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ORIGINAL ARTICLE

Energy consumption optimization in a printing company

Otimização do consumo energético em uma indústria gráfica

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Abstract: In this study, an integer linear programming model is proposed to support the Production Planning, Scheduling and Control sector of a printing company. The model considers two objective functions to deal with the problem, the first is to minimize the costs with electric energy consumption and the second is to minimize the machine operating time. Both objectives are related to the assignment to different sets of printing and finishing machines for the manufacture of the ordered items. Operating constraints at the factory are considered, such as the setup time limits, how the machine is operated, the types of printed item, the production capacity and the demand. In addition, a heuristic was developed to support the production schedule, allowing adjustments in the different production shifts but respecting the assignments obtained using the mathematical model. Computational tests were performed with a set of data provided by a printing company located in the state of São Paulo.

Keywords: Optimization; Energy efficiency; Energy consumption; Production planning and control; Printing company.

Resumo: Neste trabalho, é proposto um modelo matemático de programação linear inteira para auxiliar o setor de Planejamento, Programação e Controle da Produção de uma indústria gráfica. O modelo considera duas funções objetivos para tratar o problema, a primeira para minimizar os custos com o consumo de energia elétrica e, a segunda, para minimizar o tempo operacional das máquinas, ambas relativas à designação e utilização de conjuntos distintos de máquinas de impressão e de acabamento para a confecção dos itens demandados. São consideradas restrições operacionais da indústria, tais como, os limites de tempo de *setup* e de operação das máquinas, tipos de item impresso, capacidade de produção e atendimento de demanda. Além disso, uma heurística foi desenvolvida para auxiliar a programação da produção, permitindo ajustes nos respectivos turnos de produção da indústria, mas respeitando a designação obtida pela resolução do modelo matemático. Testes computacionais foram realizados com um conjunto de dados fornecidos por uma indústria gráfica situada no interior do estado de São Paulo.

Palavras-chave: Otimização; Eficiência energética; Energia elétrica; Planejamento e controle da produção; Indústria gráfica.

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1 Introduction

Integration between markets and accelerated development of new products has increased competitiveness between businesses. Faced with this scenario, many companies are looking to improve performance in their production processes, from the responsibility for planning and improving processes to their organizational structure.

To maintain competitiveness, internal strategies for managing materials, production systems and methods must be outlined and analyzed. As Corrêa & Corrêa (2006) stated, these strategies must ensure that production processes are aligned with the strategic intentions, in terms of financial results within the market in which it operates. Among the various factors that can affect operating costs, the high consumption of electricity, due to the use of old machinery and the high cost of the electricity tariff at certain times stand out. In Brazil, electricity tariffs are determined by the National Electricity Agency (ANEEL, 2022), which also establishes the criteria for classifying consumers and the ways in which they are charged. According to the electricity concessionaire, during the so-called "peak hours", the cost of the tariff is higher and, in the state of São Paulo, that occurs between 6pm and 9pm on working days. According to Soler et al. (2016), as electricity tariffs vary throughout the day, companies need to invest in the planning of machine operating shifts.

For Bermann (2002), there is a need to implement public policies that set objective targets for reducing energy consumption in groups of companies, through the modernization of production plants and innovations that can reduce energy consumption in the production process. On the other hand, these measures must be implemented in such a way that they do not harm the economic growth of these industries, as Goldemberg (1998) points out. Planning, strategy and risk mapping are concepts that drive the business world. To position yourself in a competitive market, you need techniques that enable you to make decisions clearly, objectively and with the least possible risk. Therefore, in order to get ahead of its competitors, a company needs technical backing for its decisions. This requires the application of consistent methods that meet the expectations of its stakeholders (Santos et al., 2015).

In this context, this study proposes the use of optimization techniques to assist in Production Planning, Scheduling and Control (PSC) in a printing company. More specifically, a mathematical model based on the task assignment problem is proposed to optimize the use of different printing and finishing machines in the factory, to reduce the costs of electricity consumption during the time the machines are in operation. On the other hand, the operational time for producing items can be optimized if the factory wants to speed up the production, completion and delivery process. Operational constraints are taken into account, relating to the operating and setup times of the printing machines, as well as the particularities of the printed item and production capacity. In addition, a heuristic was developed to help with production scheduling, making adjustments to production in the respective production shifts, while respecting the designation obtained by the optimization model. It is worth noting that this adjustment is related to the subdivision of Production Planning and Control defined in Lustosa et al. (2008) and aims to sequence, program and control the production of items after designation. The production shift considered can be daily, weekly or monthly. The proposed mathematical model was implemented using the CPLEX solver available in the GAMS software and the computer tests were carried out using data from a printing factory located in Bauru, in São Paulo state.

