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An optimization model for production planning in the drying sector of an industrial laundry

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ABSTRACT. In this work, an optimization model was developed for production planning in the drying sector of a real industrial laundry. Goal programming was used in order to minimize energy and labor costs, and to use of the full capacity of each piece of equipment, as far as possible. Constraints imposed were not to mix different types of products in each lot, dependence of lot assignment on the lots already assigned, the requirement to have a positive global contribution margin, and that each available dryer should be used within a specified capacity range. The independent variables were the numbers of items in each lot, according to product type. The Mixed Integer Linear Programming model developed was solved using GAMS and was applied to an industrial laundry located in Maringá, Paraná State, Brazil. The study demonstrated that it was possible to establish plans for efficient production and optimal allocation of resources. The existing global contribution margin of the industrial laundry ($295,405.50) was significantly smaller than the one that could be achieved with optimal operation ($647,770.00), because the existing operation did not make use of full capacity. The tool developed proved to be useful for assisting production planning in this kind of industrial process.

Keywords: goal programming, optimization, MILP.

Um modelo de otimização para o planejamento da produção no setor de secagem de uma lavanderia industrial

RESUMO. O presente trabalho desenvolve um modelo de otimização para o planejamento da produção no setor de secagem de uma lavanderia industrial. Utilizou-se de programação por metas (*Goal Programming*) para minimizar os custos com energia e mão de obra e maximizar a capacidade de uso de todas as secadoras. Restrições reais impõem: a separação por tipos de produtos em cada lote; a dependência de lotes a serem atribuídos em relação àqueles já atribuídos; margem de contribuição positiva; utilização de cada secadora disponível em um intervalo de capacidade. As variáveis independentes são as somas dos itens de cada tipo de produto em cada lote. O modelo tem a formulação de um problema de Programação Linear Inteira Mista, foi resolvido na plataforma GAMS e foi aplicado a uma lavanderia industrial localizada em Maringá, Estado do Paraná, Brasil. O estudo demonstrou que foi possível estabelecer eficientes planos de produção e alocação ótima dos recursos. A atual margem de contribuição global da lavanderia industrial ($295.405,50) é significativamente menor do que aquela que poderia ser praticada com operação ótima ($ 647.770,00), uma vez que a operação atual não utiliza toda a sua capacidade. A ferramenta desenvolvida mostrou-se útil para auxiliar no planejamento de produção desse tipo de processo industrial.

Palavras-chave: programação por metas, otimização, PLIM.

Introduction

In industrial processes, energy consumption is a major factor affecting global costs. It is also important to consider that industrial processes are generators of greenhouse gases, due to the consumption of energy that is generally produced by fuel burning. Reduction in greenhouse gas emissions has become a focus of research attention in recent decades. Among other benefits, it can make industry more competitive. This can be applied to the textile industry, with improvements in equipment, plant layout, and production programming all reflecting positively in the competitiveness of products.

A great improvement in energy costs (and also other costs) can be achieved with appropriate production planning (Hasanbeigi & Price, 2012), avoiding wasting equipment capacity or energy resources. Production planning should make the best use of the installed capacity, bearing in mind

the production demands and the energy and human resources available.

Although the textile industry is not among the largest industrial energy consumers, several papers have been published concerning heat integration and energy consumption reduction in this sector. Other studies have aimed at improving contribution margins, considering the costs of energy, labor, equipment, and other resources. For example, Kadipasaoglu, Hurley, Foote, and Khumawala (1998) presented an empirical investigation of the manufacturing, planning, and control practices associated with successful company performance. Using the Global Manufacturing Research Survey, textile industries in twelve countries around the world were classified as either successful or unsuccessful companies. It was concluded that countries with free market economies had high success coefficients, while countries with planned economies had low success coefficients. In relation to energy aspects, Palanichamy and Sundar Babu (2005) reported an energy conservation project, proposing practicable environmentally friendly energy conservation policies suitable for Indian textile industries. Kandilli and Koclu (2011) demonstrated the great potential of waste heat recovery systems for textile applications, using plate heat exchangers in a dyeing process in Turkey.

