

Multi-objective Optimization of Citric Acid Bioprocess: A Modern Approach

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The paper deals with multi-objective cost-environment optimization of bioprocesses. Citric acid is one of the most important organic acids produced by microbiological methods. Due to the fact that market is very competitive, the process economics is of paramount importance for survival. The optimization strategy can play an important role in reduction of production costs. The optimization approach consists in coupling a process simulator (i.e. SuperPro Designer) with a high-level numerical computing language (i.e. Matlab) in an optimization loop. The high-level language expands the simulator functionality by offering access to its optimization tools and the possibility of creating complex scripts (e.g. scripts for ecological evaluation of a bioprocess, mathematical models for unitary procedures etc.) which can be linked to the simulator. The aim of this strategy is to realize a complete multi-objective optimization by linking a dynamic model of the bioreactor elaborated in Matlab with a process model of the complete production plant implemented in SuperPro Designer. The obtained results show how the proposed methodology can be used to find a range of trade-off solutions for optimizing citric acid production bioprocess.

Keywords: biochemical processes, citric acid, simulation, optimization

Citric acid is one of the most important organic acids produced in a fermentation process. The market for citric acid is very competitive and the price is such that profit margins are low. The world production is approximately 1.1 million tons per year. Most of the production is achieved with *Aspergillus niger* strains using beet or cane molasses as substrate.

The biochemical mechanism by which *Aspergillus niger* accumulates citric acid has been intensively studied. Despite the many resources consumed with this research, the results were rather disappointing. There is still no explanation of the biochemical basis of this process which would consistently explain all the observed factors influencing this fermentation. Reasons for this are manifold. Firstly citric acid accumulation is subject to multifactor influence. Secondly, the biochemical knowledge of filamentous fungi is still at low levels [1].

In this context modelling an *Aspergillus niger* citric acid bioreactor is a difficult task. The model used was written by Woinaroschy et al [2] and is based on published experimental data and qualitative opinions related to inhibition found in literature [3].

The bioprocess model for citric acid fermentation from molasses using *Aspergillus niger* was developed and implemented in SuperPro Designer simulator using data from [1] and [4]. Unfortunately, SuperPro Designer simulator offers no possibility of implementing complex bioreactor models. The bioreactor model was implemented in Matlab and linked to the simulator.

The optimization approach consists in the use of Matlab optimization tools in combination with SuperPro Designer simulator. This is possible due to an original Graphical User Interface [5]. In figure 1 is presented the optimization strategy scheme.

The optimization strategy is easy to be applied, combining a useful simulator (SuperPro Designer) with a powerful high-level numerical computing language (Matlab).

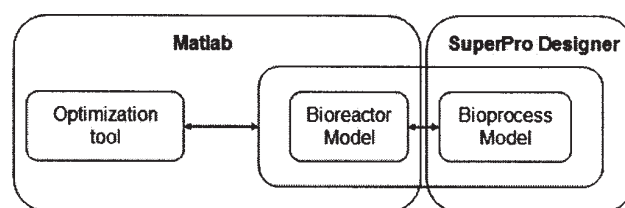


Fig. 1. Optimization strategy

This optimization method can be used in earlier stages of process development to better understand what impact would have the results of a research over the economic indexes of a plant (e.g. production cost).

Bioreactor model

The model of the fedbatch bioreactor for citric acid production using molasses, proposed in [2] consists in the following system of differential equations:

$$\frac{dx_1}{dt} = -r_s + u \cdot (x_{10} - x_1) / x_4 \quad (1)$$

$$\frac{dx_2}{dt} = r_x + r_p^* - K_d \cdot x_2 - u \cdot x_2 / x_4 \quad (2)$$

$$\frac{dx_3}{dt} = r_p - r_p^* - u \cdot x_3 / x_4 \quad (3)$$

$$\frac{dx_4}{dt} = u \quad (4)$$

$$x_4(t_f) \leq x_{4\max} \quad (5)$$

$$r_x = \mu_{\max} \cdot \frac{x_1}{K_s + x_1} \cdot \frac{K_{SP}}{K_{SP} + x_3} \cdot x_2 \quad (6)$$