The rest of the text is organized as follows. Section 2 reviews the literature on the use of scientific tools to optimize production in the printing industry. Section 3 describes the main characteristics of production planning in a printing factory. Section 4 presents and discusses the mathematical model proposed for the problem of assigning items to printing and finishing machines, with demand fulfilment and machine preparation. Section 5 describes the solution methodology used for production scheduling. Section 6 contains the computational tests carried out and an analysis of the results obtained. Conclusions and future prospects are presented in Section 7.

2 Literature review

Related to the printing industry, some studies that consider tools to optimize electricity consumption, among other factors, are discussed in this section.

Espírito Santo (2004) carried out an analysis of the costing system used in the printing industry, considering small and medium-sized companies. Various factors that influence costs are presented, such as personal expenses, depreciation, electricity, rent, auxiliary materials and administrative costs. According to the author, all costs could be calculated to make real reductions and to increase competitiveness. Lima (2007) carried out a case study in a print factory, designing and implementing a cellular layout instead of the linear layout previously used. This change brought some gains, such as an increase in productivity and reductions in time, equipment, the number of people, the area used and electricity consumed, as well as the elimination of transportation. Braun et al. (2007) presented steps for generating an eco-efficient product that can be printed with the aim of contributing to the sustainability of the sector and the environment. The proposed steps are based on other studies carried out previously in different companies.

Oliveira & Rodrigues (2009) evaluated the influence of the item management strategy on inventory management in two companies in the printing sector, one of which adopted the make-to-stock system and the other the make-to-order system, as a way of prioritizing the reduction of costs and losses and increasing the quality of their processes and products. Zeng et al. (2010) simulated an end-to-end printing process, drawing a parallel between print production design and electronic design automation. The authors modeled the production system as a network of distinct, interconnected processes. In addition, they described the simulation framework, validation against queueing theory, presented preliminary simulation results and a path to design. Agrawal et al. (2011) proposed an approach to solve an optimization problem in digital printing, addressing the simultaneous mapping of component tasks of a print job to time steps (scheduling), selection of resources for these tasks and mapping of tasks to resources (linking). The aim of the proposed model is to enable just-in-time manufacturing, i.e. minimizing the time between order completion and delivery, taking into account the opportunity cost of work orders. The proposed approach uses genetic algorithms to systematically search the space of feasible solutions and determine optimal solutions for small instances. Pedrosa & Romero (2012) developed an algorithm to help the production planning with job-shop processes, based on a case study in a printing factory. The algorithm determined an ordered list of operations for each machine, optimizing total task execution time and minimizing machine idle time.

Santos et al. (2015) proposed alternatives for reducing the time spent in the print production process, based on the concepts of process mapping and physical arrangement structuring. They also carried out a case study which pointed out the time spent searching for tools and materials to carry out activities, the main cause being the distance between the workstation and the warehouse, which enabled a leaner production process. Coser et al. (2016) presented the mapping of activities, the main management tools and the process of measuring logistics costs used in a printing company, with the aim of improving performance, customer service and reducing logistics costs. Correia (2016) presented a project to improve material and information flows in the print support and planning areas of a printing factory, which resulted in a reduction in waste in both areas, enabling the company to be more efficient and increasing its competitiveness.

Moreira (2017) studied a preventive maintenance and fault monitoring system, as well as the optimization of production processes related to the offset printing sector. Excessive set-up times and some execution difficulties related to ink not drying were identified. A reduction in overall maintenance costs and significant improvements in machine set-up and ink drying times were achieved. Vaz (2019) carried out a study of the printing processes in a printing factory on scheduling and optimization rules through simulation using SIMIO software. A new proposal was developed, aimed at increasing production through better planning and control of the flow of production processes, reducing time and eliminating costs. Kaszynki et al. (2021) proposed a method based on a mixed integer linear programming approach to optimize the physical location and task allocation of printing devices in office floor plans, taking into account the energy use of ICT assets, costs related to the purchase and service of individual devices, operating costs and distance between employees and printing devices. The applicability of the proposed model is illustrated through a case study of a company with 100 functional departments located in several office buildings in Poland.

