (F6a + F6c)

(F5a – F5b/η) = (F6a + F6c)

From overall balance, F5a = (F4a – F5b), so the above equation becomes:

[(F4a – F5b) - F5b/η] = (F6a + F6c)

F4a - (F6a + F6c) = F5b + F5b/η

F4a - (F6a + F6c) = F5b (1 + 1/η)

ii.) F5b = [F4a - (F6a + F6c)]/(1 + 1/η)

from split ratio:

iii.) F6b = F5b/η

iv.) F5a = F4a –F5b

Assumption: F5a and F5b have the same moisture content as F4a

12.) Dehydrate (See Fig. B.3)

Overall Balance

F2a = F3 + F4a + F4b

Water Balance

γ(F4a+F4b) + F3 = M0 * F2a

Water in F2a = M0 * F2a

Percent Moisture in F4a = γ; $\gamma = 0.029$

δ = fraction of dehydrated SP obtained in dehydration

δ = F4a/(F4a+F4b); $\delta = 1033/1055.4$

Note-need to obtain (F4a+F4b) below in order to obtain δ

i.) (F4a+F4b) = F4a/δ

Use overall balance and water balance to find:

F3 = [M0*F2a - γ*(F4a + F4b)]

Use the above equation and overall balance to find:

F2a = F3 + (F4a+F4b)

F2a = [M0*F2a - γ*(F4a + F4b)] + (F4a+F4b)

F2a - M0*F2a = (F4a+F4b) - γ*(F4a + F4b)

ii.) F2a = (1-γ) * (F4a+F4b)/ (1-M0)

iii.) F3 = [M0*F2a - γ*(F4a + F4b)]

iv.) F4b = F2a – F3 – F4a

Assumption: Moisture content in F0, F1a and F2a&b is the same.

13.) Shred (See Fig. B.2)

Overall Balance

F1a = F2a +F2b

β = F2a/F1a

i.) F1a = F2a/β; $\beta = 4484.3/4529$

ii.) F2b = (1-β)F1a = F1a-F2a

14.) Peel (See Fig. B.1)

Overall Balance

F0 = F1a + F1b +F1c

α = F1a/F0

i.) F0 = F1a/α $\alpha = 4529/5000$

ii.) F1b = pl * F0; pl = 460.3/5000

iii.) F1c = F0 – F1a – F1b

F1b + F1c = total losses = F0 – F1a

F0 = F1a + (F1b + F1c)

15.) Clean Up 1 (See Fig. B.7)

Overall Balance

F10 = F8 + F9 + F1b + F2b + F4b

F8 = n * d	n = 954.3/954.3 = 1
F9 = n * w1	w1 = 12.0
F10 = n (d + w1)	d = 1.7

16.) Clean Up 2 (See Fig. B.8)

Overall Balance

F13 = F11 + F12 + F5b + F6b

F11 = n * d

F12 = n * w2   w2 = 12.4

F13 = n (d + w2)

<u>Secondary Inputs</u>

M0 = total losses from dehydrator/input to dehydrator = 3451.3/4484.3 = 0.7696

st = Starch content in F1 = (0.7/ M0) * 0.14 – (M0 – 0.7) * 0.14

ca = Carb. content in F1 = (0.7/ M0) * 0.07 – (M0 – 0.7) * 0.07

su = Sugar content in F1 = (0.7/ M0) * 0.04 – (M0 – 0.7) * 0.08

ot = Other substances inF1 = 1 – st – ca – su

γ = moisture content in F4-F7 = Equation in 4.) above

ca4 = carbohydrate content in F4- F7 = 0.907 + (0.029 - γ) * 0.907

p = protein content in F4- F7 = 0.008 + (0.029 - γ) * 0.008

f = fat content in F4- F7 = 0.009 + (0.029 - γ) * 0.009

a = ash content in F4- F7 = 1- γ - ca4 – p – f

B.3 Base Case Flour ESM

Assumptions

1. The quantities of working materials in the system are not taken into account. In reality, the throughput of the system would be different at different configurations. These quantities are taken from the material balance calculations for a particular configuration and can later be considered into the total ESM.

2. The equivalence factors obtained from the ALS Baseline Values and Assumptions Document (BVAD) (Hanford, 2002) are assumed to be applicable to the sub-system under study.

3. Procedures not involving equipment are considered to involve only the crew time portion of the ESM.

4. The individual components of equation 4.1 are assumed to be independent of each other.

5. The cooling requirements are assumed to be negligible for all processes.

6. The same mass equivalence factor is assumed for all equipment.

7. The time required for one cycle of the batch process is 14.12 hours.

8. The individual equipment masses were assumed to be (kg)

Slicer	45.36
Dehydrator	24.0
Blender	3.31
Mill	69.0

9. The individual equipment volumes were assumed to be (m^3)

Slicer	0.298
Dehydrator	0.181
Blender	0.0170
Mill	0.224

10. The power requirements for individual equipment were assumed to be (kWe)

Slicer	0.373
Dehydrator	1.60
Blender	0.400
Mill	1.00

11. The cooling requirements for the individual equipment were assumed to be (kWth)

Slicer	0.00
Dehydrator	0.00
Blender	0.00
Mill	0.00

12. The annual crew time associated with the operation of the individual equipment were assumed to be (CM-h/y)

Peel	235.8
Slicer	86.86
Dehydrator	179.9
Blender	109.6
Mill	123.0
Package	27.92
Clean Up 1	208.9
Clean Up 2	341.2

Calculations

Table B.4
Summary of time usage data for flour production

Crew Time/Cycle Time Data			
Process/	**Crew Time**	**Equipment Time**	**Total Elapsed Time**
Equipment	**(min)**	**(min)**	**(min)**
1.) Peel	22.8	-	22.8
2.) Shred	8.4	4.6	8.4
3.) Dehydrate	17.4	720	737.4
4.) Pre-mill	10.6	3.8	10.6
5.) Mill	11.9	8.2	11.9
6.) Package	2.7	-	2.7
7.) Clean-Up 1	20.2	-	20.2
8.) Clean-Up 2	33	-	33
Totals	**127**	**736.6**	**847**

Cycle time in hours: 847min * (1hr/60min) = 14.12hrs

1. PEEL

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{14.12\frac{hrs}{cycle}} = 620.4\frac{cycles}{yr}$$

Crewtime for peel per cycle =22.8 min/cycle

$$CT_{peel} = Crewtime/\ year = \frac{620.4\frac{cycles}{yr} * 22.8\frac{\min}{cycle}}{60\frac{\min}{hr}} = 235.752\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$$\mathrm{M}_{\mathrm{CT},\ peel} = CT_{peel} * D * CT_{eq} = 235.75\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 131.70kg$$

$ESM_1 = ESM_{peel} = M_{CT,peel}$
$ESM_1 = ESM_{peel} = 68.5kg + 12.685kg + 0.720kg + 0kg + 79.95kg = 131.70kg$

2. **SHRED**

SLICER (Food Cutter, 2005; VS9, 2005)

Mass

Net weight = 100lb$_f$,[4] = F;   F = m*a;   m=F/A; a=g=32.174ft/s^2

$$M_{slicer} = 100lb_f * \frac{32.174 lb_m \frac{ft}{s^2}}{1 lb_f} * \frac{453.593g}{1 lb_m} * \frac{1}{32.174 \frac{ft}{s^2}}$$

$M_{slicer} = 45359.3g$
$M_{slicer} = 45.36kg$

Volume

$V_{slicer} = L*W*H$

$$V_{slicer} = (31\frac{7}{8} * 19\frac{13}{16} * 28\frac{3}{4}) in^3 \text{, [4]}$$

$V_{slicer} = (18156.2988) in^3$
$V_{slicer} = 0.298m^3$

$$V_{eq} = 215\frac{kg}{m^3}$$

$M_{v,slicer} = V* Veq = 0.298 * 215 = 64.07kg$

Power

$$P_{slicer} = 0.5hp * 0.746\frac{kW}{hp} \text{ , [4]}$$

$P_{slicer} = 0.373kW$
$P_{eq} = 237kg/kW$

$$\alpha_{slicer} = \frac{4.6 \min}{14.12hr * 60\frac{\min}{hr}} = 0.00542$$

$$M_{p,slicer} = \alpha_{slicer} * P_{slicer} * P_{eq} = 0.00542 * 88.401kg = 0.479kg$$

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr}*24\frac{hrs}{day}}{14.12\frac{hrs}{cycle}} = 620.4\frac{cycles}{yr}$$

Crewtime for slicer per cycle = 8.4 min/cycle

$$CT_{slicer} = Crewtime/year = \frac{620.4\frac{cycles}{yr}*8.4\frac{\min}{cycle}}{60\frac{\min}{hr}} = 86.86\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$$M_{CT,\ slicer} = CT_{slicer}*D*CT_{eq} = 86.86\frac{CM-hr}{yr}*0.49\,yr*1.14\frac{kg}{CM-hr} = 48.30kg$$

$ESM_2=ESM_{slicer}= M_{slicer}+M_{v,slicer}+M_{p,slicer}+M_{c,slicer}+M_{CT,slicer}$

$ESM_2=ESM_{slicer}= 45.36kg+64.07kg+0.479kg+0kg+48.30kg=158.3kg$

3. **DEHYDRATE**

DEHYDRATOR (Cabela's, 2005)

Mass

$M_{dehydrator}$ = 24kg (from label on equipment)

Volume

$V_{dehydrator}$ = L*W*H

$V_{dehydrator}$ = (22.5*20.5*24)in^3 , [5]

$V_{dehydrator}$ =(11070)in^3

$V_{dehydrator}$ = 0.1814m^3

$V_{eq} = 215\frac{kg}{m^3}$

$M_{v,dehydrator}$ = V* Veq=0.1814 *215=39.00kg

Power

$P_{dehydrator}$=*1.6 kW* (from label on equipment)

P_{eq}= *237kg/kW*

$\alpha_{dehydrator} = \frac{12hrs}{14.12hrs} = 0.850$

$M_{p,dehydrator} = \alpha_{dehydrator}*P_{dehydrator}*P_{eq} = 0.850*379.2kg$ =322.27kg

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{14.12\frac{hrs}{cycle}} = 620.4\frac{cycles}{yr}$$

Crewtime for dehydrator per cycle = 17.4 *min/cycle*

$$CT_{dehydrator} = Crewtime / year = \frac{620.4\frac{cycles}{yr} * 17.4\frac{\min}{cycle}}{60\frac{\min}{hr}} = 179.92\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$$M_{CT,\,dehydrator} = CT_{dehydrator} * D * CT_{eq} = 179.92\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 100.50kg$$

$ESM_3 = ESM_{dehydrator} = M_{dehydrator} + M_{v,dehydrator} + M_{p,dehydrator} + M_{c,dehydrator} + M_{CT,dehydrator}$

$ESM_3 = ESM_{dehydrator} = 24kg + 39kg + 322.27kg + 0kg + 100.5kg = 485.77kg$

4. **PREMILL**

BLENDER (BlendMaster, 2005)

Mass

Shipping weight for 52252 model Blendmaster Ultra 12-speed is 7.3lbs [6]

Net weight = 7.3lb_f = F; F = m*a; m=F/A; a=g=32.174ft/s^2

$$M_{blender} = 7.3lb_f * \frac{32.174lb_m\frac{ft}{s^2}}{1lb_f} * \frac{453.593g}{1lb_m} * \frac{1}{32.174\frac{ft}{s^2}}$$

$M_{blender}$ = 3311.2g

$M_{blender}$ = 3.31kg

Volume

Volume of blender (jar portion) is 40oz or 1182.9mL

$V_{blender}$ = L*W*H

$V_{blender}$ = (13*8*10)in^3 , [6]

$V_{blender}$ =(1040)in^3

$V_{blender}$ = 0.0170m^3

$$V_{eq} = 215\frac{kg}{m^3}$$

$M_{v,blender}$ = V* Veq=0.017 *215=3.655kg

Power

$P_{blender}$=*0.4 kW* , [6]

P_{eq}= 237kg/kW

$$\alpha_{blender} = \frac{3.8\min}{14.12hr*60\frac{\min}{hr}} = 0.00448$$

$M_{p,blender} = \alpha_{blender} * P_{blender} * P_{eq}$=0.00448*94.8kg=0.425kg

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr}*24\frac{hrs}{day}}{14.12\frac{hrs}{cycle}} = 620.4\frac{cycles}{yr}$$