Several optimization studies applied to textile industries have been published in the literature. Fijan, Fijan, and Sostar-Turk (2008) presented a study on how to optimize a laundering program in order to reduce the wastewater burden and achieve a more sustainable process. Camargo, Toledo, and Almada-Lobo (2014) solved a two-stage lot-sizing and scheduling problem in a spinning industry by using a combined branch-and-bound based procedure with a fix-and-optimize method (HOPS - Hamming-oriented partition search). This method is a good option for solving mixed integer problems with recognized partitions, such as the lot-sizing and scheduling problem. Nouira, Frein, and Hadj-Alouane (2014) proposed two optimization models, considering the selection of production processes and the choice of input products, in both cases considering that the demand and the price depended on the greenness of the product. A textile sector case study was presented, and it was shown that the integration of product greenness influenced profit and decision-making.

The studies mentioned above focused on single-objective problems. Multi-objective optimization problems have also been described for the textile industry, considering both production planning and the possibility of establishing more sustainable processes. The defining of production plans, in the textile or any other industry, is essential but often presents conflicting aspects. Wu and Chang (2004) presented an optimal production-planning program considering variable environmental costs in an uncertain environment. Several production alternatives for dyeing cloth in a textile-dyeing industry were studied in terms of market demand, resources availability, and the impact of environmental costs, and the optimal production strategy was determined based on the grey compromise programming approach. Rădulescu, Rădulescu, and Rădulescu (2009) proposed a multi-objective programming approach for production processes, including pollutant emissions in the problem constraints. Two alternative optimization problems (minimum pollution risk and maximum expected return) were solved, considering three contamination levels for each pollutant. Penalties proportional to the amounts of pollutants that exceeded these levels were included. Various individual cases were studied, including a numerical example for a textile plant.

An approach for dealing with a problem involving a number of conflicting objectives, all of which are considered simultaneously, is to translate each of them into a specific numeric target (goal) and to search for a solution that minimizes the deviations of the desired objectives from their targets. This can be achieved using the mathematical goal programming (GP) technique (Williams, 2007). In this linear programming model, each goal is written so as to allow the possibility of not all of them being precisely satisfied, while the deviations from the different targets are minimized. The GP technique attempts to minimize the set of deviations from pre-specified multiple goals, which are considered simultaneously but are weighted according to their relative importance (Alidi, 1996). In GP, the constraints are not rigid and include variable deviations, enabling different levels of usage of resources or production of items.

This method has been described for the resolution of multi-objective optimization problems in different areas of application. Alidi (1996) used goal programming to model the management of hazardous waste generated by the petrochemical industry, simultaneously considering different petrochemical plants, different types of hazardous waste, and different landfill sites. It was concluded that the model was a useful tool that could assist in decision-making related to the management of hazardous waste. Özgüven, Yavuz, and Özbakir (2012) successfully applied goal programming in mixed integer models for the flexible job shop

scheduling problem (FJSP), which is characterized as both a routing and a sequencing problem. This approach enabled the establishment of process plans for each of the jobs, assignment of each of the operations to only one of the available machines, and sequencing of the operations on the machines to which they were assigned, hence minimizing the production makespan and balancing the workloads of the machines. A variant optimization procedure called Multi-Choice Mixed Integer Goal Programming (Mcmigp) was used by Silva, Marins, and Montevechi (2013) to model a production planning, distribution, and energy cogeneration problem in a sugar and ethanol mill, with goals involving costs and the contributions of different products to total production during the harvest season. More recently, Gebrezgabher, Meuwissen, and Lansink (2014) used goal programming applied to manure management in The Netherlands, integrating the views of the different players concerning socio-economic benefits and environmental sustainability in the manure management chain. Nixon, Dey, Davies, Sagi, and Berry (2014) modeled the implementation of pyrolysis plants in a region of India, with the aim of simultaneously minimizing the payback period, capital costs, bio-oil and electricity production costs, and the environmental and social impacts related to field burning of agricultural waste biomass. Goal programming was used to make decisions on the location, size, and number of pyrolysis units, as well as the type and quantity of biomass, and it was successfully demonstrated that the deployment of pyrolysis plants in that region of India was technically and economically feasible.