Wang et al. (2022) analyzed the problem of flexible production scheduling in a flow shop environment, with sequence-dependent setup, and proposed a case study in a labeling company. The main objective was to develop a methodology to sequence and schedule a set of jobs in order to meet the delivery date for customers, minimizing the number of late orders. A mathematical model was proposed, as well as an alternative approach with the application of a heuristic algorithm using big data as input. The proposed approaches were compared on the basis of the case study, and it was concluded that the proposed heuristic algorithm was able to improve machine utilization in large-scale problems. Abusaq et al. (2023) proposed an approach that combined lean production methods and machine learning to improve energy efficiency in flexographic printing machines. The study showed that the lean methodology employed was efficient and that idle time on each machine was reduced by 30%, resulting in energy savings of around 35%. In addition, a multilinear regression model was developed using machine learning and a series of input parameters, such as machine speed, substrate density, machine idle time, machine working time and total machine running time, in order to predict energy consumption and optimize the scheduling of jobs on the printing machines.

In all of the studies cited, the subjects addressed are: improving the production process and management in general, be it in terms of process flow and/or layout; logistics; working per item or per stock; as well as sustainability issues such as reducing and analyzing waste and pollutants; print production design and electronic design automation; optimization in digital printing, addressing simultaneous mapping of tasks, selection of resources for those tasks and mapping of tasks to resources; optimization of the physical location and task allocation of printing devices in office floor plans. It is worth noting that Abusaq et al. (2023) addressed energy efficiency in using flexographic printing machines. However, that is different from the energy problem addressed in this study on printing and finishing machines in rotary offset presses. This study proposes an integer linear optimization model for the problem, while Abusaq et al. (2023) used lean techniques and machine learning. The topics studied by the authors in question did not directly address the subject matter here, which motivated the proposal and development of this research.

3 The printing company: history and Workflow

The printing industry in Brazil began in 1808 with a royal decree that officially established the printing press in the country. This happened with the arrival of the Portuguese royal family. The first newspaper to be published in Brazil was the Gazeta do Rio de Janeiro. From then on, various other materials began to be produced, such as scientific papers, teaching materials and some literary works. In 1922, a Rio de Janeiro printing company named Litografica Ferreira Pinto acquired the first offset machine in Brazil. The offset press arrived in São Paulo in 1924, brought by Editora Monteiro Lobato, which later passed the equipment on to São Paulo Editora. In 1928, the newspaper O Estado de São Paulo launched the first supplement printed in rotogravure (bas-relief printing using highly durable cylindrical matrices and high-speed rotary printing machines). It was in 1950 that modern printing equipment was introduced by Companhia Litográfica Ypiranga, which installed state-of-the-art equipment to print the first issue of the Seleções magazine in Brazil. In 1984, the printing companies began to be computerized. According to ABIGRAF (Associação Brasileira da Indústria Gráfica, 2015), printing companies have economic and social representation in the Brazilian economy.

3.1 Graphic industry Workflow

The Workflow of a graphic industry represents its operational flow, from the capture and formation of a portfolio of customer orders and their items, the creation of production orders and subsequent analysis of the necessary inputs by PSC, as well as their allocation to printing machines and, when necessary, to finishing machines, for later shipment to customers.

3.1.1 Customer purchase and ordered items

All the items produced by a printing company go through a series of internal processes before finally reaching customers. The first step is customer purchase through salespeople, who can be internal, working through telemarketing, or external, where it is done in person. After this, a budget is drawn up, which takes into account the entire production process of the industry in order to cost the production of a particular item. Negotiations then take place between salespeople and customers and, when approved, a production order is placed for the items requested by the customer. The items sold by a printing company are very diverse, including continuous printed or unprinted forms, used to print invoices, service orders, and so on. These items can be finished in some way, when the customer requires the formulary to have sequential numbering, the inclusion of perforations for removing receipts or stubs and so on.

3.1.2 Pre-analysis of the production order and necessary inputs

This stage is where the PSC department first comes into play. With the production order in hand, the raw materials needed to produce the items are analyzed and the production time and delivery time can be estimated. Stock levels are checked and the purchasing department formalizes the reservation and purchase of raw materials with suppliers. The finance department schedules payment and the PSC is notified of when the materials are expected to be available. With this, the PSC is able to estimate when and for how long the order will be in the production process.