Crewtime for blender per cycle = 10.0 min/cycle

$$CT_{blender} = Crewtime/year = \frac{620.4\frac{cycles}{yr}*10.0\frac{\min}{cycle}}{60\frac{\min}{hr}} = 109.6\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$ESM_4 = ESM_{blender} = M_{blender} + M_{v,blender} + M_{p,blender} + M_{c,blender} + M_{CT,blender}$

$$M_{CT,blender} = CT_{blender} * D * CT_{eq} = 109.6\frac{CM-hr}{yr}*0.49yr*1.14\frac{kg}{CM-hr} = 61.22kg$$

$ESM_4 = ESM_{blender}$=3.31kg+3.655kg+0.425kg+0kg+61.22kg=68.61kg

5. **MILL**

MILL (Quadrumat, 2005)

Mass

M_{mill} = 69kg [7a]

Volume

V_{mill} = L*W*H

V_{mill} = (700*615*520)mm^3 [7a]

V_{mill} =(223,860,000)mm^3

V_{mill} = 0.2239m^3

$$V_{eq} = 215\frac{kg}{m^3}$$

$M_{v,mill}$ = V* Veq=0.2239*215=48.14kg

Power

P_{mill}=*1.0 kW* (from label on equipment)
P_{eq}= *237kg/kW*

$$\alpha_{mill} = \frac{8.2\min}{14.12hr * 60\frac{\min}{hr}} = 0.00968$$

$M_{p,mill} = \alpha_{mill} * P_{mill} * P_{eq} = 0.00968 * 237kg = 2.294kg$

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{14.12\frac{hrs}{cycle}} = 620.4\frac{cycles}{yr}$$

Crewtime for mill per cycle = 11.9 min/cycle

$$CT_{mill} = Crewtime / year = \frac{620.4\frac{cycles}{yr} * 11.9\frac{\min}{cycle}}{60\frac{\min}{hr}} = 123.046\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$ESM_5 = ESM_{mill} = M_{mill} + M_{v,mill} + M_{p,mill} + M_{c,mill} + M_{CT,mill}$

$$M_{CT,\,mill} = CT_{mill} * D * CT_{eq} = 123.046\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 68.73kg$$

$ESM_5 = ESM_{mill} = 69kg + 48.1kg + 2.294kg + 0kg + 68.73kg = 188.124kg$

6. PACKAGE

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{14.12\frac{hrs}{cycle}} = 620.4\frac{cycles}{yr}$$

Crewtime for package per cycle = 2.7 min/cycle

$$CT_{package} = Crewtime / year = \frac{620.4\frac{cycles}{yr} * 2.7\frac{\min}{cycle}}{60\frac{\min}{hr}} = 27.92\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

$D = 0.49\ yr$

$$M_{CT,\ package} = CT_{package} * D * CT_{eq} = 27.92\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 15.596kg$$

$ESM_6 = ESM_{package} = M_{CT,package}$
$ESM_6 = ESM_{package} = 15.596kg$

7. **CLEAN UP 1**

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{14.12\frac{hrs}{cycle}} = 620.4\frac{cycles}{yr}$$

Crewtime for clean up 1 per cycle = 20.2 min/cycle

$$CT_{cleanup1} = Crewtime/year = \frac{620.4\frac{cycles}{yr} * 20.2\frac{\min}{cycle}}{60\frac{\min}{hr}} = 208.868\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

$D = 0.49\ yr$

$ESM_7 = ESM_{cleanup1} = M_{CT,cleanup1}$

$$M_{CT,\ cleanup1} = CT_{cleanup1} * D * CT_{eq} = 208.868\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 116.674kg$$

$ESM_7 = ESM_{cleanup1} = 116.674kg$

8. **CLEAN UP 2**

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{14.12\frac{hrs}{cycle}} = 620.4\frac{cycles}{yr}$$

Crewtime for clean up 2 per cycle = 33.0 min/cycle

$$CT_{cleanup2} = Crewtime/year = \frac{620.4\frac{cycles}{yr} * 33.0\frac{\min}{cycle}}{60\frac{\min}{hr}} = 341.22\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

$D = 0.49\ yr$

$$\mathrm{M}_{\mathrm{CT},\,cleanup\,2} = CT_{cleanup\,2} * D * CT_{eq} = 341.22\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 190.61kg$$

$ESM_8 = ESM_{cleanup2} = M_{CT,cleamup2}$

$ESM_8 = ESM_{cleanup2} = 190.61kg$

TOTAL ESM

Base Case

$$ESM_{BC} = \sum_{i=1}^{8} ESM_i = ESM_1 + ESM_2 + ESM_3 + ESM_4 + ESM_5 + ESM_6 + ESM_7 + ESM_8$$

$$ESM_{BC} = (131.70+158.3+485.77+68.61+188.124+15.596+116.674+190.61)kg = 1355.38kg$$

Observations

1. Total crew time for the flour technology is 740.71kg. This is approximately 54.6% of the total ESM.

$$M_{CT} = \sum_{i=1}^{16} M_{CTi} = 131.70 + 48.30 + 100.5 + 68.61 + 68.73 + 15.596 + 116.674 + 190.6 = 740.71\ kg$$

The cost associate with crew time can contribute significantly to the total ESM

2. Automation of the entire system or at least portions of the system would greatly reduce crew-time costs.
3. The dehydrator ($ESM_{Dehydrator} = 485.77$) constitutes a significant portion (approximately 35.84%) of ESM costs.
4. Equipment and procedural alternatives need to be sought out for high ESM demand portions for each process/equipment. In this case alternative should be sought for the dehydrator, and the clean up 2 process. Namely, a dehydrator sized for mass, volume, and power should be designed since the bulk of its ESM cost is due to power and partial or total automation of clean up 2 and other high crew time processes should be investigated.
5. The power specifications for each piece of equipment may be greater than the actual power required. Obtaining temperature data may be useful for comparing the actual power used/required to the power specifications for the equipment. Once the power requirement is understood it may be necessary to replace some equipment with equipment requiring less power in order to reduce costs.

B.4 Flour Alternative ESM

Assumptions

1. The quantities of working materials in the system are not taken into account. In reality, the throughput of the system would be different at different configurations. These quantities are taken from the material balance calculations for a particular configuration and can later be considered into the total ESM.

2. The equivalence factors obtained from the ALS Baseline Values and Assumptions Document (BVAD) (Hanford, 2002) are assumed to be applicable to the sub-system under study.

3. Procedures not involving equipment are considered to involve only the crew time portion of the ESM.

4. The individual components of equation 4.1 are assumed to be independent of each other.

5. The same mass equivalence factor is assumed for all equipment.

6. The time required for one cycle of the batch process is 14.12 hours.

7. The individual equipment masses were assumed to be (kg)

Peeler	52.40
Slicer	43.73
Dehydrator	20.20
Blender	3.31
Mill	19.12

8. The individual equipment volumes were assumed to be (m^3)

Peeler	0.006721
Slicer	0.005607
Dehydrator	0.011221
Blender	0.017000
Mill	0.002451

9. The power requirements for individual equipment were assumed to be (kWe)

Peeler	0.300
Slicer	0.373
Dehydrator	0.2281
Blender	0.400
Mill	1.000

10. The cooling requirements for the individual equipment were assumed to be (kWth)

Slicer	0.00
Dehydrator	0.00
Blender	0.00
Mill	0.00

11. The annual crew time associated with the operation of the individual equipment were assumed to be (CM-h/y)

Peel	52.52
Slicer	88.23

Dehydrator	182.8
Blender	105.8
Mill	125.0
Package	28.36
Clean Up 1	212.2
Clean Up 2	346.6

Calculations

Table B.5
Summary of time usage data for flour production alternatives

Crew Time/Cycle Time Data			
Process/ Equipment	**Crew Time (min)**	**Equipment Time (min)**	**Total Elapsed Time (min)**
1.) Peel	5	5	10
2.) Shred	8.4	4.6	8.4
3.) Dehydrate	17.4	720	737.4
4.) Pre-mill	10.6	3.8	10.6
5.) Mill	11.9	8.2	11.9
6.) Package	2.7	-	2.7
7.) Clean-Up 1	20.2	-	20.2
8.) Clean-Up 2	33	-	33
Totals	**109.2**	**741.6**	**834.2**

Cycle time in hours: 834.2min * (1hr/60min) = 13.90hrs

1. **PEELER** (Peeler, 2005)
The following are the calculations for the design of an automated peeler as an alternative to the original peeling process.

Volume

$V_{consumable} = 5170\ cm^3$
$V_{peeler} = 1.3 * 5170cm^3 = 6721cm3 = 0.006721m^3$
$V_{eq} = 215\frac{kg}{m^3}$
$M_{v,slicer} = V * Veq = 0.006721 * 215 = 1.44kg$

Mass

$\rho_{stainless\ steel} = 7.8g/cm^3$
$M_{peeler} = \rho_{stainless\ steel} * V_{peeler} = 7.8g/cm^3 * 6721cm^3 = 52,423.8g$
$M_{peeler} = 52.4kg$

Power

Assume P_{peeler} = 0.3kW (comparable to power requirement of the slicer)
Assume time it takes to for the peeler to run: 5 min
$P_{peeler}=0.3kW$
$P_{eq}= 237kg/kW$

$$\alpha_{peeler} = \frac{5\min}{13.9hr*60\frac{\min}{hr}} = 0.005995$$

$$M_{p,peeler} = \alpha_{peeler} * P_{peeler} * P_{eq} = 0.005995*71.1kg = 0.426kg$$

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr}*24\frac{hrs}{day}}{13.90\frac{hrs}{cycle}} = 630.2\frac{cycles}{yr}$$

Assume the time it takes a crew member to load and und unload the automated peeler:
Crewtime for peeler per cycle =5 min/cycle

$$CT_{peel} = Crewtime/\ year = \frac{630.2\frac{cycles}{yr}*5\frac{\min}{cycle}}{60\frac{\min}{hr}} = 52.52\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

$D = 0.49\ yr$

$$M_{CT,\ peel} = CT_{peel} * D * CT_{eq} = 52.52\frac{CM-hr}{yr}*0.49yr*1.14\frac{kg}{CM-hr} = 29.34kg$$

$ESM_1=ESM_{peeler} = M_{peeler}+M_{v,peeler}+M_{p,peeler}+M_{c,peeler}+M_{CT,peeler}$

$ESM_1=ESM_{peeler}= 54.2kg+1.44kg+0.426kg+0kg+29.34kg=85.406kg$

2. **SHRED**

SLICER

Volume

$V_{consumable} = 4612.8\ cm^3$

$V_{slicer} = 1.3 * V_{consumable} = 1.3 * 4612.8\ cm^3$

$V_{slicer} = 5606.64\ cm^3$

$V_{slicer} = 0.00560664 m^3$

$V_{eq} = 215 \frac{kg}{m^3}$

$M_{v,slicer} = V * Veq = .00560664 * 215 = 1.2kg$

Mass

$\rho_{stainless\ steel} = 7.8 g/cm^3$

$M_{slicer} = \rho_{stainless\ steel} * V_{slicer} = 7.8 g/cm^3 * 5606.64 cm^3 = 43{,}731.792 g$

$M_{slicer} = 43.73kg$

Power

$P_{slicer} = 0.5hp * 0.746 \frac{kW}{hp}$, [4]

$P_{slicer} = 0.373kW$

$P_{eq} = 237 kg/kW$

$\alpha_{slicer} = \frac{4.6 \min}{13.9 hr * 60 \frac{\min}{hr}} = 0.00551$

$M_{p,slicer} = \alpha_{slicer} * P_{slicer} * P_{eq} = 0.00551 * 88.401 kg = 0.465kg$

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365 \frac{days}{yr} * 24 \frac{hrs}{day}}{13.90 \frac{hrs}{cycle}} = 630.2 \frac{cycles}{yr}$$

Crewtime for slicer per cycle = 8.4 min/cycle

$$CT_{slicer} = Crewtime / year = \frac{630.2 \frac{cycles}{yr} * 8.4 \frac{\min}{cycle}}{60 \frac{\min}{hr}} = 88.23 \frac{CM - hr}{yr}$$

$CT_{eq} = 1.14 \frac{kg}{CM - hr}$

$D = 0.49\ yr$

$$\text{M}_{\text{CT, slicer}} = CT_{slicer} * D * CT_{eq} = 88.23 \frac{CM - hr}{yr} * 0.49 \, yr * 1.14 \frac{kg}{CM - hr} = 49.28 kg$$

$ESM_2 = ESM_{slicer} = M_{slicer} + M_{v,slicer} + M_{p,slicer} + M_{c,slicer} + M_{CT,slicer}$
$ESM_2 = ESM_{slicer} = 43.73kg + 1.20kg + 0.465kg + 0kg + 49.28kg = 94.68kg$

3. **DEHYDRATE**

DEHYDRATOR

Volume

$V_{consumable} = 8632.2 \text{ cm}^3$
$V_{dehydrator} = 1.3 * V_{consumable} = 1.3 * 8632.2 \text{ cm}^3$
$V_{dehydrator} = 11{,}221.86 \text{ cm}^3$
$V_{dehydrator} = 0.011221 \text{m}^3$

$$V_{eq} = 215 \frac{kg}{m^3}$$

$M_{v,dehydrator} = V * Veq = .011221 * 215 = 2.4kg$

Mass

1.) Assume the dehydrator is a cube 2.) Assume the consumable material occupies the entire interior volume of the dehydrator.
Then, the mass of the dehydrator is the mass of the shell encasing the volume for the consumables.