In the present work, a multi-objective optimization model was developed for the drying sector of an industrial laundry. The main objective of the model was to support production planning, with constraints in terms of raw material availability, products demand, and equipment capacity. This problem could be classified as multi-stage, multi-product, multi-process, multi-period, and multi-objective, combining decisions on lot sizing and sequencing. A case study of a real industrial process was used to validate the developed model, and goal programming was employed.

Material and methods

A mathematical model was developed to solve a multi-objective problem in the drying sector of a textile industry. The drying sector had different installed dryers available and processed (dried) different types of products (clothes). The operation was accomplished by assigning lots to each machine, with a time of one hour for loading, processing, and unloading. The problem was to determine the proportion of each product that should be processed each hour in each of the available machines, resulting in production lots. This problem was mathematically translated into a multi-objective optimization problem (described in this section), after which the general model was parameterized for a specific case study. Two objectives were considered in formulation of the general model: minimization of costs and making the best use of installed equipment. The model constraints were written based on real constraints. The first was that for each lot, the industrial laundry should not process mixed types of products in one machine, with only one type of product being allowed in each lot for each piece of equipment. Furthermore, lots already assigned to the machines influenced the remaining ones, depending on the demand for each product. Finally, each machine should be used within a range of capacity, and the global contribution margin should be positive.

In the following part of this section, the proposed model is described and then parameterized. Lexicographic Goal Programming (LGP) was used because of the different orders of priority among the different objectives: P1 > P2 > P3 > …> Pn. Based on the work of Chang (2007), this problem can be generalized as follows:

$$Lex\min a = \sum_{k\in h_1}\left(\alpha_k d_k^+ + \beta_k d_k^-\right),\ldots,\sum_{k\in h_q}\left(\alpha_k d_k^+ + \beta_k d_k^-\right),\ldots,\sum_{k\in h_Q}\left(\alpha_k d_k^+ + \beta_k d_k^-\right) \quad (1)$$

$$s.t.: f_k(W) - d_k^+ + d_k^- = g_k, \quad k = 1,2,\ldots,n, \quad k \in h_q, \quad q = 1,2,\ldots,Q \quad (2)$$

$$\begin{aligned} &d_k^+, d_k^- \geq 0 \quad k = 1,2,\ldots,n \\ &W \in F \qquad \text{(F is a set of possible solutions)} \end{aligned} \quad (3)$$

$$w_r, d_k^+, d_k^- \geq 0 \quad for\ r = 1,2,\ldots,p\ and\ k = 1,2,\ldots,n \quad (4)$$

where

h_q represents the index set of goals at the qth level of priority, w_r are the elements of vector W, and α_k and β_k are positive weights related to positive and negative deviations of the kth goal, which are given by Equations 5(a) and (b).

$$d_k^+ = Max\left(0, f_k(X) - g_k\right) \quad (5a)$$

$$d_k^- = Max\left(0, g_k - f_k(X)\right) \quad (5b)$$

where

$f_k(X)$ is a linear function representing the k^{th} goal, and g_k is its target value.

In the model, nonlinearities in production costs and revenue are disregarded (for example, the greater the amount of clothes to be processed, the lower the equipment costs in terms of electric energy or thermal energy supplied by the boiler).