3.1.3 Printing and finishing machines

This process uses what are known as printing machines (Figure 1), where the raw materials are allocated and, after the necessary setups, they are transformed into a product that can be customized or not. The printing machines configure the colors, serration positions, printing cylinder changes and finish types, among other product characteristics. The printing process must first obey some basic rules. As there are printers with different characteristics in the printing factory, each with its own technology, consumption and speed, it is not advisable for one type of customer item to be processed on different printers, so that there is no variation in the quality of this item, in addition to other technical standard issues, such as perforations that do not fit, overlapping traction strip holes and colors with different shades. Once the printing process is complete, the item that needs some kind of finishing will be placed in the finishing machines, in a process similar to that of the printing machines. The finishing can be varied, such as the numbering of the forms, some kind of fold or special cut, along with other less common ones.

Figure 1. Rotary offset press. Source: PRINTCS (2022).

Figure 2 shows the layout of the factory and the arrangement of the printing and finishing machines. After these processes, the material can be sent to dispatch and transported to customers.

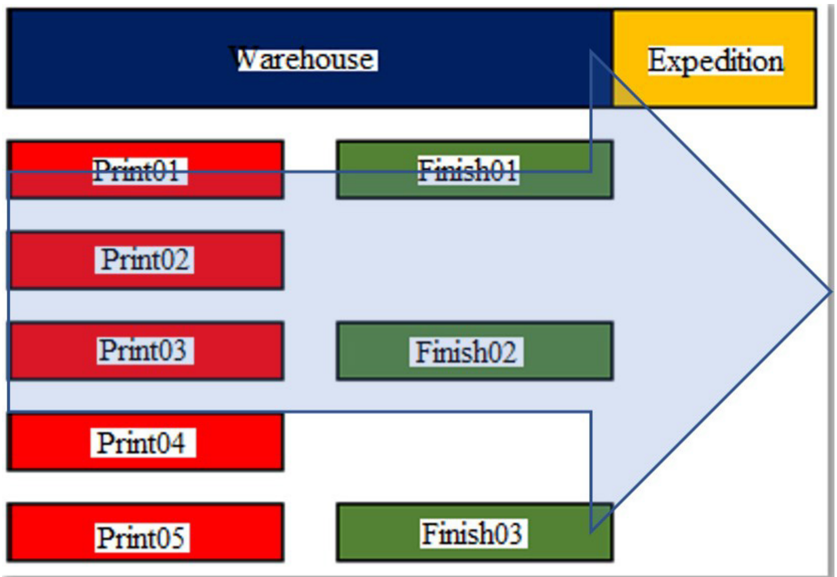

Figure 2. Layout and arrangement of machines - factory workflow. Source: author.

3.1.4 Production planning, scheduling and control

Companies in the industrial sector often have a department that works in total integration with the other sectors. This simultaneous action, when well implemented, has a lot to contribute to the company. PSC maintains this synergy between the various sectors, from direct contact with the commercial and sales sectors to the finished goods dispatch sector. According to Laugeni & Martins (2015), the PSC is one of the main sectors in the company responsible for decision-making. Its main function is to control resources within the item production process and its aim is to transform these resources efficiently into goods and services.

Taglialenha & Barbosa (2017) point out that there is a difference between the terms "planning" and "scheduling", related to the time horizon considered, with "planning" applying to medium and long-term situations while "scheduling" is linked to the short term. Chiavenato (2008) mentions that production planning seeks to define in advance what to do and how to do it, as well as when to do it and who will do it, in order to obtain the best efficiency in conjunction with the effectiveness of the process. Favaretto (2001) also mentions that decision-making is an integration between production management and other functional areas of the industry, such as the sales and finance departments.

Production scheduling is responsible for defining how items will be produced. Lustosa et al. (2008) present a subdivision that should guide decisions regarding production scheduling:

- Assignment: where the demands should be produced;
- Sequencing: the order in which the tasks should follow in production;
- Scheduling: defining when the task will be started and finished;
- Control: monitoring the sequence of the schedule so that it is followed, and if any rescheduling/intervention is necessary.

As Pape (2005) states, sometimes we may be faced with a scaling problem, which consists of deciding when demands should be produced, but taking into account time and resource constraints. In addition, Russomano (2000) mentions how difficult it is to define a priority criterion between jobs, the most common of which are meeting delivery dates, maximizing profits and minimizing costs, but in some cases it is not possible to satisfy all needs, for example, prioritizing meeting deadlines can increase production costs.