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$$r_s = \frac{r_x}{Y_{XS}} + m \cdot x_2 \quad (7)$$

$$r_p = r_x \cdot Y_{XP} \quad (8)$$

$$r_p^* = \mu_{p,max} \cdot \frac{x_3}{K_p + x_3} \cdot \frac{K_{PS}}{K_{PS} + x_1} \quad (9)$$

where:

- x_1 - sugar concentration (g/L)
- x_2 - biomass concentration (g/L)
- x_3 - citric acid concentration (g/L)
- x_4 - the volume of the liquid in the bioreactor (L)
- u - volumetric feed flowrate of sugar aqueous solution (L/h)
- x_{10} - initial sugar concentration (g/L)

The type of fedbatch considered in this paper is variable volume fed-batch process. This means a type of fed-batch in which supplementary growth medium is added during the fermentation, but no culture is removed until the end of the batch.

Process model

The process was developed using data from [1] and [4] (fig. 2). The used microorganism is *Aspergillus niger* and the substrate utilized is beet molasses.

An annual production of 13000 tons of citric acid is assumed and realized with 12 bioreactors, each with a volume of 320 m³. For a 320 m³ bioreactor, 23.387 tons/batch citric acid are obtained and 50 tons/batch beet molasses are consumed. One batch takes 189.91 h. With 330 operating days, 13300 tons of citric acid monohydrate is produced in 565 batches.

The plant require a total capital investment of 131 millions \$ and an annual operating cost of 35 millions \$. The product production cost is 2.63 \$/kg citric acid.

Environmental index of bioprocess, calculated for input streams, via arithmetic average is 0.1958.

Optimization strategy

The optimization strategy is based on idea of coupling Matlab and SuperPro Designer. In this way the simulator can benefit from the optimization tools available in Matlab [6].

A complex dynamic model of bioreactor was implemented in Matlab and linked with the citric acid process model simulation in SuperPro Designer.