In order to present the developed model, its indexes, parameters, and variables must be defined, as follows:

Indexes

i: defines the product type ($i \in I, I = \{1, 2, ..., \text{ni}\}$)

j: defines the process, *i.e.* the machine used to process the product ($j \in J, J = \{1, 2, ..., \text{nj}\}$)

t: defines the period ($t \in T, T = \{1, 2, ..., \text{nt}\}$)

y: defines the processing day ($y \in Y, Y = \{1, 2, ..., \text{ny}\}$)

Parameters

$Energy\_cost_{ij}$: energy cost associated with one item of product of type *i* being processed by process *j*

Goal_cost: goal for the total cost

$Goal\_product_i$: goal for the number of items of product of type *i* to be produced

$Labor\_cost_{ij}$: labor cost of the drying sector associated with one item of product of type *i* being processed by process *j*

Lot_max_{ij}: maximum number of items of product of type *i* to be processed by process *j*

Lot_min_{ij}: minimum number of items of product of type *i* to be processed by process *j*

Max_day_i: upper bound for the number of items of product of type *i* to be processed daily

Min_day_i: lower bound for the number of items of product of type *i* to be processed daily

ni: total number of product types

nj: total number of available processes

nt: total number of periods in a day

ny: total number of days of production considered

PR_i: price of product of type *i*

Variables

Ava_{ty}: number of product items available to be processed for period *t* of day *y*

CM: global contribution margin for processing all *i* products, by means of all *j* machines

$Costs_{ty}$: costs for period *t* of day *y*

$Costs\_proc_j$: costs of process *j*

d_cost^-: negative deviation from the goal for the total cost

d_cost^+: positive deviation from the goal for the total cost

$d\_product_i^-$: negative deviation from the goal for the number of items of product of type *i* to be produced

$d\_product_i^+$: positive deviation from the goal for the number of items of product of type *i* to be produced

PC_{ijty}: number of items of product of type *i* processed by process *j* for period *t* of day *y*

PC_period_{ty}: number of processed items of products of all types for period *t* of day *y*

$Quantity_{ity}$: number of items of product of type *i* processed for period *t* of day *y*

$Quantity\_product_i$: total number of processed items of product of type *i*

$Quantity\_total_{ty}$: total number of items processed for period *t* of day *y*

$Revenue_{ity}$: gross revenue related to product of type *i* processed for period *t* of day *y*

$Revenue\_product_i$: total gross revenue related to the processing of product of type *i*

$Revenue\_total_{ty}$: total gross revenue for period *t* of day *y*

X_{ijty}: binary variable that determines if product of type *i* must be ($X_{ijty} = 1$) processed by process *j* for period *t* of day *y*

As already stated, the mathematical model considers two criteria:

Criterion 1: Minimization of all variable costs.

Criterion 2: Maximization of the drying process production, allocating each lot to the most appropriate pieces of equipment.

As shown in Equation (6), the quantity of processed material of a type of product for all periods must be equal to the specified goal, with corrections by the positive and negative deviations. The cost goal must be equal to the sum of all costs, corrected by the deviations, according to Equation (7).

$$Goal\_product_i = \sum_{t \in T} \sum_{y \in Y} Quantity_{ity} + d\_\text{product}_i^- - d\_product_i^+ \quad (6)$$

$$Goal\_\text{cost} = \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} \sum_{y \in Y} \text{Energy\_cost}_{ij} \cdot PC_{ijty} + \sum_{i \in I} \sum_{j \in J} \sum_{t \in T} \sum_{y \in Y} \text{Labor\_cost}_{ij} \cdot PC_{ijty} + d\_\text{cost}^- - d\_\text{cost}^+ \quad (7)$$

The lexographic function used in this work is given by Equation (8), in which costs must be minimized, so deviations above the specified goal for costs are required to be minimized. Furthermore, production is limited by the capacity of the machines, and in the ideal situation, the full capacity should be used.

$$Min\ D = \left\{ d\_\cos t^{+} + \sum_{i=1}^{I} d\_product_{i}^{-} \right\} \quad (8)$$