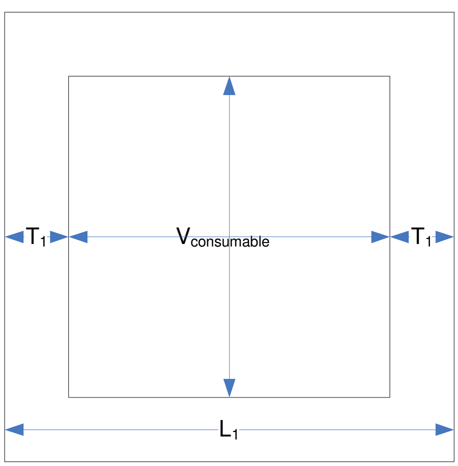

Figure B.9. Two-dimensional depiction of dehydrator dimensions

$V_{dehydrator} = 11{,}221.86 \text{ cm}^3$
$V_{dehydrator} = L_1^3$

$L_1 = 22.388\text{cm}$
Exterior volume (shell only) = $V_{dehydrator, E}$
$V_{dehydrator, E} = V_{dehydrator} + V_{consumable}$

$V_{dehydrator, E}$ = (11,221.86-8632.2)cm^3
$V_{dehydrator, E}$ = 2589.66cm^3
$\rho_{stainless\ steel}$ = 7.8g/cm^3
$M_{dehydrator} = \rho_{stainless\ steel}\ (V_{dehydrator} + V_{consumable})$
$M_{dehydrator}$ = 7.8g/cm^3 (2589.66cm^3)
$M_{dehydrator}$ = 20,199.34g
$M_{dehydrator}$ = 20.20kg

Power

1.) Use the temperature change of the streams entering and exiting the dehydrator and the specific heat capacity of the sweetpotato material to calculate the energy requirement.
2.) Use the energy and the time requirement to calculate the power requirement.

T_2-stream entering the dehydrator
T_4-material stream exiting the dehydrator
$T_2 = 25^oC$
$T_4 = 160^oC$
$Q_{dehydrator, A1} = M_{moist, SP} * C_{p, moist\ SP} * (T_4 - T_2) + M_{water} * H_v^{latent}$
Where $M_{moist, SP}$= mass of moist sweetpotato = F2a and
H_v^{latent} = Latent heat of vaporization of the water in the sweetpotato and
M_{water} = Mass of water in sweetpotato entering the dehydrator = M0*F2a
$C_{p, moist\ SP}$ = 0.837 + 3.348 * M, where $C_{p, moist\ SP}$ [=] (kJ/kg.K) and
M =M0 =moisture content of F2a
$C_{p, moist\ SP}$ = 0.837 + 3.348 * (0.7696)
$C_{p, moist\ SP}$ = 3.41 kJ/kg.K
$(T_4-T_2) = (160^oC - 25^oC) = 135\ ^oC$
$Q_{dehydrator, A1}$ = (4.4843kg * 3.41 kJ/kg.K) * (135 K) + (3.4513kg * 2257 kJ/kg)
$Q_{dehydrator, A1}$ = 2064.34kJ + 7789.5841kJ
$Q_{dehydrator, A1}$ = 9853.93kJ
$P_{dehydrator, A1}$ = 9853.93kJ/(12hr*3600s/hr)
$P_{dehydrator, A1}$ = 0.2281kJ/s = 0.2281kW

$P_{dehydrator, A1} * P_{eq}$ = *0.2281kW *237kg/kW=54.0597kg*

$$\alpha_{dehydrator} = \frac{12hrs}{13.9rs} = 0.863$$

$M_{p,dehydrator} = \alpha_{dehydrator} * P_{dehydrator} * P_{eq} = 0.863 * 54.06kg$ =46.65kg

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{13.90\frac{hrs}{cycle}} = 630.2\frac{cycles}{yr}$$

Crewtime for dehydrator per cycle = 17.4 *min/cycle*

$$CT_{dehydrator} = Crewtime / year = \frac{630.2\frac{cycles}{yr} * 17.4\frac{\min}{cycle}}{60\frac{\min}{hr}} = 182.76\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$$M_{CT,\ dehydrator} = CT_{dehydrator} * D * CT_{eq} = 182.76\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 102.09kg$$

$ESM_3 = ESM_{dehydrator} = M_{dehydrator} + M_{v,dehydrator} + M_{p,dehydrator} + M_{c,dehydrator} + M_{CT,dehydrator}$

$ESM_3 = ESM_{dehydrator} = 20.20kg + 2.4kg + 46.65kg + 0kg + 102.09kg = 171.34kg$

4. **PREMILL**

BLENDER (BlendMaster, 2005)

Mass

Shipping weight for 52252 model Blendmaster Ultra 12-speed is 7.3lbs [6]

Net weight = 7.3lb_f = F; F = m*a; m=F/A; a=g=32.174ft/s^2

$$M_{blender} = 7.3lb_f * \frac{32.174 lb_m \frac{ft}{s^2}}{1lb_f} * \frac{453.593g}{1lb_m} * \frac{1}{32.174\frac{ft}{s^2}}$$

$M_{blender}$ = 3311.2g

$M_{blender}$ = 3.31kg

Volume

Volume of blender (jar portion) is 40oz or 1182.9mL

$V_{blender}$ = L*W*H

$V_{blender}$ = (13*8*10)in^3 , [6]

$V_{blender}$ =(1040)in^3

$V_{blender}$ = 0.0170m^3

$$V_{eq} = 215\frac{kg}{m^3}$$

$M_{v,blender}$ = V* Veq=0.017 *215=3.655kg

Power

$P_{blender}$=*0.4 kW* , [6]

P_{eq}= *237kg/kW*

$$\alpha_{blender} = \frac{3.8\min}{13.9hr * 60\frac{\min}{hr}} = 0.004556$$

$M_{p,blender} = \alpha_{blender} * P_{blender} * P_{eq}$=0.004556*94.8kg=0.432kg

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{13.90\frac{hrs}{cycle}} = 630.2\frac{cycles}{yr}$$

Crewtime for blender per cycle = 10.0 min/cycle

$$CT_{blender} = Crewtime / year = \frac{630.2\frac{cycles}{yr} * 10.0\frac{\min}{cycle}}{60\frac{\min}{hr}} = 105.03\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$$M_{CT,\ blender} = CT_{blender} * D * CT_{eq} = 105.03\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 58.67kg$$

$ESM_4 = ESM_{blender} = M_{blender} + M_{v,blender} + M_{p,blender} + M_{c,blender} + M_{CT,blender}$

$ESM_4 = ESM_{blender} = 3.31kg + 3.655kg + 0.432kg + 0kg + 58.67kg = 66.067kg$

5. **MILL**

MILL

Volume

$V_{consumable}$ = 1885.4 cm^3

V_{mill} = 1.3 * $V_{consumable}$ = 1.3 * 1885.4cm^3

V_{mill} = 2451.02cm^3

V_{mill} = 0.0024510m^3

$V_{eq} = 215\frac{kg}{m^3}$

$M_{v,mill}$ = V* Veq=.0024510 *215=0.526963kg

Mass

$\rho_{stainless\ steel}$ = 7.8g/cm^3

$M_{mill} = \rho_{stainless\ steel} * V_{mill}$ = 7.8g/cm^3 * 2451.02cm^3 = 19,117.956g

M_{mill} = 19.12kg

Power

P_{mill}=*1.0 kW* (from label on equipment)

P_{eq}= *237kg/kW*

$$\alpha_{mill} = \frac{8.2\min}{13.9hr * 60\frac{\min}{hr}} = 0.00983$$

$M_{p,mill} = \alpha_{mill} * P_{mill} * P_{eq} = 0.00983 * 237kg = 2.32971kg$

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{13.90\frac{hrs}{cycle}} = 630.2\frac{cycles}{yr}$$

Crewtime for mill per cycle = 11.9 min/cycle

$$CT_{mill} = Crewtime/year = \frac{630.2\frac{cycles}{yr} * 11.9\frac{\min}{cycle}}{60\frac{\min}{hr}} = 124.9897\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$$M_{CT,mill} = CT_{mill} * D * CT_{eq} = 124.9897\frac{CM-hr}{yr} * 0.49yr * 1.14\frac{kg}{CM-hr} = 69.82kg$$

$ESM_5 = ESM_{mill} = M_{mill} + M_{v,mill} + M_{p,mill} + M_{c,mill} + M_{CT,mill}$

$ESM_5 = ESM_{mill} = 19.12kg + 0.527kg + 2.33kg + 0kg + 69.82kg = 91.797kg$

6. PACKAGE

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{14.12\frac{hrs}{cycle}} = 620.4\frac{cycles}{yr}$$

Crewtime for package per cycle = 2.7 min/cycle

$$CT_{package} = Crewtime/year = \frac{630.2\frac{cycles}{yr} * 2.7\frac{\min}{cycle}}{60\frac{\min}{hr}} = 28.359\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$$M_{CT,\,package} = CT_{package} * D * CT_{eq} = 28.359\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 15.841kg$$

ESM₆=ESM_package= M_CT,package

$ESM_6 = ESM_{package} = M_{CT,package}$

$ESM_6 = ESM_{package} = 15.841kg$

7. **CLEAN UP 1**

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{13.90\frac{hrs}{cycle}} = 630.2\frac{cycles}{yr}$$

Crewtime for clean up 1 per cycle = 20.2 min/cycle

$$CT_{cleanup1} = Crewtime / year = \frac{630.2\frac{cycles}{yr} * 20.2\frac{\min}{cycle}}{60\frac{\min}{hr}} = 212.167\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$$M_{CT,\,cleanup1} = CT_{cleanup1} * D * CT_{eq} = 212.167\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 118.52kg$$

$ESM_7 = ESM_{cleanup1} = M_{CT,cleanup1}$

$ESM_7 = ESM_{cleanup1} = 118.52kg$

8. **CLEAN UP 2**

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{13.90\frac{hrs}{cycle}} = 630.2\frac{cycles}{yr}$$

Crewtime for clean up 2 per cycle = 33.0 min/cycle

$$CT_{cleanup2} = Crewtime / year = \frac{630.2\frac{cycles}{yr} * 33.0\frac{\min}{cycle}}{60\frac{\min}{hr}} = 346.61\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$$\mathrm{M}_{\mathrm{CT},\,cleanup\,2} = CT_{cleanup\,2} * D * CT_{eq} = 346.61\frac{CM - hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM - hr} = 193.62kg$$

$ESM_8 = ESM_{cleanup2} = M_{CT,cleamup2}$

$ESM_8 = ESM_{cleanup2} = 193.62kg$

TOTAL ESM

Base Case

$$ESM_{BC} = \sum_{i=1}^{8} ESM_i = ESM_1 + ESM_2 + ESM_3 + ESM_4 + ESM_5 + ESM_6 + ESM_7 + ESM_8$$

ESM_{BC}

$=(131.70+158.3+485.77+68.61+188.124+15.596+116.674+190.61)kg=1355.38kg$

Alternative 1

$$ESM_{A1} = \sum_{i=1}^{8} ESM_i = ESM_1 + ESM_2 + ESM_3 + ESM_4 + ESM_5 + ESM_6 + ESM_7 + ESM_8$$

ESM_{A1}

$=(85.406+94.68+171.34+66.067+91.797+15.841+118.52+193.62)kg=837.271kg$

APPENDIX C : CEREAL PRODUCTION CALCULATIONS

Appendix C contains sample calculations for the cereal production technology. Section C.1 contains material balance calculations for the forward direction while section C.2 contains material balance calculations for the reverse direction. The material balances were calculated utilizing data provided from Tuskegee University on February 14, 2006. Section C.3 contains base case cereal production ESM calculations while section C.4 contains ESM calculations for alternatives to the base case configuration.