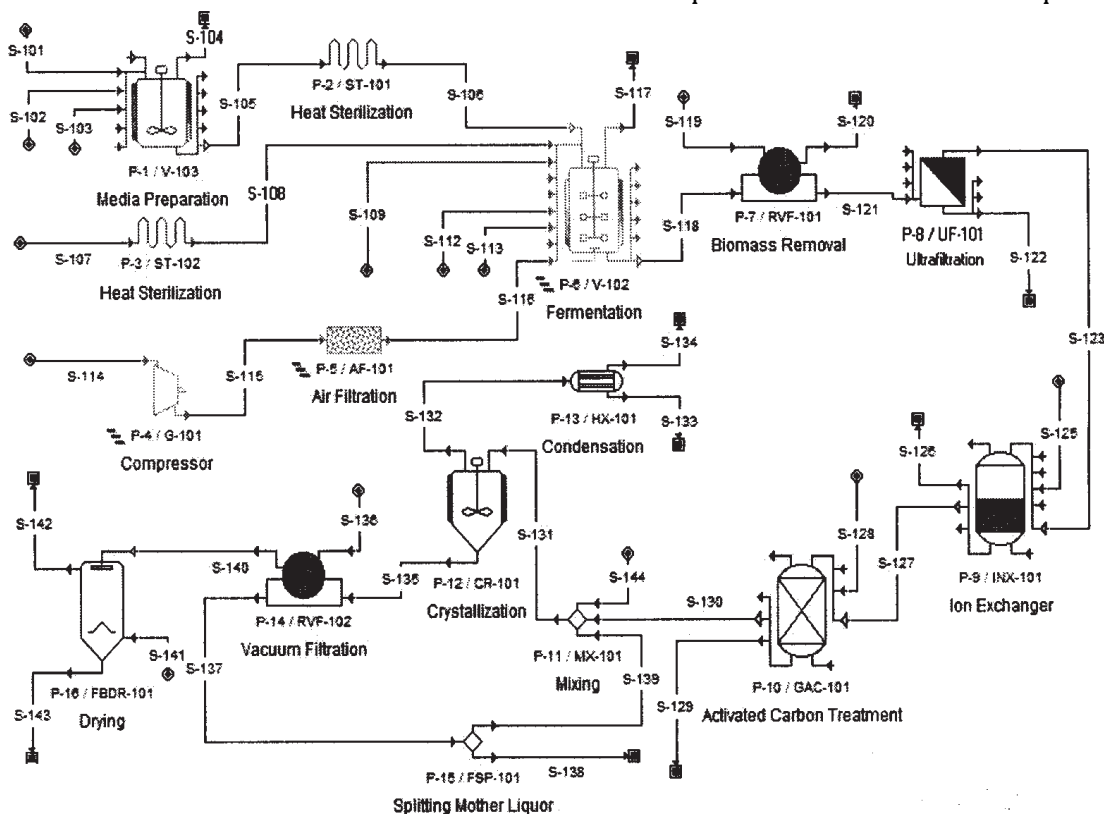


Fig. 2. Citric acid bioprocess model

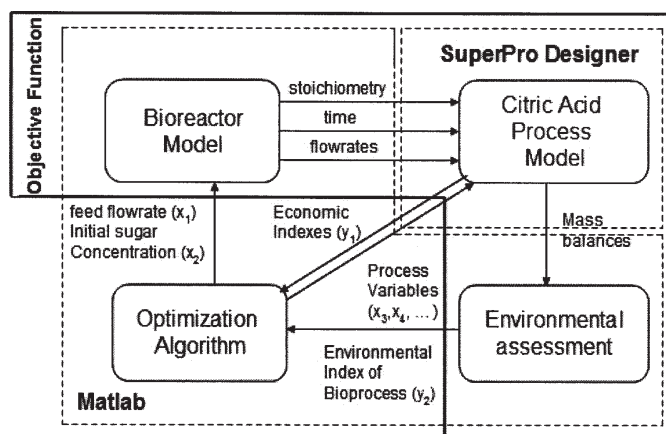


Fig. 3. Variables flow in the optimization application

The goal of this strategy is to realize a complete multi-objective cost-environment optimization of citric acid bioprocess.

The process model of citric acid production uses a simple mass based stoichiometric equation for the bioreactor. It requires data about stoichiometry and kinetics. This data are taken from bioreactor model.

Figure 3 shows a detailed scheme of the application. The Genetic Algorithm generates a population of vectors $v_i = (x_1, x_2, x_3, x_4)$ whose components are the process independent variables. The objective function takes each vector and sends the initial sugar concentration x_1 and sugar feed flow rate x_2 to the bioreactor model. The splitting fraction in P-15 x_3 and crystallization time in P-12 x_4 are send to the process model. Using x_1 and x_2 the bioreactor model computes fermentation time and stoichiometric coefficients. In order to obtain economic and ecologic accurate results, the amount of molasses, ammonium nitrate (nitrogen source) and potassium dehydrogenate phosphate (phosphorus source) are also computed. These data are transferred to citric acid process model. The process model computes mass/energy balance and economic calculations. The Environmental Assessment module implemented in Matlab calculates environmental index using mass balances provided by process model. The environmental and economic indexes computed by Environmental Assessment module and process model are transferred to the optimization algorithm and the corresponding value of fitness for the v_i vector is computed.

Implementation

The optimization strategy involves three major steps:

a) Process modelling

SuperPro Designer was chosen for this application due to his ability of communicating with other software through Designer Type Library [7].

b) Formulation of the multi-objective optimization problem

In order to solve the multi-criteria optimization problems of cost-environment type, a vectorial objective function with two components was defined:

$$f(x_1, x_2, x_3, x_4) = (y_1, y_2) \quad (10)$$

where:

$y_1 = \text{UPC} + w \cdot \text{TCI}$ - the economic component, where UPC is the unit production cost (\$/kg citric acid), TCI is the total capital investment (\$), and w is a scale and weighting coefficient.

$y_2 = \text{EI}_{\text{Bioprocess}}$ - the ecological component represented by an index which describes the bioprocess impact on the environment [8].

The objective function is the key of the proposed algorithm, being the link between Matlab and SuperPro Designer and making possible the data transfer between these two software.

In order to create the objective function, a friendly Graphical User Interface (GUI) was elaborated, a new and extended version of a previous one [5]. This GUI automatically generates the objective function code, and contains two modules:

- Module one: generating the economic component y_1 of the objective function.