Some constraints must be written in order to correctly model the problem. The global contribution margin (*CM*) for processing all *i* products, by means of all *j* machines, is calculated for each period *t* of any day *y*, according to Equation (9).

$$CM = \left[\left(\sum_{i\in I} \sum_{j\in J} PR_i \cdot PC_{ijty} \right) - \begin{pmatrix} \sum_{i\in I} \sum_{j\in J} \text{Energy\_cost}_{ij} \cdot PC_{ijty} + \\ \sum_{i\in I} \sum_{j\in J} \text{Labor\_cost}_{ij} \cdot PC_{ijty} \end{pmatrix} \right] \forall t \in T, \forall y \in Y \quad (9)$$

Additionally, constraints on processed clothes demands and daily production limits are imposed in the model. In order to assign lots to the different machines in the different periods of each day, the model calculates them based on the remaining demands for each product (i.e., there is a dependence of lots to be assigned on lots already assigned).

$$PC\_period_{ty} = \sum_{i\in I} \sum_{j\in J} PC_{ijty}\ \forall t \in T, \forall y \in Y \quad (10)$$

$$Ava_{ty} = Ava_{(t-1)y} - PC\_period_{(t-1)y} \geq PC\_period_{ty} \forall t \in T, \forall y \in Y \quad (11)$$

$$PC\_period_{ty} \leq Ava_{ty}\ \forall t \in T, \forall y \in Y \quad (12)$$

$$Min\_day_i \leq \sum_{j\in J} \sum_{t\in T} PC_{ijty} \leq Max\_day_i \forall i \in I, \forall y \in Y \quad (13)$$

Furthermore, only one type of clothes can be processed in each dryer *j* for each period *t* of day *y* (Equation 14).

$$\sum_{i\in I} X_{ijty} = 1 \quad (14)$$

These same binary variables help to define the amount of product (dried clothes) produced by each piece of equipment, since the amount must be null whenever a piece of equipment is not being used for a specified product *i* and it must not exceed the capacity nor be lower than an acceptable minimum for each type of dryer. The maximum (capacity) and minimum amount for each dryer *j* is defined as the maximum and minimum lot size for each product of type *i*.

$$PC_{ijty} \leq (Lot\_\max_{ij}) \cdot X_{ijty} \forall i \in I, \forall j \in J, \forall t \in T, \forall y \in Y \quad (15)$$

$$PC_{ijty} \geq (Lot\_\min_{ij}) \cdot X_{ijty} \forall i \in I, \forall j \in J, \forall t \in T, \forall y \in Y \quad (16)$$

$$Quantity_{ity} = \sum_{j\in J} PC_{ijty}\ \forall i \in I, \forall t \in T, \forall y \in Y \quad (17)$$

$$Quantity\_product_i = \sum_{t\in T} \sum_{y\in Y} Quantity_{ity}\ \forall i \in I \quad (18)$$

$$Quantity\_total_{ty} = \sum_{i\in I} Quantity_{ity}\ \forall t \in T, \forall y \in Y \quad (19)$$

$$\text{Revenue}_{ity} = \sum_{j\in J} PC_{ijty} \cdot PR_i \forall i \in I, \forall t \in T, \forall y \in Y \quad (20)$$

$$\text{Re venue\_product}_i = \sum_{t\in T} \sum_{y\in Y} \text{Revenue}_{ity} \forall i \in I \quad (21)$$

$$\text{Revenue\_total}_{ty} = \sum_{i\in I} \text{Revenue}_{ity}\ \forall t \in T, \forall y \in Y \quad (22)$$

$$Costs_{ty} = \sum_{i\in I} \sum_{j\in J} \text{Energy\_cost}_{ij} \cdot PC_{ijty} + \sum_{i\in I} \sum_{j\in J} \text{Labor\_cost}_{ij} \cdot PC_{ijty}\ \forall t \in T, \forall y \in Y \quad (23)$$