3.2 Description of the production process in a printing factory

Once customer demands have been defined, an order portfolio is organized and production orders are entered. The items required go through a series of internal processes before being finalized and delivered. In general, these items are very diverse, particularly the continuous printed or unprinted form used, for example, for invoices and work orders. These forms (items) may need some kind of finishing, such as sequential numbering, some kind of fold, special cuts and the inclusion of perforations to separate receipts or stubs, among other less common items.

With the production order in hand, stock levels are checked, and the production time is estimated. Different printing and finishing machines are used to produce the items required. Once the raw materials have been allocated to the printing machines, the colors, serration positions, printing cylinder changes, types of finishes and other product characteristics are configured. Items are assigned to the printers, considering their different characteristics and avoiding variation in the quality of the item and other technical standards issues. Item that needs some kind of finishing are allocated to the finishing machines.

Once the printing process is complete, the item that needs some kind of finishing will be allocated to the finishing machines, in a process similar to that of the printing machines. It should be noted that during the item production process, each printing or finishing machine must receive one item at a time and can produce more than one item during the production shift. Afterwards, items are read to be transported to customers.

3.3 Aspects of production specific to the factory

In Section 4, a mathematical model is proposed to deal with the problem described in Section 3.2. Some complementary issues observed in the factory and considered in the modeling need to be highlighted: all items to be produced necessarily pass through the printing machines, but not all require finishing; each machine receives one item at a time and can produce more than one item during the production shift; each item is made by only one printing and finishing machine (when necessary).

Due to the complexity of proposing and implementing the model, some issues relating to the sizing and sequencing of production were disregarded, such as long production planning periods, production stocks, long-term demands, deadlines for fulfilling order portfolios, labor costs (scalability) and production control, among others. Therefore, disregarding the restrictions mentioned and proposing a simplified model that considered all the data about the production process in a factory in the state of São Paulo, opting only to assign the items to machines, separated into, first, printing machines and, after, finishing machines, respecting the operational constraints of the plant and meeting all the demand. Then, the production of these items was planned in the respective production shifts, which could be daily, weekly or monthly.

For this reason, a heuristic was proposed that takes into account the production priorities established by the company. In this study, daily production shifts (8 hours plus a possible two extra hours a day) were used which help to sequence the production, prioritizing the items that need both the printing and finishing machines.

In addition, the company considered in this case study does not work with a stock of items and so this was not included in the model.

4 Mathematical model for the printing factory

This section describes the mathematical model proposed to address the assignment problem.

It is important to note that, before the stage of assigning items to machines, PSC takes into account some factors present in the production process, such as the availability of inputs and the delivery times to be met. This information is therefore represented by parameters in the model.

For each production shift, the model takes into account the demand for items and machine data, such as the setup times, processing speeds and energy consumption. Once the items have been assigned to the machines, all the other planning steps have to be completed, i.e. sequencing, scheduling and controlling the production of the items taking into account the periodic production shifts. These complementary steps are carried out in a subsequent analysis using an adjusting production heuristic, described in Section 5.

Next the sets, parameters and decision variables of the mathematical model are presented.

Sets:

$M = \{1, \dots, |M|\}$: set of printing machines (index *m*);

$N = \{1, \dots, |N|\}$: set of finishing machines (index *n*);

$I = \{1, \dots, |I|\}$: set of items to be produced (index *i*).

$F = \{1, \dots, |F|\}$: set of items that require printing and finishing (index *i*, $F \subseteq I$).

Parameters:

c unit cost of kWh, supplied by the energy concessionaire;

kp_m energy consumption in kWh of the printing machine m;

kf_n energy consumption in kWh of the finishing machine n;

cp_m cost of the energy consumption of printing machine m $(c \cdot kp_m)$;

cf_n cost of the energy consumption of finishing machine n $(c \cdot kf_n)$;

v_m operating speed of the printing machine *m*, in meters/minute;

v_n operating speed of finishing machine *n*, in meters/minute;

TP_{im} printing time per meter of item *i* on the printing machine m $(1/v_m)$;

TF_{in} production time per meter of item *i* on the finishing machine n $(1/v_n)$;

T_m maximum operating time of printing machine *m*, in minutes, defined by the planning horizon;

T_n maximum operating time of finishing machine *n*, in minutes, defined by the planning horizon;

AP_{im} average setup time for item *i* on the printing machine m;

AF_{in} average setup time for item *i* on the finishing machine n;

G sufficiently large number;

D_i demand for item *i*, in meters.