The available variables from SuperPro Designer are classified in seven categories, corresponding to seven buttons on the interface (fig. 4). Behind each button lies the variables list category to be picked out by the user. Example: variable x_1 corresponding to the molasses flow in S-109 stream is part of the StreamVariables category. From this list it is selected the item "Specified Ingredient (pure component/mixture) mass flow in stream" (fig. 5).

The following additional data are also required:

Stream Name: S-109;

Comp. Local Name: Molasses.

The objective function is generated by pressing Generate M-File button (fig. 4).

- Module two: generating the environmental component y_2 of the objective function.

The environmental component of the objective function is represented by an index ($\text{EI}_{\text{Bioprocess}}$) that indicates the environmental relevance of the whole bioprocess. $\text{EI}_{\text{Bioprocess}}$ is calculated by the method proposed in [4]. The method requires material flows (provided by SuperPro Designer and used to compute Mass Indices, which is a metric for the material intensity of the process) and ABC classification (provided by user and applied in computing of the Environmental Factors EF_i - a metric for the environmental impact of each component i). The ABC classification is used to select components in environmental impact relevance classes (high, medium, or low relevance). From Mass Indices and Environmental Factors, the total $\text{EI}_{\text{Bioprocess}}$ is computed (fig. 6).

After completing the interface table, the function generated by pressing Generate M-File button (fig. 7), is able to calculate $\text{EI}_{\text{Bioprocess}}$ by extracting mass flows from SuperPro Designer and using ABC classification provided by user.

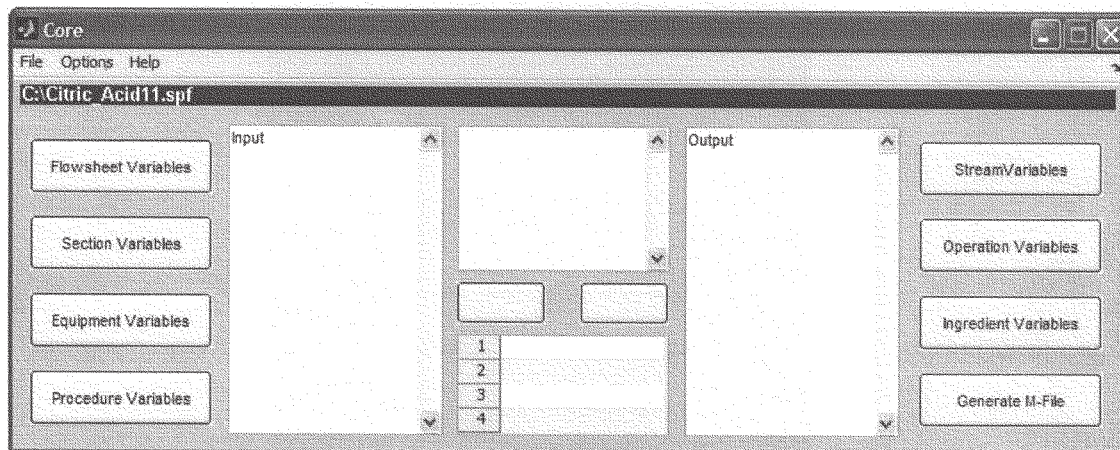


Fig. 4. Matlab Graphical User Interface used for generation of economical component of the objective function

