Published in final edited form as:

ESCAPE. 2018 ; 43: 391–396. doi:10.1016/B978-0-444-64235-6.50071-1.

Towards a Quantitative Food-Energy-Water Nexus Metric to Facilitate Decision Making in Process Systems: A Case Study on a Dairy Production Plant

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Abstract

While the importance of the Food-Energy-Water Nexus (FEW-N) has been widely accepted, a holistic approach to facilitate decision making in FEW-N systems, along with a quantitative index assessing the integrated FEW-N performance is rather lacking. In this work, we propose a FEW-N metric along with a framework to facilitate decision making for FEW-N process systems through a FEW-N integrated approach.

The framework and metric are illustrated through a case study on a dairy production and processing plant. The dairy industry is a significant user of water and energy, with water being a top issue for most dairy industries and organizations worldwide. Following the framework, we develop a mixed-integer scheduling model, with alternative pathways, that faithfully replicated the major food, energy, and water aspects of a real cottage-cheese production plant. Using the developed FEW-N metric we were able to optimize the cottage-cheese plant process and observe different trade-offs between the FEW-N elements.

Keywords

Food-Energy-Water Nexus; Multi-Objective Optimization

1. Introduction

The Food-Energy-Water Nexus (FEW-N) is becoming an increasingly significant and active area of research in Process Systems Engineering. Elements of the FEW-N are tightly interlinked and interdependent. For example, 70% of global water use and 30% of global energy use goes towards food production (Garcia and You, 2016).

However, interactions and trade-offs between FEW elements, as well as trade-offs with factors relevant to a decision maker (e.g. Profit), remain difficult to quantify. From a process systems engineering perspective, this makes it very challenging to account for the trade-offs between elements when designing optimized process systems.

The goal of this work is to provide ideas and analysis towards the development of a FEW- N metric, and develop a methodology that will account for the interactions between elements in the FEW-N in a manner that is specific enough to be used in process optimization.

2. FEW-N metric

2.1. Elements and Dependencies of the FEW-N metric

The FEW-N metric can be decomposed into dimensions, indicators, and indexes. In our case-study for example, a dimension we consider is the “Water Dimension.” Indicators for the “Water Dimension” include the amount of water used for cleaning and water used for pasteurization. These “Water Indicators” are then normalized to develop a “Water Index.” This index is then aggregated with the other indices to form a metric.

To develop and analyse a FEW-N metric, we have firstly detailed its components and aggregated their dependencies, illustrated in Table 1.

All dependencies must be developed through extensive research and analysis for each particular process system, therefore a single metric for all FEW Nexus systems is unlikely. Therefore, a methodology for developing such a metric for FEW-N systems will be presented.

The FEW-N metric developed in this work is meant to be used as an ‘optimizable’ measure of a process system’s impact on the FEW-N. The purpose of the metric is not to describe the system relative to other completely different process systems, but to compare the system to other iterations or alternatives of the same system.

2.2. Mathematical Form of the metric

We have tested four different mathematical forms for aggregating FEW elements along with any other element that interest the decision maker (e.g. cost, safety, environmental impact) into one composite metric. For all methods, the objective is to maximize the metric. Metrics include: i) linear average (LA), ii) bilinear average (BA), iii) trilinear average (TA) and iv) quadrilinear average (QA). Metrics are all determined using Eq. 1.

$$r^{\text{th}} \text{ order avrage} = \frac{\text{Sum of all } r^{\text{th}} \text{ order multiplicative combinations of decision indexes}}{C_r^n} \quad (1)$$

where C_r^n is the total number of possible r^{th} order combinations of n decision indexes. In our study, each index is given the same weight.

2.2.1. Linear average (LA)—The mathematical form of this metric is the simple arithmetic mean of the dimension indexes. Emphasis can be placed on one or more elements by multiplying the element index by a weighting factor. The key property of LA is that it implies perfect substitutability between the elements of the FEW-N. That means that an improvement in one area can be neutralized by proportional worsening in another area.

2.2.2. Higher order averages (BA, TA, QA)—Weighting for those mathematical forms is done by raising the indexes to the power of the weight factor. With increasing order of the average the substitutability between dimensions is decreasing, until the order is equal to the number of dimension elements, where it allows for the least substitutability, and gives the greatest implicit weight to elements that are low in value.

2.3. Normalization scheme

The decision indexes are normalized to values between 0 and 1. The normalization is based upon the maximum and minimum values of each element index that are possible in the process system under investigation. A value of 1 represents the ‘best-case’ scenario (e.g. minimum energy, maximum food, etc.) for the element in the process system.

The proposed metrics were applied to the cottage cheese plant case-study to determine the effect of the mathematical form of the metric on the optimal solution.

3. Case study: Cottage cheese plant

To develop and test our metric and methodology, we used a cottage cheese plant (CCP) case study taken largely from the work of Stefanis et al. (1997). We made considerable additions to Stefanis’ model to better represent the FEW-N trade-offs.

The dairy industry consumes a huge amount of energy and water. In the United States alone, there are over 5,000 dairy plants that discharge over 200 billion liters of waste – water. This waste water is high in Biological Oxygen Demand and contains harmful pollutants and suspended solids and therefore must be treated in energy intensive processes. Still, roughly 40% of this wastewater is discharged directly into bodies of freshwater (Northwest Food Processor Association, 2017).

Cottage cheese in particular requires a large amount of water to be produced, somewhere between 0.8 and 12.4 kg of water per kg of milk processed (Northwest Food Processor Association, 2017). For these reasons, a cottage cheese plant is an excellent case study to observe the FEW Nexus interactions.