$$Costs\_proc_j = \sum_{i\in I} \sum_{t\in T} \sum_{y\in Y} \text{Energy\_cost}_{ij} \cdot PC_{ijty} + \sum_{i\in I} \sum_{t\in T} \sum_{y\in Y} \text{Labor\_cost}_{ij} \cdot PC_{ijty}\ \forall y \in J \quad (24)$$

$$X_{ijty} \in \{0,1\};$$

$$d\_\cos t^{-} \geq 0; d\_\cos t^{+} \geq 0$$

$$CM \geq 0$$

$$d\_product_i^{-} \geq 0; d\_product_i^{+} \geq 0\ \ \forall i \in I$$

$$Quantity\_product_i \geq 0; \text{Revenue\_product}_i \geq 0 \qquad \forall i \in I$$

$$Costs\_\text{Proc}_j \geq 0\ \forall j \in J \quad (25)$$

$$Ava_{ty} \geq 0; Costs_{ty} \geq 0; PC\_period_{ty} \geq 0\ \forall t \in T, \forall y \in Y$$

$$Quantity\_total_{ty} \geq 0; \text{Revenue\_total}_{ty} \geq 0\ \forall t \in T, \forall y \in Y$$

$$Quantity_{ity} \geq 0; \text{Revenue}_{ity} \geq 0\ \ \forall i \in I, \forall t \in T, \forall y \in Y$$

$$PC_{ijty} \geq 0\ \forall i \in I, \forall j \in J, \forall t \in T, \forall y \in Y$$

Case study: model parameterization and assumptions

The data used were for an industrial laundry located in Maringá, Paraná State, Brazil. Production planning in the laundry considered the total amount of clothes to be processed during a month, which determined the goals for one day and for one week of work. There were six types of products: pants, jacket, skirt, slacks, bermuda, and shirt ($ni = 6$).

According to the daily demand for each type of clothes (real data for the industrial laundry), the clothes to be processed were 80% pants, 2% jackets, 6% skirts, 1% slacks, 8% bermudas, and 3% shirts.

Lots were made up according to the capacity of each piece of equipment for each type of clothes

(which defined the desired goal for each type of clothes). Only one lot could be processed in each dryer for each period of one hour. The processing time was 45 minutes and 15 minutes were allowed between sequential lots for unloading and loading the dryer. Furthermore, each lot consisted of only one type of clothes. Ten dryers were available (nj = 10), with total capacity of 922.50 kg h^{-1} (see Table 1). The mass of the clothes was converted into the number of pieces, according to the average mass of each type of clothes.

The dryers consumed 1199.70 kWh $month^{-1}$, corresponding to 11.8% of the total electric energy consumption of the industrial laundry.

Since the model was developed to assist production planning, it could be employed for different time horizons and the planning of production in different periods, for example enabling revision of the schedule in response to a change in product demand. Initially, three scenarios were considered: twenty-one hours of daily work (nt = 21, Scenario 1); one week of six working days (ny = 6, Scenario 2); and twenty-six working days in the month (ny = 26, Scenario 3), including all the three shifts. In each scenario, the model was required to distribute the production capacity into lots for each dryer.

For these three scenarios, the installed capacity provided a guide for specifying the production goals. In order to have lower bounds for the goals, it was considered that each dryer should operate with at least two thirds of its maximum load (Table 1). Hence, for the first scenario, which considered one day of work, the production goal was between 12,915 and 19,372.50 kg of clothes. In the second scenario, with one week of work (6 working days), the stipulated goal was between 77,490 and 116,235 kg of clothes. In the third scenario (one month, or 26 working days) the goal was between 335,790 and 503,685 kg of clothes.

Equations (6) and (7) were used to calculate the production and cost goals, respectively, for each of the three scenarios. In each case, the objective was to minimize costs and maximize production. The maximum production costs for Scenarios 1, 2, and 3 were \$643.00, \$3,858.00, and \$16,718.00, respectively.