Decision variables

z_{im} quantity (in meters) of item *i* to be printed on the printing machine m;

w_{in} quantity (in meters) of item *i* to be finished on the finishing machine n ($i \in F$);

$$x_{im} = \begin{cases} 1, \text{if item } i \text{ is assigned to the printing machine } m, \\ 0, \text{otherwise.} \end{cases}$$

$$y_{in} = \begin{cases} 1, \text{if item } i \text{ is assigned to the finishing machine } n, \\ 0, \text{otherwise.} \end{cases}$$

Mathematical Model

$$\text{Minimize } \sum_{m \in M} \sum_{i \in I} cp_m (TP_{im} z_{im} + AP_{im}\, x_{im}) + \sum_{n \in N} \sum_{i \in F} cf_n (TF_{in} w_{in} + AF_{in} y_{in}) \qquad (1)$$

Subject to:

$$\sum_{i \in I} (TP_{im} z_{im} + AP_{im}\, x_{im}) \le T_m;\ m \in M; \qquad (2)$$

$$\sum_{i \in J} (TF_{in}\, w_{in} + AF_{in}\, y_{in}) \le T_n;\ n \in N; \qquad (3)$$

$$\sum_{m \in M} z_{im} = D_i; i \in I; \qquad (4)$$

$$\sum_{n \in N} w_{in} = D_i;\ i \in J; \qquad (5)$$

$$z_{im} \le G x_{im};\ i \in I;\ m \in M; \qquad (6)$$

$$w_{in} \le G y_{in};\ i \in F;\ n \in N; \qquad (7)$$

$$\sum_{i \in I} x_{im} \ge 1;\ m \in M; \qquad (8)$$

$$\sum_{i \in J} y_{in} \ge 1;\ n \in N; \qquad (9)$$

$$\sum_{m \in M} x_{im} = 1;\ i \in I; \qquad (10)$$

$$\sum_{n \in N} y_{in} = 1;\ i \in F; \qquad (11)$$

$$z_{im} \in Z_+;\ i \in I;\ m \in M; \qquad (12)$$

$$w_{in} \in Z_+;\ i \in F;\ n \in N; \qquad (13)$$

$$x_{im} \in \{0,1\};\ i \in I;\ m \in M; \qquad (14)$$

$$y_{in} \in \{0,1\};\ i \in F;\ n \in N. \qquad (15)$$

In the model (1)-(15), the Objective Function (1) minimizes the cost of energy consumption for the production of the items required, considering the printing and finishing machines, taking into account the setup time of the machines and the production time of the items. Constraint (2) ensures that the capacity of each printing machine over the planning horizon is respected. Similarly, Constraint (3) ensures that the time used on each finishing machine during the planning horizon is less than or equal to the available capacity. Constraints (4) and (5) ensure that the demand for each item over the planning horizon is met exactly. It can be seen that if production periods *t* were considered in the model, these restrictions could be of the type "<=" if stock were considered or ">=" if leftovers of item *i* were considered. In the simplified model, no stock or leftovers were taken into account. The set of Constraints (6) relate the production and designation variables associated with the printing machines. Item *i* will be printed on machine *m* only if item *i* is assigned to machine *m*. Similarly, Constraints (7) relate the production and assignment variables associated with finishing machines.

(8)-(11) are the assignment constraints. Constraint (8) ensures that each printing machine receives at least one item during the planning horizon. The same goes for each finishing machine, in Constraint (9). These constraints meet the reality and practice of the factory but it is possible to treat them as "≤" inequalities, making it possible to increase and prioritize production on one machine while possibly making another machine inoperative in the production process. Constraint (10) ensures that each item is assigned to a single printing machine. Similarly, Constraint (11) ensures that each item that needs finishing is assigned to a single finishing machine. Finally, Constraints (12)-(15) define the domain of the decision variables.

For some particularity, it can be interesting for the company to minimize the machine operating time. In this case, the mathematical model (1)-(15) must be redefined by replacing Objective Function (1) by the Objective Function (16).

$$\text{Minimize } \sum_{m\in M}\sum_{i\in I}(TP_{im}z_{im} + AP_{im}\, x_{im}) + \sum_{n\in N}\sum_{i\in F}(TF_{in}w_{in} + AF_{in}y_{in}) \tag{16}$$

5 Production adjustment heuristic

After solving the mathematical model (1)-(15) or (2)-(16), which assigns the ordered items to the printing and finishing machines, a production adjustment heuristic is applied, which respects the assignment determined by the solution of the model for the planning horizon and aims to establish a production schedule to adjust the manufacture of the items in the respective production shifts at the factory into which the planning horizon is divided.