3.1. Process Description

The process is largely taken from Stefanis et al. (1997), and modifications were made to introduce energy and water elements in the process. The plant specifications are kept the same as in Stefanis et al. (1997), with the required production of cheese being 137.7 t over 5508 h/y production time. Skimmed milk is fed to the process and after pasteurization, is mixed with culture in up to three vat processors with different design specifications for 240 minutes to produce curd and whey. Optionally, the curd is stored before further processing.

The curd is then drained (30 min) and the solidified curd is blended with cream for 60 minutes to produce cottage cheese which is then filled into different size containers (Fillers 1 and 2). The final products are then stored in warehouses for delivery.

The whey by-product is further processed to recover the concentrated protein and lactose (sold as by-products) in two membrane separation stages: the ultrafiltration stage (240 min) and the reverse osmosis stage (60 min). For constant recovery, the ultrafiltration stage is maintained at 4 atm pressure drop while protein by-product recovery and waste generation depend on the operating pressure of the reverse osmosis unit (1.7 – 3.8 atm).

Cleaning-in-Place (CIP) is an essential part of dairy plant operation. All units that involve heating of milk must be cleaned after each use. For this case study, this means that the Pasteurizer, all Vats, and the Drainer must all be cleaned.

Cleaning takes 30 minutes and uses 100 kg of detergent. Detergent is made in the CIP Tank by mixing chlorinated water with NaOH to form a 0.5% NaOH solution. After cleaning, roughly half of the detergent can be recycled. Used detergent is then either stored or sent to nanofiltration (60 minutes) for 90% recovery of clean detergent.

3.1.1. Food aspect of the CCP—The food aspect of the process does not only include the cheese produced, that is constant at 137.7 t per year of operation, but also includes the protein and lactose by-products. Although the amount of cheese and protein produced never varies, there is variability in the amount of lactose that is produced. This variability stems from the pressure of the reverse osmosis unit. At higher pressures, more lactose is produced at increased economic and energy cost.

3.1.2. Energy aspect of the CCP—The energy required to raise the cleaning water from room temperature to 50°C was also accounted for and the higher the amount of cleaning, the more energy required (Clark and Potter, 2007). Moreover, we included the energy required to refrigerate the stored milk, cheese, curd, and cream in their respective storage tanks (Sun et al., 2017). These calculations all assumed a constant value for the amount of energy lost per unit time and a coefficient-of- performance for refrigeration. Finally, the amount of energy required to operate the pasteurizer as a function of throughput was accounted for.

3.1.3. Water aspect of the CCP—The water aspects of the process included the steam used for pasteurization, the water used for cleaning, the water used for washing curd (roughly 2.5 times the amount of milk processed) (Clark and Potter, 2007), and the waste water generated by the process. The amount of Waste 2 generated varied with the amount of lactose produced. The more lactose produced, the lower the amount of Waste 2, at the expense of higher energy and operating costs.

The developed scheduling model was implemented in GAMS and consisted of 4,096 equations, 1,241 integer variables and 2,518 continuous variables. The detailed model was excluded here due to page restrictions but can be provided upon request.

4. Optimal solutions

The dimension elements of the FEW-N metric for the case study included the three FEW- N elements and the profit element (Revenue – Operating/Fixed Cost). For each FEW-N metric an optimization problem was formed with objective to maximize each the metric subject to the constraints of the CCP schedule model. For comparison purposes, another four optimization problems were formed and solved to maximize profit and food produced, and minimize energy used and water used.

All optimization problems were solved to 2% optimality using global optimization solvers (BARON and ANTIGONE) for mixed-integer non-linear optimization problems.

The numerical solutions for of each problem created from the metrics are presented in Table 2 and are compared with the value of each metric for various objectives that a decision maker may consider. Objectives included: maximize profit, maximize food production, minimize energy use, and minimize water use. The solution schedule for the LA metric is presented in Fig.2. The full detailed numerical solutions, along with the schedules for BA, TA and QA FEW-N metrics were excluded from the document due to page limitations but can be provided upon request.

5. Conclusions

In this work, we were able to define a framework for the development of a quantitative index assessing the integrated FEW-N performance of different process systems that can be used to facilitate decision making in process optimization. The metrics developed were able to accurately quantify the impact of the CCP system on the FEW-N and are general enough that they can be adjusted and applied to a wide variety of process systems while considering any number of decision elements. For the CCP process, it was observed that using any of the mathematical forms of the FEW-N metric we were able to get much better FEW-N solution that optimizing different FEW-N elements individually.

Acknowledgement

We are grateful to NIEHS Superfund Research Program (P42 ES027704), Texas A&M Superfund Research Center, Texas A&M University and Texas A&M Energy Institute for the financial support. We are also grateful to the Department of Chemical Engineering of Imperial College London for an EPSRC-funded Doctoral Training Partnership (DTP) studentship.

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Figure 1.
Flowsheet of the Cottage Cheese Plant

Figure 2.
Optimal Schedule for maximum LA FEW-N metric

Table 1

Components dependencies of the FEW-N metric

Dimensions	<ul style="list-style-type: none"> • FEW elements (produced or used) • Dimensions can include any other decision elements that are relevant to the decision maker (e.g. profit)
Indicators	<ul style="list-style-type: none"> • The method used to measure each of the dimension elements • The boundary definition of the process system
Dimension Index	<ul style="list-style-type: none"> • Normalization scheme • Mathematical Form of the metric
Composite	<ul style="list-style-type: none"> • Weight assigned to each index • Mathematical Form of the metric

Table 2

FEW-N metric value

	Optimal	Maximum Profit	Maximum Food	Minimum Energy	Minimum Water
LA	0.823	0.598	0.598	0.378	0.765
BA	0.660	0.297	0.297	0.085	0.567
TA	0.496	0.098	0.098	0	0.405
QA	0.345	0	0	0	0.279