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Biochemical Engineering Journal 27 (2005) 155–160

Biochemical Engineering Journal

www.elsevier.com/locate/bej

A new methodology for the optimal design of batch fermentation plants

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Received 25 January 2005; received in revised form 13 June 2005; accepted 2 August 2005

Abstract

In the design of batch and fed-batch fermentation plants, the problem of determining the adequate combination of number and size of the fermentors to be used, so to accomplish the desired production schedule must be faced. The problem has infinite solutions, as for any fermentor size, a number of units of that size will do the work, but not all solutions are equal from an economical standpoint. The problem of determining the optimum number of pieces of equipment and the optimum operation schedule has been addressed by several authors in the process engineering field.

The optimal combination of size and number of fermentors will be the one that maximizes the net present value. The objective of this work was to develop a methodology for the optimal design of batch fermentation plants based in the maximum net present value criterion and to compare it with the more restricted criterion of minimum investment in production fermentors.

Results show that considering only the investment in production fermentors underestimates the optimum number of fermentation units, probably because it only considers the investment in production fermentors and its assumptions of equal preparation and discharge times. On the other hand, the method proposed in this work, although somewhat more complex, gives a more accurate result.

Keywords: Batch fermentation plants; NPV; Production fermentor

1. Introduction

Industrial fermentation plants consist of three main sections: preparation, fermentation and product recovery. The preparation section usually contains operations such us medium preparation and sterilization and inoculum propagation. The fermentation section is the heart of the plant where the transformation of raw material into products takes place. The product recovery section encompasses the downstream operations needed to obtain the product of interest with the required purity [1].

Fermentations may be run in one of three modes of operation: batch, continuous or semi-continuous, also referred to as fed-batch. Large-volume fermentations for the production of commodities are usually run in the fed-batch or batch modes, while batch operation is used for small-volume processes for the production of fine biologicals. Continuous fermentations are extensively used in research and development and in effluent treatment processes, but are seldom used in industrial fermentations, mainly because of the possibility of contamination and mutation [2,3].

In the design of fed-batch and batch fermentation plants, the problem of figuring out the adequate combination of number and size of the fermentors to be used, so to accomplish the desired production schedule, must be faced. In principle, the problem has infinite solutions, as for any fermentor size, a number of units of that size will do the work. Nevertheless, not all solutions are equal from an economical standpoint. The problem of determining the optimum number of pieces of equipment and the optimum operation schedule has been addressed by several authors in the process engineering field [4–6]. Recently, Simpson el al. [7] presented a complete study on the optimization of batch retort battery design and operation in canneries. Nevertheless, an equivalent approach has rarely been presented for the fermentation industry.

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doi:10.1016/j.bej.2005.08.003

Nomenclature

A	proportionality constant, Eq. (11)
a	cost exponent, Eq. (6)
B	boiler size
b	cost exponent, Eq. (27)
C	product concentration
C_f	fermentor cost
C_P	product cost per m^3 of broth
F	hourly flow rate of broth to downstream section, Eq. (1)
F'	yearly flow rate of broth to downstream section, Eq. (33)
i	interest rate
I	total investment
I_a	total investment in ancillary equipment
I_b	investment in the boiler
I_c	investment in pipe and fittings
I_P	investment in propagators
I_f	total investment in fermentors, propagators included
j	number of periods, Eq. (31)
K	proportionality constant, Eq. (36)
K_f	proportionality constant, Eq. (6)
M	mass of product produced per year
N_f	number of production fermentors
N_f^*	optimum number of production fermentors
NPV	net present value, Eq. (14)
n	number of propagation steps, Eq. (22)
P	sell price per m^3 of broth
t_y	hours of operation per year
t_d	fermentor discharge time
t_f	fermentation time
t_p	Batch preparation time
V	total volume of each production fermentor
V^*	optimal volume of each production fermentor
V_L	liquid volume of each production fermentor
V_p	propagator volume

Greek symbols

α	proportionality constant, Eq. (16)
β_A,	total benefit
β_j	annual benefit
η	product recovery efficiency
ϕ	proportionality constant, Eq. (26)
φ	proportionality constant, Eq. (25)
λ	cost exponent, Eq. (26)

The optimal combination of size and number of fermentors can be considered as the one that requires the lowest investment in equipment. A restricted interpretation of this condition would be to circumscribe the investment to that in production fermentors only, as proposed by Borzani [8]. A more general approach would be to consider the solution that gives the highest net present value of the investment in equipment for the complete plant as optimal.

The objective of this research is to develop a methodology for the optimal design of batch fermentation plants based on the maximum net present value criterion and to compare it with the criterion of minimum investment in production fermentors.

2. Optimization methodology based on minimum investment in production fermentors

The following is the methodology developed by Borzani [8]. This approach requires that the following set of conditions apply:

(a) Continuous operation of the downstream section of the plants is desirable, irrespectively of the batch operation of the fermentors. This can be achieved by having a battery of N_f fermentors scheduled in such a way that there is always one of them discharging.
(b) All production fermentors are of the same size.
(c) In each fermentor, the discharge time (t_d) equals the preparation time (t_p).
(d) The cost of the fermentors can be represented by $C_f = K_f V^a$ [9], where K_f and a are constants in the considered volume range.

The continuous flow of fermented broth to the downstream section will be given by:

$$F = \frac{M}{t_y C \eta} \quad (1)$$

The discharge time will be:

$$t_d = \frac{V_L}{F} \quad (2)$$

The operation cycle of one fermentor (t_t) equals:

$$t_t = t_p + t_f + t_d \quad (3)$$

In order to comply with condition (a), the number of fermentors must be given by:

$$N_f = \frac{t_p + t_f + t_d}{t_d} \quad (4)$$

Using Eq. (2) and applying condition (c) to Eq. (4):

$$N_f = 2 + \frac{F t_f}{V_L} \quad (5)$$

The cost of one fermentor, as stated in condition (d) is given by:

$$C_f = K_f V^a \quad (6)$$

The objective function to be minimized is:

$$C_T = K_f V^a N_f \quad (7)$$