C.1 Material Balance Calculations (Forward Direction)

Table C.1
Primary input for cereal production (forward)

Cereal Production		
Primary Input	**Symbol**	**Value**
Ingredients w/o added water	B0	1214.3

Table C.2
Secondary inputs for cereal production

Cereal Production		
Secondary Inputs (Breakfast Cereal)	**Symbol**	**Default Value**
Fraction of flour in ingredients	$\theta 1$	**0.823519723**
Fraction of water in ingredients	$\iota 1$	**0**
Fraction of brown sugar in ingredients	$\kappa 1$	**0.117680968**
Fraction of baking soda in ingredients	$\lambda 1$	**0.011776332**
Fraction of maple syrup in ingredients	$\mu 1$	**0.035246644**
Fraction of cinnamon in ingredients	$\nu 1$	**0.011776332**
Fraction of flour in formulation	$\theta 2$	**0.777179427**
Fraction of water in formulation	$\iota 2$	**0.056270975**
Fraction of brown sugar in formulation	$\kappa 2$	**0.111059081**
Fraction of baking soda in formulation	$\lambda 2$	**0.011113713**
Fraction of maple syrup in formulation	$\mu 2$	**0.033263092**
Fraction of cinnamon in formulation	$\nu 2$	**0.011113713**
Fraction lost from mixing ingredients	ξ	**0.004199951**
Fraction lost from package 1	p	**0.024038086**
Percent moisture in B0	q	**0.099621337**
Fraction of B4b lost as residue	l	**0.004058378**
Fraction of B4b used for moisture analysis	m	**0.019979708**
Fraction lost from equilibrate	r	**0**
Moisture Content of B8&B11	τ	**0.05**
Fraction lost from extruder	σ	**0.100519792**
Fraction lost from extruder B6b	s	**0.171837709**
Fraction lost from extruder B7	t	**0.399363564**
Fraction lost from extruder B8	u	**0.428798727**
Fraction lost from pre-drying (B9b)	v	**0**
Percent moisture in stream from oven	y	**0.029**
Fraction lost from oven	z	**0**
Fraction of vapor lost from oven	w	**0.035384068**
Fraction lost from package 2	x	**0.012995392**
Fraction lost from vacuum sealer	j	**0.01**
Multiple of default primary input (user input/default input)	n	**1**
Detergent amount per 1214.3g input	d	**1.7**
Water amount per 1214.3g input (for clean up 1)	w1	**1787.5**
Water amount per 1214.3g input (for clean up 2)	**w2**	**7.6**

Breakfast Cereal Production

Formulas

Mix Ingredients

Sample Calculations

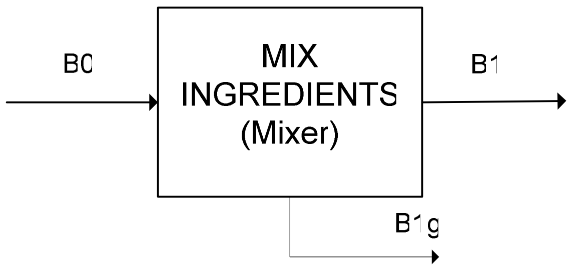

Fig. C.1. Mass balance for mix ingredients.

Overall Balance

B0 = B1 + B1g

B0 is given as a primary input

ξ = fraction lost from mix

ξ = B1g/B0

1.) B1g = ξ*B0

2.) B1 = B0 – B1g

3.) B0a = θ1 * B0

4.) B0b = ι1 * B0

5.) B0c = κ1 * B0

6.) B0d = λ1 * B0

7.) B0e = μ1 * B0

8.) B0f = ν1 * B0

9) B1a = θ1 * B1

10.) B1b = ι1 * B1

11.) B1c = κ1 * B1

12.) B1d = λ1 * B1

13.) B1e = μ1 * B1

14.) B1f = ν1 * B1

Formulas

Mix with H2O

ξ = 5.1/1214.3=0.004199951

1.) B1g = .0041999*1214.3 = 5.1

2.) B1 = 1214.3 - 5.1 = 1209.2

3.) B0a = (1000/1214.3)*1214.3 = 1000

4.) B0b = (0/1214.3)*1214.3 = 0

5.) B0c = (142.9/1214.3)*1214.3= 142.9

6.) B0d = (14.3/1214.3)*1214.3= 14.30

7.) B0e = (42.8/1214.3)*1214.3= 42.80

8.) B0f = (14.3/1214.3)*1214.3= 14.30

9.) B1a = (1000/1214.3)*1209.2 = 995.80

10.) B1b = (0/1214.3)**1209.2 =0.00

11.) B1c = (142.9/1214.3)*1209.2 = 142.30

12.) B1d = (14.3/1214.3)**1209.2 = 14.24

13.) B1e = (42.8/1214.3)*1209.2 = 42.62

14.) B1f = (14.3/1214.3)**1209.2 = 14.24

Sample Calculations

Must solve equations in reverse order:

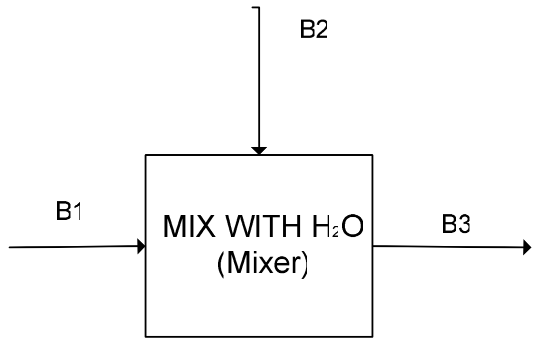

Fig. C.2. Mass balance for mix with H_2O.

Overall Balance
1.) B3 = B1 + B2
Water Balance
$\iota1*B1 + B2 = \iota2*B3$
2.) $B2 = \iota2*B3 - \iota1*B1$
Substisute 2.) into 1.) and solve for B3
$B3 = B1 + (\iota2*B3 - \iota1*B1)$
$B3 - \iota2*B3 = B1 - \iota1*B1$
$B3 * (1- \iota2) = B1 * (1- \iota1)$
3.) $B3 = B1 * (1- \iota1)/(1- \iota2)$
4.) $B3a = \theta2 * B3$
5.) $B3b = \iota2 * B3$
6.) $B3c = \kappa2 * B3$
7.) $B3d = \lambda2 * B3$
8.) $B3e = \mu2 * B3$
9.) $B3f = \nu2 * B3$

3.) B3 = 1209.2*(1-0)/(1-0.05627)
B3 = 1281.3

2.) B2 = 0.05627*1281.3 – 0*1209.2
B2 = 72.1
Note: Only 3.) and 2.) are used in Excel
1.) B3 = 1209.2 + 72.1 = 1281.3

4.) B3a = (995.8/1281.3)*1281.3 = 995.8
5.) B3b = (72.1/1281.3)*1281.3 = 72.1
6.) B3c = (142.3/1281.3)*1281.3 = 142.3
7.) B3d = (14.24/1281.3)*1281.3 = 14.24
8.) B3e = (42.62/1281.3)*1281.3 = 42.62
9.) B3f = (14.24/1281.3)*1281.3 = 14.24

Formulas

Package 1

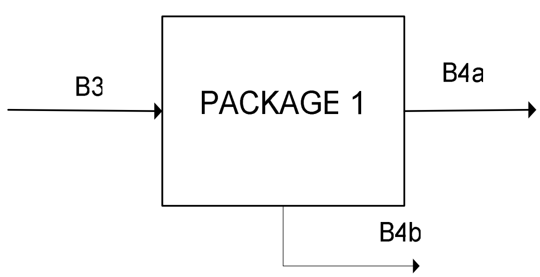

Fig. C.3. Mass balance for first packaging process.

Sample Calculations

1.) (B4a + B4b) = 1281.3

Overall Balance
1.) (B4a + B4b) = B3
p = fraction lost from Package 1
p = B4b/(B4a+B4b)
2.) B4b = p * (B4a + B4b)

3.) B4a = (1-p)*B4b/p

p = 30.8/1281.3 = 0.024038086
2.) B4b = (0.024038086*1281.3) = 30.8
3.) B4a = (1-0.024) * 30.8/0.024 = 1250.50

Formulas
Equilibrate 1 & 2

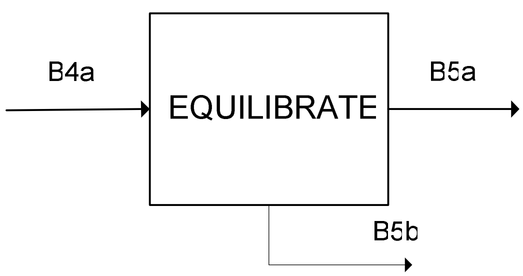

Fig. C.4. Mass balance for equilibrate (1&2).

Overall Balance
1.) B4a = (B5a +B5b)
r = fraction lost in equilibrate 1 & 2
r = B5b/(B5a+B5b)
2.) B5b = r * (B5a+B5b)
3.) B5a = (1-r)*B5b/r OR B5a = B4a – B5b

Sample Calculations

1.) (B5a+B5b) = 1250.50

r = 0/1250.5 = 0
2.) B5b = 0*1250.5 = 0
3.) B5a = 1250.50 – 0 = 1250.50

Formulas
Extrude

Sample Calculations

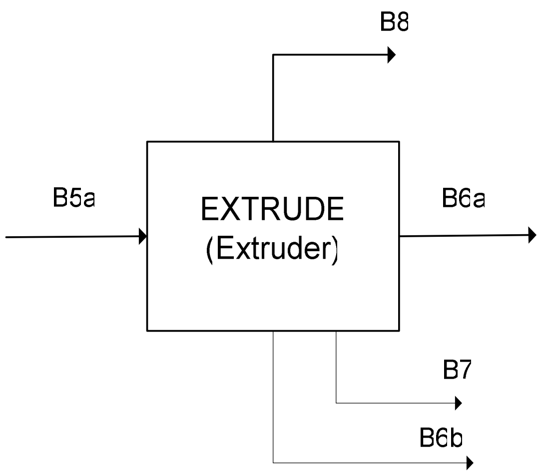

Fig. C.5. Mass balance for extrude.

Overall Balance

1.) B5a = (B6a + B6b + B7 + B8)

σ = fraction lost from extruder

σ = (B6b+B7+B8)/(B6a+B6b+B7+B8)

σ*(B6a+B6b+B7+B8) = (B6b+B7+ B8)

σ * (B6a + B6b +B7 +B8) = σ * B5a

2.) σ * B5a = (B6b +B7 + B8)

s = B6b/(B6b +B7 + B8)

3.) B6b = s * (B6b +B7 + B8)

OR B6b= s*σ *B5a

t = B7/(B6b +B7 + B8)

4.) B7 = t * (B6b +B7 + B8)

Or B6 = t*σ * B4

u = B8/(B6b +B7 + B8)

5.) B8 = u * (B6b +B7 + B8) = u*σ*B5a

6.) B6a = B5a - (B6b +B7 + B8)

<u>Formulas</u>

Prep for Drying

1.) (B6a+B6b+B7+B8) = 1250.50

σ=(75.5+50.2)/(1250.5)

σ = 0.100519792

2.) (B6b+B7+B8)= 0.1005*1250.5 = 125.7

s = 21.6/(75.5+50.2) = 0.171837709

23.) B6b = 0.1718*125.7 = 21.6

t = 50.2/(75.5+50.2) = 0.399363564

4.) B7 = 0.399363564*125.7=50.2

u = (125.7-50.2-21.6)/125.7 = 0.428798727

5.) B8 = 0.428798727*125.7 = 53.9

6.) B6a = 1250.5 - 125.7 = 1124.8

<u>Sample Calculations</u>

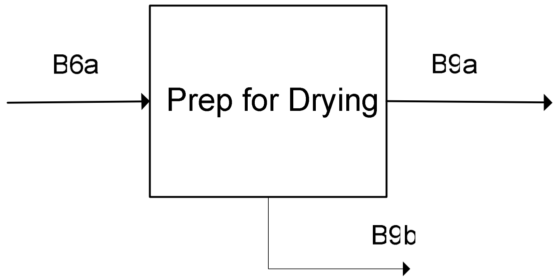

Fig. C.6. Mass balance for drying preparations.