A fourth scenario was considered, using a period of one month (ny = 26, Scenario 4), with the existing laundry production used as a reference (390,000 clothes, corresponding to 229,515 kg). In this case, the lower bound was less than two thirds of the maximum load, because the existing laundry production was less than 335,790 kg. As before, the objective was to minimize costs and maximize production. The maximum production cost was \$16,718.00 (the same as in the third scenario). Table 2 presents the limits for the production goals in terms of items per type of product for each scenario considered. The data in Table 2 were calculated based on the range of production (in mass) for each scenario, the mass of each type of clothes, and the percentage of the number of items processed daily corresponding to each type of product.

Table 1. Installed capacity of each dryer.

Machine	Maximum load (kg)	Maximum number of units					
		Pants	Jacket	Skirt	Slacks	Bermuda	Shirt
Dryer 01	75.0	115	115	214	167	250	375
Dryer 02	75.0	115	115	214	167	250	375
Dryer 03	75.0	115	115	214	167	250	375
Dryer 04	75.0	115	115	214	167	250	375
Dryer 05	112.5	173	173	321	250	375	563
Dryer 06	112.5	173	173	321	250	375	563
Dryer 07	112.5	173	173	321	250	375	563
Dryer 08	112.5	173	173	321	250	375	563
Dryer 09	150.0	231	231	429	333	500	750
Dryer 10	22.5	35	35	64	50	75	113

Table 2. Minimum and maximum number of items per type of product for all scenarios.

Type of clothes	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
Pants	17,556	26,335	105,339	158,010	456,469	684,703	156,000	312,000
Jacket	439	658	2,633	3,950	11,412	17,118	3,900	7,800
Skirt	1,317	1,975	7,900	11,850	34,234	51,351	11,700	23,400
Slacks	219	329	1,316	1,973	5,701	8,551	1,950	3,900
Bermuda	1,756	2,633	10,533	15,800	45,645	68,468	15,600	31,200
Shirt	658	988	3,950	5,925	17,117	25,675	5,850	11,700

Results and discussion

All the scenarios were evaluated using the GAMS/Cplex solver. It was assumed that the types of clothes in each lot were not mixed, and the best distribution of lots to the dryers was searched for each hour (one lot per machine for each hour) in order to enable production to be as close to the goal as possible, while at the same time not exceeding the costs goal. Table 3 presents the results for the four scenarios evaluated. For Scenario 1 (one working day), the individual goals were only achieved for slacks and shirts. It was also found that in addition to maximizing production (distributing lots for better use of dryer capacity), the optimum cost was better than its goal. As an example of the distribution of the lots, Table 4 presents the Scenario 1 results for the first four hours of the day.

In Scenario 2 (one week of work), individual goals were achieved for skirts, bermudas, and shirts (Table 3). The goal for the production cost was achieved. Another important result for this scenario concerned the contribution margin. The optimum calculated value was $149,484.00, while company reports stated that the existing contribution margin for this period was $62,400.00 (Table 5).

In Scenario 3, the goal was only achieved for the quantity of shirts (Table 3). However, in Scenario 4, which considered the existing laundry production, all the goals were achieved. It was therefore clear that the existing operation of the laundry did not make use of the full capacity of the ten dryers.

Table 6 presents a comparison of the existing conditions and the optimum conditions found using the optimization procedure (i.e., making use of the full capacity of the available dryers). Obviously, operation of the dryers section in the laundry could be improved, avoiding energy consumption for the production of only a few clothes units. Human and capital resources could also be better used. The gross revenue and the global contribution margin could be increased by around 120% from the existing value. The existing operation of the drying sector of the laundry did not make use of full capacity.