The proposed production adjustment heuristic aims to determine the production schedule based on the assignment of items to machines obtained by solving the mathematical model (1)-(15) or (2)-(16). For the description of the heuristic, the sequencing and scheduling of the items are defined according to the steps described below, remembering that production control should be considered at a later stage in Step iv).

Heuristic steps:

i) Select the items that need finishing;

ii) In order to obtain a shorter idle time for the finishing machines, allocate to the printing machines, among the items selected in step i), those that require the shortest production time as a priority, since these items will then be assigned to the finishing machines when considering the objective function (1), relating to minimizing the cost of energy consumption, or when considering the objective function (16), relating to minimizing production operating time;

iii) The daily operating time of the printing and finishing machines must not exceed ten hours, eight hours of which must be in the daily shift, including a possible two hours of overtime;

iv) Items that are not finished in one shift must be started in the next shift on the same machine. If the item is finished at the end of the shift (without the need for overtime), the next item assigned to that machine will start production on the following shift. And when the items are not finished within the planning horizon, it will automatically be allocated to the next horizon.

Section 6 presents the results of the computational experiments carried out for the two objective functions, defined by expressions (1) and (16) of the mathematical model, for this case study, based on order portfolios containing the demands of each customer.

6 Computational tests

To verify the performance of the proposed solution method, computational tests were carried out with data supplied by the printing factory. The instances used in the tests were created from three (3) order portfolios that were already being scheduled in production. The production shift considered was 8 hours per day, which could be extended up to a maximum of 2 hours per day in terms of extra machine operating time.

The mathematical model (1)-(15) and heuristic procedure were implemented on the GAMS 34.3.0 using the CPLEX solver 12.10, and a computer with an Intel® Core™ i5 processor and 4GB of RAM. The tests using the machines available in the company print area, which are: five (5) printing machines (Print) and three (3) finishing machines (Finish). Table 1 shows their general characteristics as speed (meter/hour), setup (hour), and the consumption (kWh). The cost of electricity supplied by the utility company is R$0.86 per kWh during its off-peak operating hours (the value of parameter c considered for the calculations of cp_m and cf_m in the model defined in Section 4).

Table 1. Technical data on the machines at the printing company.

Machine	Speed (m/h)	Setup (h)	Consumption (kWh)
Print01	10,500	0,25	40
Print02	3,000	0,5	112
Print03	7,800	0,33	49.2
Print04	12,600	0,17	24
Print05	9,000	0,25	2.2
Finish01	7,800	0,5	40
Finish02	12,000	0,75	112
Finish03	10,800	0,75	50

The portfolios containing the ordered items (Portfolios I, II and III), with the respective quantified item demands (Qtf) in meters (m) and the demands (Dem) are shown in Tables 2 to 4. The demands for items that require finishing are highlighted in Tables 2 to 4, which are the demands D01 to D05 (Table 2), demands D01 to D10 (Table 3) and demands D01 to D35 (Table 4).

Table 2. Portfolio I - customer items.

Dem	Qtf (m)
D01	15,000
D02	20,000
D03	55,000
D04	85,000
D05	50,000
D06	60,000
D07	70,000
D08	80,000
D09	90,000
D10	18,000

Table 3. Portfolio II - customer items.

Dem	Qtf (m)	Dem	Qtf (m)
D01	15,000	D11	13,000
D02	20,000	D12	28,000
D03	55,000	D13	59,000
D04	85,000	D14	82,000
D05	50,000	D15	55,000
D06	60,000	D16	61,000
D07	70,000	D17	77,000
D08	80,000	D18	84,000
D09	90,000	D19	91,000
D10	18,000	D20	70,000

Table 4. Portfolio III - customer items.