1.) (B9a + B9b)= 1124.8

Overall Mass Balance
1.) B6a = (B9a + B9b)
v = fraction lost in break = B9b/(B9a+B9b)
2.) B9b = v * (B9a + B9b)
3.) B9a = B6a-B9b

v = 0/1124.8 = 0
2.) B9b = 0*1124.8 = 0
3.) B9a = 1124.8-0 = 1124.8

<u>Formulas</u>

Drying

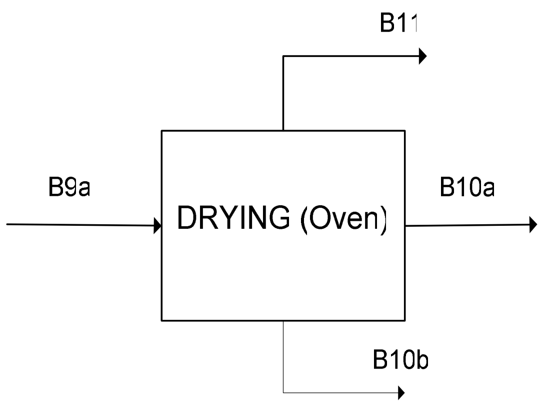

Fig. C.7. Mass balance for drying.

Overall Mass Balance
B9a = (B10a+B10b) + B11
w = fraction of vapor lost from oven
w = B11/B9a
1.) B11 = w * B9a
Substitute 1.) into overall mass balance for oven
(B10a +B10b) = B9a –B11
2.) (B10a+B10b) = B9a – w*B9a

z =fraction lost from oven
z = B10b/(B10a+B10b)
3.) B10b = z * (B10a + B10b)
4.) B10a = B9a – B10b –B11

<u>Sample Calculations</u>

w = 39.8/1124.8 = 0.035384068
1.) B11 = 0.035384068*1124.8 = 39.8

2.) (B10a+B10b) = 1124.8 – 39.8 = 1085.0

z = 0/1085.0 = 0
3.) B10b = 0*1085.0 = 0
4.) B10a = 1124.8-0-39.8 = 1085.0

Formulas

Package 2

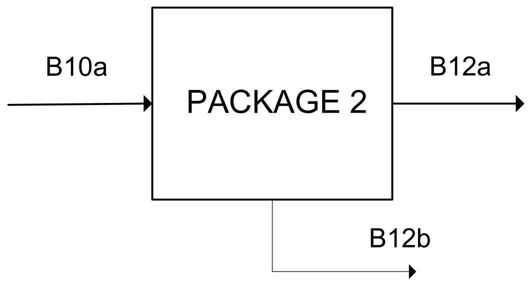

Fig. C.8. Mass balance for second packaging process.

Overall Mass Balance

1.) B10a = (B12a + B12b)

x = fraction lost from Package 2

x = B12b/(B12a + B12b)

2.) B12b = x * (B12a + B12b)

3.) B12a = B10a – B12b

Sample Calculations

1.) (B12a+B12b) = 1085.0

x = 14.1/1085.0 = 0.012995392

2.) B12b = 0.012995392*1085 = 14.10

3.) B12a = 1085.0 – 14.1 = 1070.9

Formulas

Clean Up 1

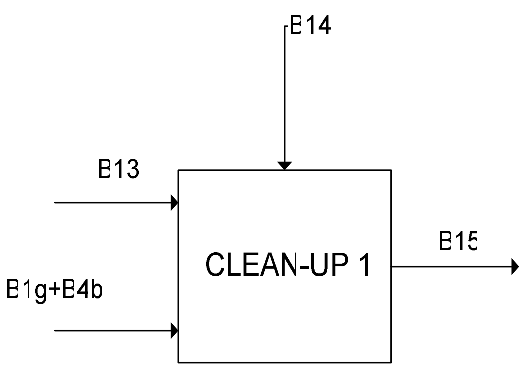

Fig. C.9. Mass balance for first clean up process.

Overall Mass Balance

B15 = B13 + B14 + B1g + B4b

n = Multiple of default primary input (user input/default input)

d = Detergent amount per 1214.3g input

w1 = Water amount per 1214.3g input (for

Sample Calculations

n = 1214.3/1214.3 =1

d = 1.7

w1 = 1787.5

1.) B13 = 1.7

2.) B14 = 1787.5

3.) B15 = 1789.2

clean up 1)
1.) B13 = n * d
2.) B14 = n * w1
3.) B15 = n (d + w1)

Formulas

Clean Up 2

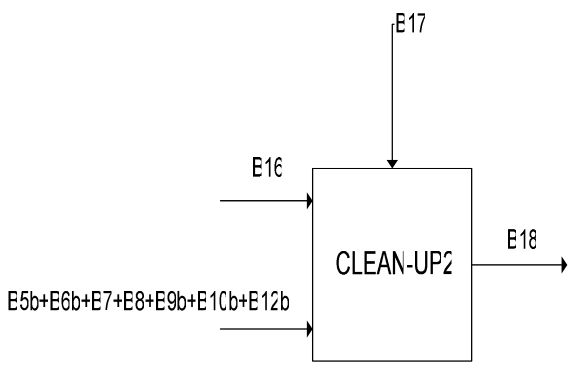

Fig. C.10. Mass balance for second clean up process.

Overall Mass Balance

B18 = B16 + B17 + B5b + B6b + B7 + B8 + B9b + B10b + B12b

n = Multiple of default primary input (user input/default input)

d = Detergent amount per 1214.3g input

w2 = Water amount per 1214.3g input (for clean up 2)

1.) B16 = n * d
2.) B17 = n * w2
3.) B18 = n (d + w2)

Sample Calculations

n = 1214.3/1214.3 =1

d = 1.7
w2 = 7.6

1.) B16= 1.7
2.) B17 = 7.6
3.) B18 = 9.3

C.2 Material Balance Calculations (Backward Direction)

Table C.3
Primary input for cereal production (reverse)

Cereal Production		
Primary Input	**Symbol**	Value
Packaged Extruded Product	B12a	1070.9

The secondary inputs for cereal production for the calculations in the reverse direction are the same as for the calculation in the forward direction (see Table C.2).

Breakfast Cereal Production

Formulas	Sample Calculations
Package 2 (See Fig. C.8)	
Overall Mass Balance	
1.) B10a = B12a + B12b	B12a = 1070.9
	1.) see below
x = fraction lost from Package 2	
x = B12b/(B12a + B12b)	x = 14.1/1085.0 = 0.012995392
2.) B12b = x * B12a/(1-x)	2.) B12b = 0.013*1085/(1 - 0.013)
	B12b = 14.10
	1.) B10a = 1070.9 + 14.10 = 1085.0

Formulas	Sample Calculations
Drying (See Fig. C.7)	
Overall Mass Balance	
B9a = B10a+B10b + B11	
z =fraction lost from oven	
z = B10b/(B10a+B10b)	z = 0/1085.0 = 0
B10b = z * (B10a + B10b)	
1.) B10b = z * B10a/(1-z)	1.) B10b = 0*1085.0/(1-0) = 0
w = fraction of vapor lost from oven	
w = B11/B9a	w = 39.8/1124.8 = 0.035384068
2.) B9a = B11/w	
B9a-B11 = B10a +B10b	
(B11/w)-B11 = B10a +B10b	
3.) B11 = (B10a+B10b)/((1/w)-1)	3.) B11 = 1085/((1/0.035)-1) =39.8
	2.) B9a = 39.8/0.035 = 1124.8

Formulas	Sample Calculations
Prep for Drying (See Fig. C.6)	
Overall mass balance	
1.) B6a = (B9a + B9b)	
	Now know: B9a = 1124.8

v = fraction lost in break = B9b/(B9a+B9b)
B9b = v * (B9a + B9b)
2.) B9b = v * B9a/ (1-v)

v = 0/1124.8 = 0

2.) B9b = 0*1124.8/(1-0) = 0
1.) B6a = 1124.8 + 0 = 1124.8

Formulas

Extrude (See Fig. C.5)

Overall Balance

1.) B5a = B6a + (B6b + B7 + B8)
First find (B6b + B7 + B8) using σ
σ = fraction lost from extruder
σ = (B6b+B7+B8)/(B6a+B6b+B7+B8)
σ*[B6a+(B6b+B7+B8)] = (B6b+B7+B8)
σ * B6a+σ*(B6b +B7 +B8) = (B6b+B7+B8)
σ * B6a = (B6b +B7 + B8) (1-σ)
2.) (B6b +B7 + B8) = σ * B6a/(1-σ)
s = B6b/(B6b +B7 + B8)
3.) B6b = s * (B6b +B7 + B8)
OR B6b= s*σ *B5a
t = B7/(B6b +B7 + B8)
4.) B7 = t * (B6b +B7 + B8)
Or B6 = t*σ * B4
u = B8/(B6b +B7 + B8)
5.) B8 = u * (B6b +B7 + B8) = u*σ*B5a

Sample Calculations

1.) see below

σ=(75.5+50.2)/(1250.5)
σ = 0.100519792

2.) (B6b+B7+B8)= 0.1005*1250.5/(1-0.1005) = 125.70
s = 21.6/(75.5+50.2) = 0.171837709
23.) B6b = 0.1718*125.7 = 21.6

t = 50.2/(75.5+50.2) = 0.399363564
4.) B7 = 0.399363564*125.7=50.2

u = (125.7-50.2-21.6)/125.7 = 0.428798727
5.) B8 = 0.428798727*125.7 = 53.9
1.) B5a = 1124.8 + 125.70 = 1250.5

Formulas

Equilibrate 1 & 2 (See Fig. C.4)

Overall Balance

1.) B4a = (B5a +B5b)
r = fraction lost in equilibrate 1 & 2
r = B5b/(B5a+B5b)
B5b = r * (B5a+B5b)
2.) B5b = r *B5a/(1-r))

Sample Calculations

1.) see below

r = 0/1250.5 = 0

2.) B5b = 0*1250.5/(1-0) = 0
1.) B4a = 1250.5 + 0 = 1250.5

Formulas

Package 1 (See Fig. C.3)

Overall Balance

1.) B3 = B4a + B4b
p = fraction lost from Package 1
p = B4b/(B4a+B4b)
2.) B4b = p *B4a/(1-p)

Sample Calculations

1.) see below
p = 30.8/1281.3 = 0.024038086
2.) B4b = (0.024*1250.5/(1-.024))
B4b = 30.8
1.) B3 = 1250.5 + 30.8 = 1281.3

<u>Formulas</u>

Mix with H2O (See Fig. C.2)

Overall Balance

1.) $B3 = B1 + B2$

Water Balance

$\iota1*B1 + B2 = \iota2*B3$

2.) $B2 = \iota2*B3 - \iota1*B1$

Substisute 2.) into 1.) and solve for B1

$B3 = B1 + (\iota2*B3 - \iota1*B1)$

$B3 - \iota2*B3 = B1 - \iota1*B1$

$B3 * (1- \iota2) = B1 * (1- \iota1)$

3.) $B1 = B3 * (1- \iota2)/(1- \iota1)$

4.) $B3a = \theta2 * B3$

5.) $B3b = \iota2 * B3$

6.) $B3c = \kappa2 * B3$

7.) $B3d = \lambda2 * B3$

8.) $B3e = \mu2 * B3$

9.) $B3f = \nu2 * B3$

<u>Sample Calculations</u>

Must solve equations in reverse order:

3.) $B1 = 1281.3*(1-0.05627)/(1-0)$

$B1 = 1209.2$

2.) $B2 = 0.05627*1281.3 – 0*1209.2$

$B2 = 72.1$

Note: Only 3.) and 2.) are used in Excel

1.) $B3 = 1209.2 + 72.1 = 1281.3$

4.) $B3a = (995.8/1281.3)*1281.3 = 995.8$

5.) $B3b = (72.1/1281.3)*1281.3 = 72.1$

6.) $B3c = (142.3/1281.3)*1281.3 = 142.3$

7.) $B3d = (14.24/1281.3)*1281.3 = 14.24$

8.) $B3e = (42.62/1281.3)*1281.3 = 42.62$

9.) $B3f = (14.24/1281.3)*1281.3 = 14.24$

<u>Formulas</u>

Mix Ingredients (See Fig. C.1)

Overall Balance

$B0 = B1 + B1g$

ξ = fraction lost from mix

$\xi = B1g/B0$

1.) $B0 = B1g/\xi$

Plug 1.) into overall balance to obtain

$B1g/\xi = B1 + B1g$

$B1g/\xi – B1g = B1$

2.) $B1g = B1/((1/\xi) – 1)$

3.) $B0a = \theta1 * B0$

4.) $B0b = \iota1 * B0$

5.) $B0c = \kappa1 * B0$

6.) $B0d = \lambda1 * B0$

7.) $B0e = \mu1 * B0$

8.) $B0f = \nu1 * B0$

<u>Sample Calculations</u>

$\xi = 5.1/1214.3=0.004199951$

1.) see below

2.) $B1g = 1209.2/((1/0.004199951)-1) = 5.1$

1.) $B0 = 5.1/0.004199951 = 1214.3$

3.) $B0a = (1000/1214.3)*1214.3 = 1000$

4.) $B0b = (0/1214.3)*1214.3 = 0$

5.) $B0c = (142.9/1214.3)*1214.3= 142.9$

6.) $B0d = (14.3/1214.3)*1214.3= 14.30$

7.) $B0e = (42.8/1214.3)*1214.3= 42.80$

8.) $B0f = (14.3/1214.3)*1214.3= 14.30$

9) B1a = $\theta 1$ * B1	9.) B1a = (1000/1214.3)*1209.2 = 995.80
10.) B1b = $\iota 1$ * B1	10.) B1b = (0/1214.3)**1209.2 =0.00
11.) B1c = $\kappa 1$ * B1	11.) B1c = (142.9/1214.3)*1209.2 = 142.30
12.) B1d = $\lambda 1$ * B1	12.) B1d = (14.3/1214.3)**1209.2 = 14.24
13.) B1e = $\mu 1$ * B1	13.) B1e = (42.8/1214.3)*1209.2 = 42.62
14.) B1f = $\nu 1$ * B1	14.) B1f = (14.3/1214.3)**1209.2 = 14.24

Formulas	Sample Calculations
Clean Up 1 (See Fig. C.9)	
Overall Mass Balance	
B15 = B13 + B14 + B1g + B4b	
n = Multiple of default primary input (user input/default input)	n = 1070.9/1070.9 =1
d = Detergent amount per 1214.3g input	d = 1.7
w1 = Water amount per 1214.3g input (for clean up 1)	w1 = 1787.5
1.) B13 = n * d	1.) B13 = 1.7
2.) B14 = n * w1	2.) B14 = 1787.5
3.) B15 = n (d + w1)	3.) B15 = 1789.2

Formulas	Sample Calculations
Clean Up 2 (See Fig.C.10)	
Overall Mass Balance	
B18 = B16 + B17 + B5b + B6b + B7 + B8 + B9b + B10b + B12b	
n = Multiple of default primary input (user input/default input)	n = 1070.9/1070.9 =1
d = Detergent amount per 1214.3g input	d = 1.7
w2 = Water amount per 1214.3g input (for clean up 2)	w2 = 7.6
1.) B16 = n * d	1.) B16= 1.7
2.) B17 = n * w2	2.) B17 = 7.6
3.) B18 = n (d + w2)	3.) B18 = 9.3

C.3 Base Case Cereal ESM

Assumptions

1. The quantities of working materials in the system are not taken into account. In reality, the throughput of the system would be different at different configurations.

2. The equivalence factors obtained from the ALS Baseline Values and Assumptions Document (BVAD) (Hanford, 2002) are assumed to be applicable to the sub-system under study.

3. Procedures not involving equipment are considered to involve only the crew time portion of the ESM.

4. The individual components of equation 4.1 are assumed to be independent of each other.

5. The cooling requirements are assumed to be negligible for all processes.

6. The only difference accounted for between the ESM calculations for the different alternatives was in terms of replacing the oven.

7. The same mass equivalence factor is assumed for all equipment.

8. The time required for one cycle of the batch process is 16.83 hours.

9. The individual equipment masses were assumed to be (kg)

Mixer	11.34
Extruder	204.12
Oven	334.00

10. The individual equipment volumes were assumed to be (m^3)

Mixer	0.0445
Extruder	0.680
Oven	0.633

11. The power requirements for individual equipment were assumed to be (kWe)

Mixer	0.45
Extruder	5.60
Oven	2.20

12. The cooling requirements for the individual equipment were assumed to be (kWth)

Mixer	0.00
Extruder	0.00
Oven	0.00

13. The annual crew times associated with the operation of the individual equipment were assumed to be (CM-h/y)

Measure Ingredients	52.82
Mix Manually	75.47

Add H2O & Mix	23.75
Mixer	17.35
Package	32.96
Clean Up 1	114.51
Equilibrate 1	8.68
Equilibrate 2	0
Extruder	103.23
Drying Prep	43.38
Oven	38.2
Package 2	23.42
Clean Up 2	421.60

Calculations

Table C.4
Summary of time usage data for cereal production

Crew Time/Cycle Time Data			
Process/	**Crew Time**	**Equipment Time**	**Total Elapsed Time**
Equipment	**(min)**	**(min)**	**(min)**
1.) Measure Ingredients	10.9	-	10.9
2.) Mix Manually	8.7	-	8.7
3.) Mix Electronically	1	10	11
4.) Add H2O & mix manually	4.9	-	4.9
5.) Mix Electronically	1	4.4	5.4
6.) Package 1	3.8	-	3.8
7.) Clean-Up 1	13.2	-	13.2
8.) Equilibrate 1	1	720	721
9.) Equilibrate 2	-	-	60
10.) Preheat Extruder	0.25	26.6	26.85
11.) Preheat Oven	0.2	25	25.2
12.) Extrude Formulation	11.9	8.2	11.9
13.) Prep for Drying	5	-	5
14.) Drying	0.5	50	50.5
15.) Package 2	2.7	-	2.7
16.) Clean-Up 2	48.6	-	48.6
Totals	113.7	734.4	1009.7

Cycle time in hours: 1009.7min * (1hr/60min) = 16.83 hrs

1. MEASURE INGREDIENTS

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{16.83\frac{hrs}{cycle}} = 520.50\frac{cycles}{yr}$$

Crewtime for measure ingredients per cycle = 10.9 min/cycle

$$CT_{measureingredients} = Crewtime/\,year = \frac{520.50\frac{cycles}{yr} * 10.9\frac{\min}{cycle}}{60\frac{\min}{hr}} = 94.56\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

$$\mathrm{M}_{\mathrm{CT},\,measureingredients} = CT_{measureingredients} * D * CT_{eq}$$

$$\mathrm{M}_{\mathrm{CT},\,measureingredients} = 94.56\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 52.82kg$$

D = 0.49 yr

$ESM_1 = ESM_{rmeasure\ ingredients} = M_{CTmeasure\ ingredients}$

$ESM_1 = ESM_{measure\ ingredients} = 52.82kg$

2. MIX MANUALLY

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{16.83\frac{hrs}{cycle}} = 520.50\frac{cycles}{yr}$$

Crewtime for mix manually per cycle = 8.7 min/cycle

$$CT_{mixmanually} = Crewtime/\,year = \frac{520.5\frac{cycles}{yr} * 8.7\frac{\min}{cycle}}{60\frac{\min}{hr}} = 75.47\frac{CM-hr}{yr}$$

$$\mathrm{M}_{\mathrm{CT},\,mixmanually} = CT_{mixmanually} * D * CT_{eq} = 75.47\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 42.16kg$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$ESM_2 = ESM_{mix\ manually} = M_{CT,mix\ manually}$
$ESM_2 = ESM_{mix\ manually} = 42.16kg$

3. <u>MIX ELECTRONICALLY</u> (SEE 5.)

4. <u>ADD H2O AND MIX MANUALLY</u>

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{16.83\frac{hrs}{cycle}} = 520.50\frac{cycles}{yr}$$

Crewtime for add H2O and mix per cycle = 4.9 min/cycle

$$M_{CT,addH2Oandmix} = CT_{addH2Oandmix} * D * CT_{eq}$$

$$M_{CT,addH2Oandmix} = 42.51\frac{CM-hr}{yr} * 0.49yr * 1.14\frac{kg}{CM-hr} = 23.75kg$$

$$CT_{addH2Oandmix} = Crewtime/\ year = \frac{520.5\frac{cycles}{yr} * 4.9\frac{\min}{cycle}}{60\frac{\min}{hr}} = 42.51\frac{CM-hr}{yr}$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

$D = 0.49\ yr$

$ESM_1 = ESM_{add\ H2O\ and\ mix} = M_{CT,add\ H2O\ and\ mix}$
$ESM_1 = ESM_{add\ H2O\ and\ mix} = 23.75kg$

5. <u>MIX ELECTRONICALLY</u> (3. AND 5. BOTH UTILIZE THE MIXER)

<u>MIXER</u> (KitchenAid, 2005)

Specifications are for a Model KM25G0XWH KitchenAid Mixer (Commercial 5 Series, 5-Quart/11 cup mixer, white)

Mass

Net weight = 25lb_f , [8] = F; F = m*a; m=F/A; a=g=32.174ft/s^2

$$M_{mixer} = 25lb_f * \frac{32.174lb_m\frac{ft}{s^2}}{1lb_f} * \frac{453.593g}{1lb_m} * \frac{1}{32.174\frac{ft}{s^2}}$$

$M_{mixer} = 11340g$
$M_{mixer} = 11.340kg$

Volume

$V_{mixer} = L*W*H$

$V_{mixer} = (14\frac{19}{32} * 16\frac{1}{2} * 11\frac{9}{32})in^3$

V_{mixer} =(2716.49)in^3

V_{mixer} = 0.04452m^3

$V_{eq} = 215\frac{kg}{m^3}$

$M_{v,mixer}$ = V* Veq=0.04452 *215=9.572kg

Power

P_{mixer}=*0.45 kW* , [8]

P_{eq}= *237kg/kW*

$$\alpha_{mixer} = \frac{14.4\min}{16.83hr * 60\frac{\min}{hr}} = 0.0143$$

$M_{p,mixer} = \alpha_{mixer} * P_{mixer} * P_{eq} = 0.0143 * 106.65kg$ =1.525kg

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{16.83\frac{hrs}{cycle}} = 520.50\frac{cycles}{yr}$$

Crewtime for mixer per cycle = 2 min/cycle

$$CT_{mixer} = Crewtime / year = \frac{520.5\frac{cycles}{yr} * 2\frac{\min}{cycle}}{60\frac{\min}{hr}} = 17.35\frac{CM - hr}{yr}$$

$$M_{CT,mixer} = CT_{mixer} * D * CT_{eq} = 17.35\frac{CM - hr}{yr} * 0.49yr * 1.14\frac{kg}{CM - hr} = 9.69kg$$

$CT_{eq} = 1.14\frac{kg}{CM - hr}$

D = 0.49 yr

$ESM_3 + ESM_5 = ESM_{mixer} = M_{mixer} + M_{v,mixer} + M_{p,mixer} + M_{c,mixer} + M_{CT,mixer}$

$ESM_3 + ESM_5 = ESM_{mixer} = 11.3 + 9.57 + 1.525 + 0 + 9.69kg = 32.08kg$

6. <u>PACKAGE 1</u>

Crew Time

$$\textit{Number of cycles per year} = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{16.83\frac{hrs}{cycle}} = 520.50\frac{cycles}{yr}$$