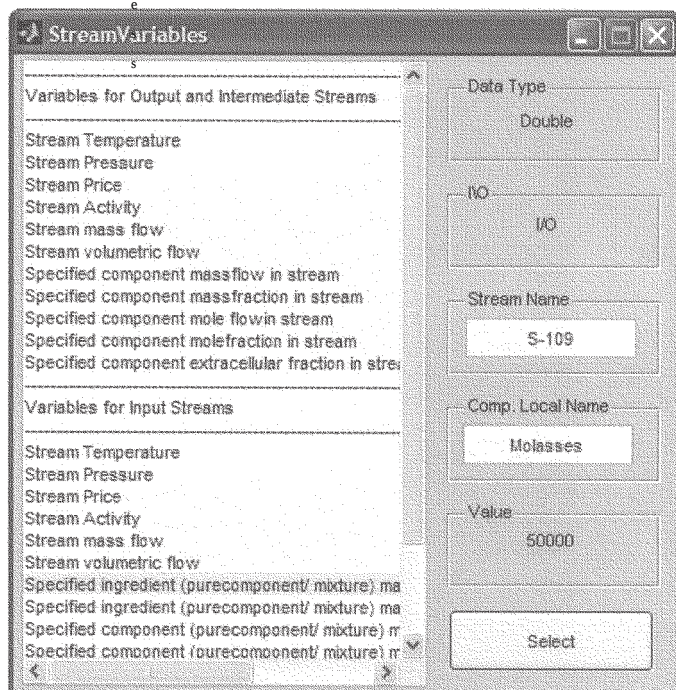


Fig. 5. Stream Variables list

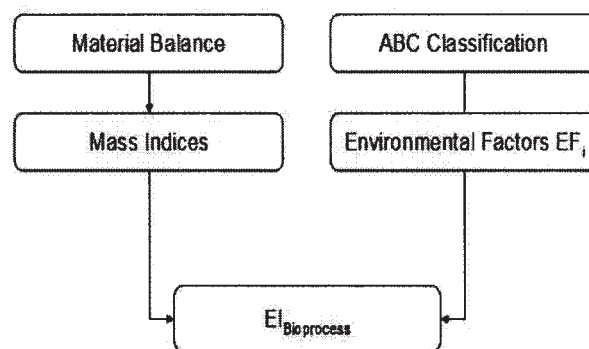


Fig. 6. Calculation of $EI_{Bioprocess}$

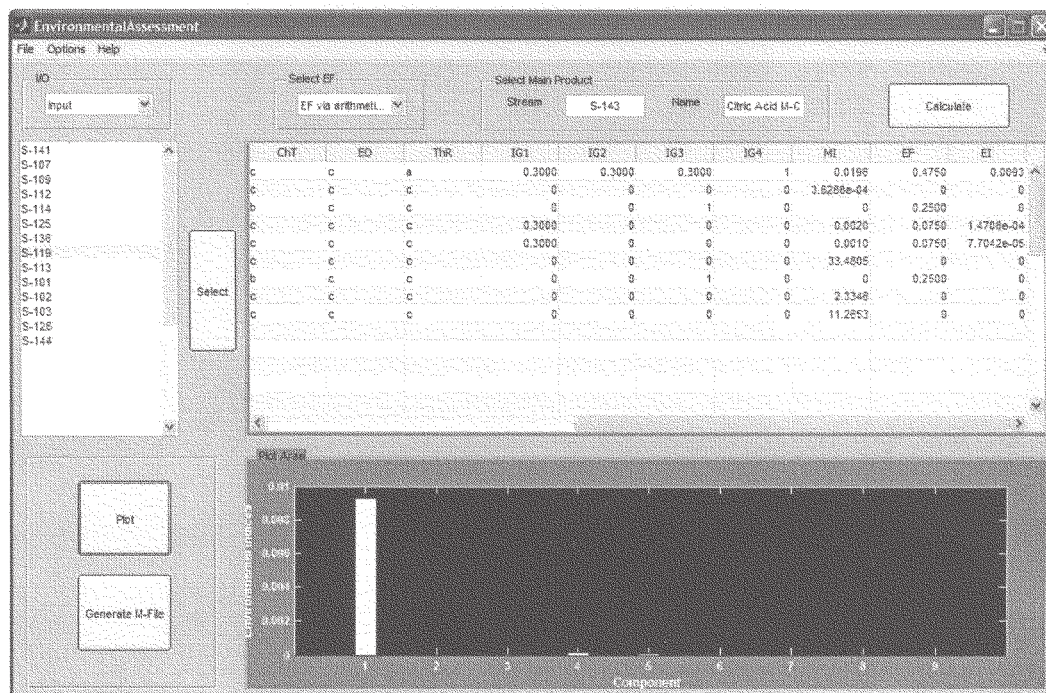


Fig. 7. Matlab Graphical User Interface used for generation of environmental component of the objective function

c) Multi-objective optimization and the choice of the best compromise

Because the two considered criteria present antagonist goals, a Multi-objective Genetic Algorithm based on Pareto front was chosen for optimization. On the base of Pareto front can be selected the solution which represents the

best compromise between the economical and ecological objective.

Results and discussions

Table 1 displays the parameters of the genetic algorithm used for multi-criteria optimization.