Observation of Dryer 09, the machine with the largest capacity, which was able to process 231 pants daily, indicated that the average number of pants processed daily was 150. For all types of clothes, the amounts of processed items were lower than the capacities of the machines, demonstrating that the existing production lots were not properly planned. Furthermore, even with the reduced load, the average processing time (which should be 45 minutes) was 59 minutes. The ideal working temperature was 70ºC, but in practice the temperature was between 53 and 58ºC, due to lack of continuous cleaning of the internal box, where residues accumulated. Furthermore, the dryers were randomly opened in order to check whether the clothes were still wet to the touch, which delayed the drying time. All these factors combined resulted in significant losses for the overall industrial process.

Table 3. Results for all scenarios.

Type of clothes	Scenario 1		Scenario 2		Scenario 3		Scenario 4	
	Goal	Optimum value	Goal	Optimum value	Goal	Optimum value	Goal	Optimum value
Pants	26,335	26,321	158,010	157,878	684,703	684,127	312,000	312,000
Jacket	658	623	3,950	3,936	17,118	17,073	7,800	7,800
Skirt	1,975	1,974	11,850	11,850	51,351	51,347	23,400	23,400
Slacks	329	329	1,973	1,969	8,551	8,550	3,900	3,900
Bermuda	2,633	2,625	15,800	15,800	68,468	68,463	31,200	31,200
Shirt	988	988	5,925	5,925	25,675	25,675	11,700	11,700
Total Cost ($)	643.00	642.24	3,858.00	3,858.00	16,718.00	16,718.00	16,718.00	16,718.00

Table 4. Distribution of lots for the first four hours of the day in Scenario 1.

Machine	Type of clothes	t = 1	t = 2	t = 3	t = 4
Dryer 1	Pants	-	-	115	115
	Bermuda	250	250	-	-
Dryer 2	Pants	115	115	-	115
	Bermuda	-	-	250	-
Dryer 3	Pants	115	115	115	115
Dryer 4	Pants	115	115	115	115
Dryer 5	Pants	173	173	173	173
Dryer 6	Pants	173	173	173	173
Dryer 7	Pants	173	173	173	173
Dryer 8	Pants	173	173	173	173
Dryer 9	Pants	231	-	231	231
	Jacket	-	231	-	-
Dryer 10	Skirt	64	64	64	64

Table 5. Current and optimum contribution margins (CM) for Scenario 2.

Day	Current CM	Optimum CM
Day 1	$10,468,00	$24,870.00
Day 2	$10,200.00	$25,040.00
Day 3	$10,357.00	$24,849.00
Day 4	$10,109.00	$24,638.00
Day 5	$11,284.00	$24,955.00
Day 6	$9,982.00	$25,132.00
TOTAL	$62,400.00	$149,484.00

Table 6. Current and optimum values for one month of work.

Type of clothes	Current situation	Optimum situation
Pants	312,000 units	684,127 units
Jacket	7,800 units	17,073 units
Skirt	23,400 units	51,347 units
Slacks	3,900 units	8,550 units
Bermuda	31,200 units	68,463 units
Shirt	11,700 units	25,675 units
Gross revenue	$303,030.00	$664,487.00
Energy cost	$4,366,92	$4,366.92
Labor cost	$9,392.72	$9,392.72
Global contribution margin	$295,402.50	$647,770.00

In order to provide information concerning the size of the model in each scenario, Table 7 presents the main data used to solve the problem, considering the number of continuous and binary variables and the number of equations.

Table 7. Model sizes in the different scenarios.

Item	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Number of variables	2,916	17,180	107,637	74,321
Number of binary variables	1,260	7,560	32,760	32,760
Number of equations	3,182	18,712	115,252	80,893

Conclusion

A mathematical model was developed in order to improve and optimize the drying process in an industrial laundry. The problem was formulated as multi-objective and the model was classified as mixed-integer linear programming (MILP). Goal programming was used and GAMS was employed to solve the problem. It was demonstrated that substantial improvements could be achieved, because capital, operating, and human resources were not being well utilized. The results demonstrated that better production planning could be obtained by using the developed model as a valuable tool to assist in production lot distribution.

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