Crewtime for package 1 per cycle = 3.8 min/cycle

$$CT_{\text{package 1}} = Crewtime / year = \frac{520.5\frac{cycles}{yr} * 3.8\frac{\min}{cycle}}{60\frac{\min}{hr}} = 32.96\frac{CM - hr}{yr}$$

$$\text{M}_{\text{CT, package 1}} = CT_{\text{package 1}} * D * CT_{eq} = 32.96\frac{CM - hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM - hr} = 18.41kg$$

$$CT_{eq} = 1.14\frac{kg}{CM - hr}$$

D = 0.49 yr

$ESM_6 = ESM_{package\ 1} = M_{CT,\ package\ 1}$
$ESM_6 = ESM_{package\ 1} = 18.41kg$

7. <u>CLEAN UP 1</u>

Crew Time

$$\textit{Number of cycles per year} = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{16.83\frac{hrs}{cycle}} = 520.50\frac{cycles}{yr}$$

Crewtime for mixer per cycle = 13.2 min/cycle

$$CT_{cleanup1} = Crewtime / year = \frac{520.5\frac{cycles}{yr} * 13.2\frac{\min}{cycle}}{60\frac{\min}{hr}} = 114.51\frac{CM - hr}{yr}$$

$$\text{M}_{\text{CT},\,cleanup1} = CT_{cleanup1} * D * CT_{eq} = 114.51\frac{CM - hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM - hr} = 63.96kg$$

$$CT_{eq} = 1.14\frac{kg}{CM - hr}$$

D = 0.49 yr

$ESM_7 = ESM_{clean\ up\ 1} = M_{CT,\ clean\ up\ 1}$
$ESM_7 = ESM_{clean\ up\ 1} = 63.96kg$

8. EQUILIBRATE 1

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr}*24\frac{hrs}{day}}{16.83\frac{hrs}{cycle}} = 520.50\frac{cycles}{yr}$$

Crewtime for equilibrate1 per cycle = 1.0 min/cycle

$$CT_{equilibrate1} = Crewtime/year = \frac{520.5\frac{cycles}{yr}*1.0\frac{\min}{cycle}}{60\frac{\min}{hr}} = 8.68\frac{CM-hr}{yr}$$

$$\mathrm{M}_{\mathrm{CT},\,equilibrate1} = CT_{equilibrate1}*D*CT_{eq} = 8.68\frac{CM-hr}{yr}*0.49\,yr*1.14\frac{kg}{CM-hr} = 4.85kg$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$ESM_8 = ESM_{equilibrate\ 1} = M_{CT,\ equilibrate\ 1}$

$ESM_8 = ESM_{equilibrate\ 1} = 4.85kg$

9. EQUILIBRATE 2

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr}*24\frac{hrs}{day}}{15.3\frac{hrs}{cycle}} = 572.55\frac{cycles}{yr}$$

Crewtime for equilibrate 2 per cycle = 5 min/cycle

$$CT_{equilibrate2} = Crewtime/year = \frac{520.5\frac{cycles}{yr}*0\frac{\min}{cycle}}{60\frac{\min}{hr}} = 0.0\frac{CM-hr}{yr}$$

$$\mathrm{M}_{\mathrm{CT},\,mixer} = CT_{mixer}*D*CT_{eq} = 0.0\frac{CM-hr}{yr}*0.49\,yr*1.14\frac{kg}{CM-hr} = 0.0kg$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$ESM_1 = ESM_{mixer} = M_{mixer} + M_{v,mixer} + M_{p,mixer} + M_{c,mixer} + M_{CT,mixer}$

$ESM_1 = ESM_{mixer} = 0.0kg$

10. PREHEAT EXTRUDER (SEE 12.)

11. PREHEAT OVEN(SEE 14.)

12. EXTRUDE FORMULATION (10. AND 12. UTILIZE THE EXTRUDER)

EXTRUDER (Extruder, 2005)
(For company contact info and additional info)
Assumption: Total weight of extruder and all supporting equipment is approximately 450lbf
Mass

Net weight = $450 lb_f$ = F; F = m*a; m=F/A; a=g=32.174ft/s^2

$$M_{extruder} = 450\ lb_f * \frac{32.174 lb_m \frac{ft}{s^2}}{1 lb_f} * \frac{453.593 g}{1 lb_m} * \frac{1}{32.174 \frac{ft}{s^2}}$$

$M_{extruder} = 204116.9g$

$M_{extruder} = 204.12\ kg$

Volume
Assume: Length is approximately 3 feet, Width is approximately 2 feet and height is approximately 4 feet.

$V_{extruder} = L*W*H$

$V_{extruder} = (36*24*48) in^3$

$V_{extruder} = (41472.00) in^3$

$V_{extruder} = 0.680 m^3$

$V_{eq} = 215 \frac{kg}{m^3}$

$M_{v,extruder} = V* Veq = 0.680*215 = 146.12kg$

Power

$P_{extruder} = 7.5hp*0.746kW/hp$ (from label on equipment)

$P_{extruder} = 5.595kW$

$P_{eq} = 237kg/kW$

$$\alpha_{extruder} = \frac{34.8 \min}{16.83 hr * 60 \frac{\min}{hr}} = 0.0345654$$

$M_{p,extruder} = \alpha_{extruder} * P_{extruder} * P_{eq} = 0.0345 * 1324.8 kg = 45.70kg$

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{16.83\frac{hrs}{cycle}} = 520.50\frac{cycles}{yr}$$

Crewtime for extruder per cycle = 11.9 min/cycle

$$CT_{extruder} = Crewtime / year = \frac{520.5\frac{cycles}{yr} * 11.9\frac{\min}{cycle}}{60\frac{\min}{hr}} = 103.23\frac{CM-hr}{yr}$$

$$\mathrm{M}_{\mathrm{CT},\,extruder} = CT_{extruder} * D * CT_{eq} = 103.23\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 57.66kg$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$ESM_{10}+ESM_{12}=ESM_{extruder}= M_{extruder}+M_{v,extruder}+M_{p,extruder}+M_{c,extruder}+M_{CT,extruder}$

$ESM_{10}+ESM_{12}=ESM_{extruder}=204.12kg+146.12kg+45.70kg+0kg+57.66=453.60kg$

13. PREP FOR DRYING

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{16.83\frac{hrs}{cycle}} = 520.50\frac{cycles}{yr}$$

Crewtime for drying prep per cycle = 5 min/cycle

$$CT_{dryingprep} = Crewtime / year = \frac{520.5\frac{cycles}{yr} * 5\frac{\min}{cycle}}{60\frac{\min}{hr}} = 43.38\frac{CM-hr}{yr}$$

$$\mathrm{M}_{\mathrm{CT},\,dryingprep} = CT_{dryingprep} * D * CT_{eq}$$

$$\mathrm{M}_{\mathrm{CT},\,dryingprep} = 43.38\frac{CM-hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM-hr} = 24.23kg$$

$$CT_{eq} = 1.14\frac{kg}{CM-hr}$$

D = 0.49 yr

$ESM_{13}=ESM_{drying\ prep}= M_{CT,drying\ prep}$

$ESM_{13}=ESM_{drying\ prep}=24.23kg$

14. <u>DRYING</u> (11. AND 14. REQUIRE THE OVEN)

OVEN (Shellab, 2005)

Basis: Shel Lab Oven Model HF4-2 (horizontal air flow oven)
Capacity: 4.7 cu. Ft (133L)=0.13309m^3
Interior dimensions: (20.5*20*20.1)in^3 or (52*50.8*51)cm^3 (~0.1347m^3)
Exterior dimensions: (35*29*38)in^3 or (89*73.7*96.5)cm^3 (~0.633m^3)
Power: 2200Watts
Composition: Stainless steel interior (assume 1.75in thick) ρ=8.0g/cm^3; fiberglass exterior (insulation; given:3.5in thick) ρ=124.8lb/ft^3
Temperature range: ambient +15^{O}C to 300^{O}C

Mass

M_{oven} = Encasement Mass + Interior Mass
Interior volume= [(20.5*20*20.1)-(20.5-1.75)*(20-1.75)*(20.1-1.75)]in^3
Interior volume= [(20.5*20*20.1)-(18.75*18.25*18.35)]in^3
Interior volume= 1961.859375in^3
Interior volume= 0.0321m^3
Interior: $M_{oven,1}$ = 0.0321m^3*8.0g/cm^3=256,800g
$M_{oven,1}$ =256.8kg

Encasement volume=[(89-52)*(73.7-50.8)*(96.5-51)]cm^3
Encasement volume=(37*22.8*45.5)cm^3
Encasement volume=38552.15cm^3
Encasement volume=0.03855215m^3
Encasement: $M_{oven,2}$ = 0.0385m^3*124.8lbm/ft^3*453.593g/lbm*$(3.2808ft)^3/m^3$
$M_{oven,2}$ =76.96kg
M_{oven} = Encasement Mass + Interior Mass
M_{oven} = $M_{oven,1}$ +$M_{oven,2}$ =257kg+77kg
M_{oven} =334kg

Volume

Using exterior dimensions
V_{oven} = L*W*H
V_{oven} = (89*73.7*96.5)cm^3
V_{oven} = (632972)cm^3
V_{oven} = 0.633m^3
$V_{eq} = 215\frac{kg}{m^3}$
$M_{v,oven}$ = V* Veq=0.633*215=136.095kg

Power

$P_{oven}=2.2\ kW$, [9]
$P_{eq}= 237kg/kW$

$$\alpha_{oven} = \frac{75\min}{16.83hr * 60\frac{\min}{hr}} = 0.0743$$

$M_{p,oven} = \alpha_{oven} * P_{oven} * P_{eq} = 0.0743 * 521.4kg = 38.74kg$

Cooling

None

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{16.83\frac{hrs}{cycle}} = 520.50\frac{cycles}{yr}$$

Crewtime for oven per cycle = 0.7 min/cycle

$$CT_{oven} = Crewtime / year = \frac{520.5\frac{cycles}{yr} * 0.7\frac{\min}{cycle}}{60\frac{\min}{hr}} = 6.07\frac{CM - hr}{yr}$$

$$M_{CT,oven} = CT_{oven} * D * CT_{eq} = 6.07\frac{CM - hr}{yr} * 0.49yr * 1.14\frac{kg}{CM - hr} = 3.39kg$$

$$CT_{eq} = 1.14\frac{kg}{CM - hr}$$

D = 0.49 yr

$ESM_1 = ESM_{oven} = M_{oven} + M_{v,oven} + M_{p,oven} + M_{c,oven} + M_{CT,oven}$

$ESM_1 = ESM_{oven} = 334kg + 136kg + 38.74kg + 0kg + 3.39kg = 512.13kg$

15. PACKAGE 2

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{15.3\frac{hrs}{cycle}} = 572.55\frac{cycles}{yr}$$

Crewtime for package 2 per cycle = 2.7 min/cycle

$$CT_{package2} = Crewtime / year = \frac{520.5\frac{cycles}{yr} * 2.7\frac{\min}{cycle}}{60\frac{\min}{hr}} = 23.42\frac{CM - hr}{yr}$$

$$M_{CT,\ package2} = CT_{package2} * D * CT_{eq} = 23.42 \frac{CM-hr}{yr} * 0.49\,yr * 1.14 \frac{kg}{CM-hr} = 13.08kg$$

$$CT_{eq} = 1.14 \frac{kg}{CM-hr}$$

D = 0.49 yr

ESM_{15}=$ESM_{package\ 2}$= $M_{CT,package}$
$ESM5_1$=$ESM_{package}$= 13.08kg

16. CLEAN UP 2

Crew Time

$$Number\ of\ cycles\ per\ year = \frac{365 \frac{days}{yr} * 24 \frac{hrs}{day}}{16.83 \frac{hrs}{cycle}} = 520.50 \frac{cycles}{yr}$$

Crewtime for clean up2 per cycle = 48.6 min/cycle

$$CT_{cleanup2} = Crewtime / year = \frac{520.5 \frac{cycles}{yr} * 48.6 \frac{\min}{cycle}}{60 \frac{\min}{hr}} = 421.60 \frac{CM-hr}{yr}$$

$$M_{CT,\ mixer} = CT_{mixer} * D * CT_{eq} = 421.60 \frac{CM-hr}{yr} * 0.49\,yr * 1.14 \frac{kg}{CM-hr} = 235.50kg$$

$$CT_{eq} = 1.14 \frac{kg}{CM-hr}$$

D = 0.49 yr

ESM_{16}=$ESM_{clean\ up\ 2}$= $M_{CT,clean\ up\ 2}$
ESM_{16}=$ESM_{clean\ up\ 2}$=235.50kg

TOTAL ESM

Base Case

$ESM_{BC} = \sum_{i=1}^{16} ESM_i$ = $ESM_1 + ESM_2 + ESM_3 + ESM_4 + ESM_5 + ESM_6 + ESM_7 + ESM_8$ $+ ESM_9 + ESM_{10} + ESM_{11} + ESM_{12} + ESM_{13} + ESM_{14} + ESM_{15} + ESM_{16}$

ESM_{BC}=(52.82 + 42.16 + 23.75 + 32.08 + 18.41 + 63.96 + 4.85 + 0 + 453.60 + 24.23 +13.08+235.50+512.13)=1476.57kg

Observations

1. Total crew time for the breakfast cereal technology is 549.5kg. This is approximately 37.2% of the total ESM.

$$M_{CT} = \sum_{i=1}^{16} M_{CTi} = 52.82 + 42.16 + 23.75 + 9.69 + 18.41 + 63.96 + 4.85 + 57.66 + 24.23 + 13.08 + 235.5 + 3.39 = 549.5kg$$

The cost associate with crew time can contribute significantly to the total ESM.