Table 1
GENETIC ALGORITHM PARAMETERS

		Variable	Lower bound	Upper Bound
Population Size	40	x_1 t/batch	15	50
		x_2 kg/m ³	175	300
Population Number	100	x_3	0.95	0.99
		x_4 sec	14400	23400

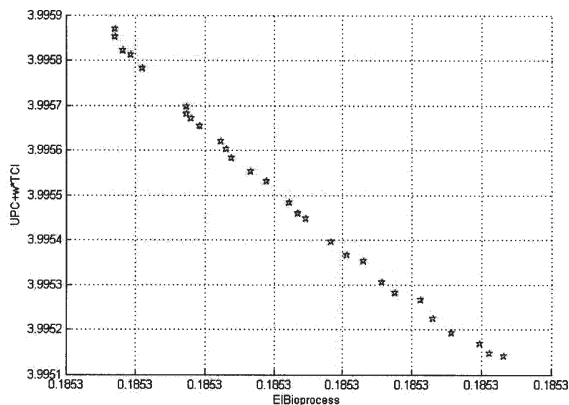


Fig. 8. Pareto Optimal Solutions: $UPC+w*TCl$ vs. $EI_{Bioprocess}$

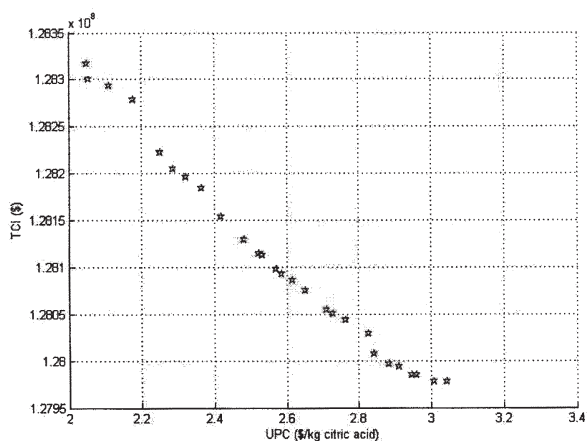


Fig. 9. Pareto Optimal Solutions: UPC vs. TCI

Other parameters used for Genetic Algorithm multi-objective optimization are:

- Solver: gamultiobj – Multi-objective Optimization using Genetic Algorithm

- Number of Variables: the length of the input vector to the fitness function. In the presented application this number is 4.

- Population options:

Creation function (the function that creates the initial population): “Use constraint dependent default – Feasible population” creates a random initial population that satisfies the bound constraint.

- Selection:

The selection function used is “Tournament”, which selects each parent by choosing individuals at random and then choosing the best individual out of that set to be a parent. The number of parents selected can be specified by Tournament size, which in the present case is 2.

- Reproduction:

Reproduction options determine how the genetic algorithm creates children at each new generation. Crossover fraction (the fraction of the next generation that crossover produces) is 0.8. Mutation produces the remaining individuals in the next generation.

- Mutation:

Mutation function used: “Use constraint dependent default – Adaptive feasible”: randomly generates directions that are adaptive with respect to the last successful or unsuccessful generation. A step length is chosen along each direction so that bounds constraints are satisfied.

- Crossover:

Crossover function used: “Intermediate” - creates children by a random weighted average of the parents.