2. Automation of the entire system or at least portions of the system would greatly reduce crew-time costs.
3. The oven ($ESM_{Oven} = 512.13kg$) constitutes a significant portion (approximately 34.7%) of ESM costs.
4. Equipment and procedural alternatives need to be sought out for high ESM demand portions for each process/equipment. In this case alternative should be sought for the oven, extruder, and clean up 2 step. Namely, a smaller size or scale extruder and oven should be sought since the bulk of the ESM cost is due to mass and volume and partial or total automation of clean up 2 should be investigated.

C.4 Cereal Alternative ESM

Sizing of the oven based on actual amounts of working material is explored in this analysis. Below are the calculations for the oven. All other equipment and procedure calculations remained the same.

14. DRYING (11. AND 14. REQUIRE THE OVEN)

OVEN

Volume

(See Fig. C.11)

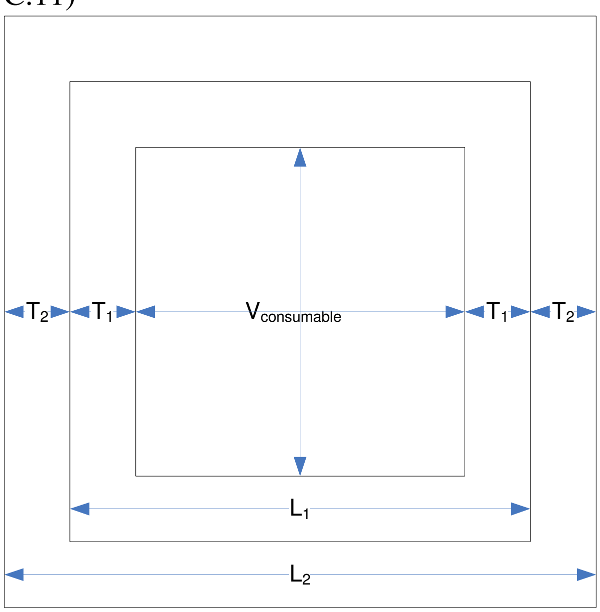

Fig.C.11. Two-dimensional depiction of oven dimensions.

Assume 30% scale up (Peters and Timmerhaus, 1986).
$V_{consumable}$ = 4500.2 cm^3
V_{oven} = 1.3 * 4500.2 cm^3
V_{oven} = 5850.26cm3
V_{oven} = 0.005850.26m^3
$V_{eq} = 215\frac{kg}{m^3}$
$M_{v,oven}$ = V* Veq
$M_{v,oven}$ = 0.005850*215
$M_{v,oven}$ = 1.26kg

Mass
Basis: Shel Lab Oven Model HF4-2 (horizontal air flow oven) (Shellab, 2005) Lengths: L_1=34in; L_2 = 20in; Composition:
Stainless steel interior (assume 1.75in thick) ρ=8.0g/cm^3; fiberglass exterior (insulation; given:3.5in thick) ρ=124.8lb/ft^3

$\rho_{stainless\ steel}$ = 8.0g/cm^3
$\rho_{fiber\ glass}$ = 124.8lb/ft^3
$\rho_{fiber\ glass}$ = 185.720kg/m^3
T_1/L_1 = 0.0875
T_2/L_2 = 0.103

Mass
M_{oven} = Stainless steel Mass + Fiberglass Mass
$M_{oven} = M_{oven,S} + M_{oven,F}$
V_{oven} = Total volume = 1.3 * $V_{consumable}$
V_{oven} = 1.3 * 4500.2 cm^3
V_{oven} = 5850.26cm^3
$V_{oven} = (L_2)^3$
L_2 =18cm
$T_2 = L_2$ * 0.103 = 1.854
L_2/ L_1 = 1.7
$L_1 = L_2/1.7$
L_1 = 10.6cm
$T_1 = L_1$* 0.0875 = 10.6cm * 0.0875
T_1 = 0.9275cm

$V_{oven,S}$ = Volume of stainless steel encasement
$V_{oven,S} = V_{oven} - (T_2)^3 - V_{consumable}$
$V_{oven,S}$ = (5850.26-6.37-4500.2)cm^3
$V_{oven,S}$ = 1343.69cm^3
$M_{oven,S}$ = 8.0g/cm^3*1343.69cm^3
$M_{oven,S}$ = 10, 749.52g
$M_{oven,S}$ = 10.7 kg

$V_{oven,F}$ = Volume of fiberglass encasement
$V_{oven,F} = V_{oven} - (T_1)^3 - V_{consumable}$
$V_{oven,F}$ = (5850.26-0.9275-4500.2)cm^3
$V_{oven,F}$ = 1349.26 cm^3
$M_{oven,F}$ = 185.720kg/m^3*1m^3/(100cm)^3*1343.69cm^3
$M_{oven,F}$ = 0.25058kg

$M_{oven} = M_{oven,S} + M_{oven,F}$
M_{oven} = 10.7kg + 0.251kg
M_{oven} = 10.951kg

Power

Calculate power requirement using specific heat capacity (Snokes, 2006) and temperature data.
Calculating specific heat capacity for food and agricultural products:
Wet Basis:
Based on moisture content (M=M0) with C_p [=] kJ/kg.K
Above freezing: $C_p = 0.837 + 3.348*M$
Below freezing: $C_p = 0.837 + 1.256*M$

Dry Basis:
$C_{p,sp} = 4.180 * x_w + 1.711*x_p + 1.928*x_f + 1.547*x_c + 0.908*x_a$
Where x_w = mass fraction of water
x_p = mass fraction of protein
x_f = mass fraction of fat
x_c = mass fraction of carbohydrate
x_a = mass fraction of ash

The composition of the sweetpotato cereal stream entering the oven is as follows:
$x_w = 0.029$
$x_p = 0.8424$
$x_f = 0.089$
$x_c = 0.0096$
$x_a = 0.03$

$C_{p,sp}$=
4.180*(0.029)+1.711*(0.8424)+1.928*(0.089)+1.547*(0.0096)+0.908*(0.03)
$C_{p,sp}$ = 1.776 kJ/kg.K
$T_9 = 25^oC$ = temperature of cereal entering the drying oven
$T_{10} = 70^oC$ = temperature of cereal exiting the drying oven
$Q_{p,sp} = M_{sp} * C_{p,sp} (T_{10}-T_9)$
$Q_{p,sp}$ = (1.1248kg)(1.776 kJ/kg.K) (70-25) K
$Q_{p,sp}$ = 89.89 kJ = 89,890J
P_{sp} = 89,890J/3000s = 29.963 W
P_{sp} = 0.029963 kW

For the air being heated by the oven

$C_{p,air} = 1000$ J/kg.K = 1kJ/kg.K

$\rho_{air} = 1.2929$kg/m^3

$M_{air} = V_{oven} * \rho_{air}$

$M_{air} = 5850.26cm^{3*}1.2929kg/m^3*1m^3/(100cm)^3$

$M_{air} = 0.0075638$kg

$Q_{p,air} = 0.0075638$kg *1000 J/kg.K * (70-25) K

$Q_{p,air} = 340.371$ J

$P_{air} = 340.371$ J/1500s = 0.226914W

$P_{air} = 0.0002269$kW

$P_{oven} = P_{sp} + P_{air}$

$P_{oven} = 0.029963$ kW + 0.0002269kW

$P_{oven} = 0.0323$kW

$P_{eq} = 237kg/kW$

$$\alpha_{oven} = \frac{75\min}{16.83hr * 60\frac{\min}{hr}} = 0.0743$$

$M_{p,oven} = \alpha_{oven} * P_{oven} * P_{eq} = 0.0743 * 7.66kg = 0.569$kg

Cooling

None

Crew Time

$$\textit{Number of cycles per year} = \frac{365\frac{days}{yr} * 24\frac{hrs}{day}}{16.83\frac{hrs}{cycle}} = 520.50\frac{cycles}{yr}$$

Crewtime for oven per cycle = 0.7 min/cycle

$$CT_{oven} = Crewtime / year = \frac{520.5\frac{cycles}{yr} * 0.7\frac{\min}{cycle}}{60\frac{\min}{hr}} = 6.07\frac{CM - hr}{yr}$$

$$M_{CT,oven} = CT_{oven} * D * CT_{eq} = 6.07\frac{CM - hr}{yr} * 0.49\,yr * 1.14\frac{kg}{CM - hr} = 3.39kg$$

$$CT_{eq} = 1.14\frac{kg}{CM - hr}$$

$D = 0.49$ yr

$ESM_1 = ESM_{oven} = M_{oven} + M_{v,oven} + M_{p,oven} + M_{c,oven} + M_{CT,oven}$

$ESM_1 = ESM_{oven} = 10.951kg + 1.26kg + 0.569kg + 0kg + 3.39kg = 16.17kg$

<u>TOTAL ESM</u>

Base Case

$$ESM_{BC} = \sum_{i=1}^{16} ESM_i = ESM_1 + ESM_2 + ESM_3 + ESM_4 + ESM_5 + ESM_6 + ESM_7 + ESM_8 + ESM_9 + ESM_{10} + ESM_{11} + ESM_{12} + ESM_{13} + ESM_{14} + ESM_{15} + ESM_{16}$$

$$ESM_{BC}=(52.82 + 42.16 + 23.75 + 32.08 + 18.41 + 63.96 + 4.85 + 0 + 453.60 + 24.23 +13.08+235.50+512.13)=1476.57kg$$

Alternative 1

$$ESM_{A1} = \sum_{i=1}^{16} ESM_i = ESM_1 + ESM_2 + ESM_3 + ESM_4 + ESM_5 + ESM_6 + ESM_7 + ESM_8 + ESM_9 + ESM_{10} + ESM_{11} + ESM_{12} + ESM_{13} + ESM_{14} + ESM_{15} + ESM_{16}$$

$$ESM_{A1}=(52.82 + 42.16 + 23.75 + 32.08 + 18.41 + 63.96 + 4.85 + 0 + 453.60 + 24.23 +13.08+235.50+16.17)=980.61kg$$

Observations

1. Total crew time for the breakfast cereal technology is 549.5kg. This is approximately 37.2% of the total ESM.

$$M_{CT} = \sum_{i=1}^{16} M_{CTi} = 52.82 + 42.16 + 23.75 + 9.69 + 18.41 + 63.96 + 4.85 + 57.66 + 24.23 + 13.08 + 235.5 + 3.39 = 549.5kg$$

The cost associate with crew time can contribute significantly to the total ESM.

2. Automation of the entire system or at least portions of the system would greatly reduce crew-time costs.
3. The base case ESM for the oven was $ESM_{Oven} = 512.13kg$ and constituted approximately 34.7% of the ESM costs. By sizing an oven based on the amount of material that passes through the oven, the oven ESM was reduced to $ESM_{Oven,A1} = 16.17kg$. In the first alternative case, the oven only constitutes 1.65% of the ESM and it coincides with the 33.6% reduction in ESM costs.
4. Equipment and procedural alternatives need to be sought out for high ESM demand portions for each process/equipment. In this case an alternative was demonstrated for the oven. Alternatives should also be sought for the extruder and the second clean up step. Namely, a smaller size or scale extruder should be sought since the bulk of the ESM cost is due to its mass and volume, and partial or total automation of clean up 2 should be investigated.

VITA

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