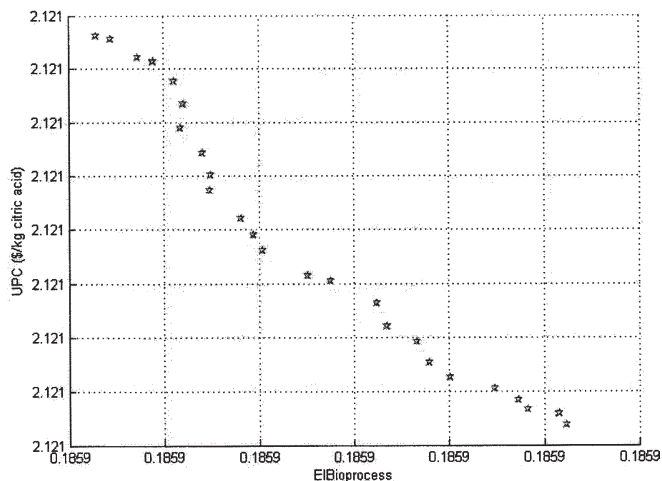


Fig. 10. Pareto Optimal Solutions: UPC vs. $EI_{Bioprocess}$

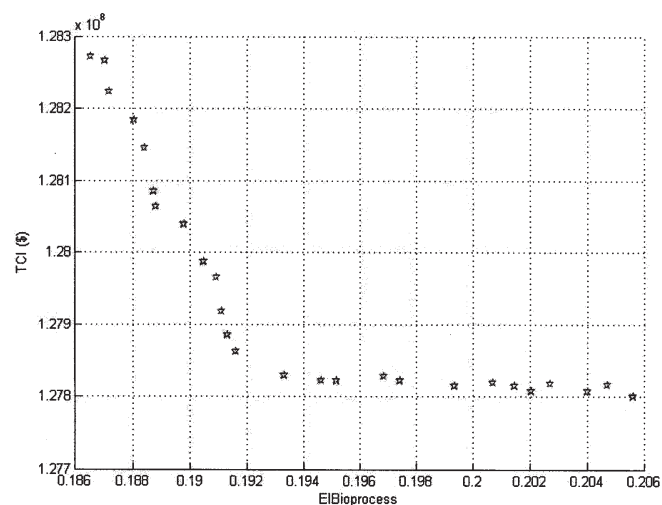


Fig. 11. Pareto Optimal Solutions: TCI vs. $EI_{Bioprocess}$

- Migration:

Migration is the movement of individuals between subpopulations.

- Direction: Forward

- Fraction: 0.2 - controls how many individuals move between subpopulations;

- Interval: 20 - controls how many generations pass between migrations.

- Multi-objective problem settings:

Distance measure function: distance crowding - is a measure of the concentration of the population.

Pareto front population fraction: 0.7. This keeps the fit population down to the specified fraction in order to maintain a diverse population.

The results show the classical compromise between the two antagonist aims. It can be selected a desired compromise between economical and environmental aims, or between two economical indexes.

First $UPC+w*TCl$ and environmental index of bioprocess were considered. Figure 8 shows the results. The environmental impact of the bioprocess is low and very little sensitive to process variables, so it is chosen a solution so that economic index to be as low as possible.

In unit production cost and total capital investment Pareto front (fig. 9), a lower value for UPC is preferred because it has a greater impact on process economics. Also the variation of total capital investment is very low and can be quickly compensated by a lower unit production cost.

Figure 10 and figure 11 shows the results of unit production cost, total capital investment and environmental

Table 2
OPTIMIZATION RESULTS

	y_1	y_2	x_1	x_2	x_3	x_4
	UPC+w*TCI	EI _{Bioprocess}				
UPC+w*TCI Vs EI _{Bioprocess}	3.9951	0.1853	49.9988	290.033	0.99	22077
	UPC	TCI				
UPC Vs TCI	2.1105	1.2829*10 ⁸	45.3991	290.033	0.9865	22525
	UPC	EI _{Bioprocess}				
UPC Vs EI _{Bioprocess}	2.1211	0.1859	46.2807	249.369	0.99	17575
	TCI	EI _{Bioprocess}				
TCI Vs EI _{Bioprocess}	1.2780*10 ⁸	0.2056	17.4704	182	0.9545	22134

index of bioprocess. The chosen solution must consider a low value of environmental index.

It can be seen that for any selected solution, economical and ecological performances of the bioprocess are improved in comparison with initial values.

Table 2 presents the selected solutions and the corresponding values of the independent variables at which they occur.

Conclusions

The optimization strategy was successfully applied to the bioprocess of citric acid production from molasses, using *Aspergillus niger*. The obtained results show that improvements in ecological and economical indexes are possible.

The main advantages of the presented methodology are:

- easy to use and provide accurate results;
- do not require user advanced programming knowledge.

Some disadvantages are:

- the computer time needed is high for complex applications;

- not all the process variables are given in the Designer Type Library of SuperPro Designer server. This fact restricts the optimization applications that a user can develop;

The models associated with unit procedures are simple and for complex optimization applications these must be

completed with models developed in Matlab. SuperPro Designer was not designed for this kind of use and continuous change of process variables may lead sometimes to unexpected error message.

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