Dem	Qtf (m)	Dem	Qtf (m)	Dem	Qtf (m)	Dem	Qtf (m)	Dem	Qtf (m)
D01	15,000	D11	13,000	D21	77,000	D31	17,000	D41	55,000
D02	20,000	D12	28,000	D22	54,000	D32	46,000	D42	67,000
D03	55,000	D13	59,000	D23	10,000	D33	98,000	D43	43,000
D04	85,000	D14	82,000	D24	13,000	D34	78,000	D44	45,000
D05	50,000	D15	55,000	D25	67,000	D35	11,000	D45	12,000
D06	60,000	D16	61,000	D26	35,000	D36	98,000	D46	17,000
D07	70,000	D17	77,000	D27	12,000	D37	45,000	D47	74,000
D08	80,000	D18	84,000	D28	98,000	D38	85,000	D48	33,000
D09	90,000	D19	91,000	D29	43,000	D39	35,000	D49	42,000
D10	18,000	D20	70,000	D30	40,000	D40	27,000	D50	17,000

The data presented in Tables 1 to 4 produced the results of which printing and finishing machines should be active in order to minimize the cost of energy consumption of the machines, based on their processing time to meet the production demands of customers.

In addition to minimizing the cost of energy consumption, the minimization of operating time was also tested by replacing the Objective Function (1) with the Objective Function (16). The results are presented and compared in Section 6.1.

6.1 Results

The results from solving model (1)-(15), which aims to minimize the cost of consumption, are shown in Table 5. It shows the times that the printing and finishing machines were in operation to make all the items, as well as the number of items (Num. items) allocated and which orders were assigned to each machine, for each portfolio, respectively. In addition, the last three lines of these tables show the total time (hours), total energy consumption (kWh) and total cost (R$) to produce Portfolios I, II and III, respectively. The times shown already include the setups required for each of the machines. The last line of Table 5 shows the total execution time by GAMS-CPLEX (seconds) for Portfolios I, II and III, respectively.

Table 5. Results for Portfolios I, II and III (minimizing the cost of energy consumption).

Machine	Portfolio I			Portfolio II			Portfolio III		
	Time (h)	Num. items	Dem (m)	Time (h)	Num. items	Dem (m)	Time (h)	Num. items	Dem (m)
Print01	10,02	2	D02 D08	29,95	4	D07 D14 D16 D19	64	8	D14, D18, D19 D20 D33, D36 D38, D43
Print02	5,5	1	D01	4,83	1	D11	3,8	1	D23
Print03	2,26	1	D10	22,46	2	D08 D09	1,74	1	D35
Print04	19,32	4	D03 D05 D06 D07	29,99	9	D02 D03 D05 D06 D10 D12 D13 D15 D20	89,98	28	D01, D02, D03 D05 D10, D11 D12, D13 D15 D16, D22, D24 D26, D28, D29 D31 D32, D37 D39, D40 D41 D42, D44, D45 D46, D48, D49 D50
Print05	19,94	2	D04 D09	30	4	D01 D04 D17 D18	90	12	D04, D06, D07 D08 D09, D17 D21, D25 D27 D30, D34, D47
Finsh01	3,06	1	D02	29,42	5	D01 D02 D03 D05 D07	90	20	D01, D02, D03 D05, D10, D11 D12, D14, D15 D16, D17, D23 D24, D26, D27 D29, D30, D31 D32, D35
Finish02	2	1	D01	5,75	1	D06	32,58	3	D19, D28, D33
Finish03	19,84	3	D03 D04 D05	28	4	D04 D08 D09 D10	89,92	12	D04, D06, D07 D08, D09, D13 D18, D20, D21 D22, D25, D34
Total Time (h)	81,94			180,4			462,02		
Total consumption (kWh)	2973,94			6.850,55			17177,05		
Total cost (R$)	2557,59			5891,47			14772,26		
CPLEX time (sec)	0,141			10,25			1,641		

The results from solving model (2)-(16), which aims to minimize operational production time, are shown in Table 6, in a similar way to those in Table 5, for Portfolios I, II and III, respectively. The same data from Tables 1 to 4 were used.

Table 6. Results for Portfolios I, II and III (minimizing operational production time).

Machine	**Portfolio I**			**Portfolio II**			**Portfolio III**		
	Time (h)	**Num. items**	**Dem (m)**	**Time (h)**	**Num. items**	**Dem (m)**	**Time (h)**	**Num. items**	**Dem (m)**
Print01	19,8	3	D05 D06 D09	29,95	4	D07 D14 D16 D19	89,89	11	D08, D09, D18 D19, D20, D28 D34, D36, D38 D42, D47
Print02	5,5	1	D01	4,83	1	D11	3,83	1	D23
Print03	2,26	1	D10	22,46	2	D08 D09	0,33	1	D30
Print04	19,71	4	D02 D03 D04 D08	29,99	9	D02 D03 D05 D06 D10 D12 D13 D15 D20	90	30	D01, D02, D03 D05, D10, D11 D12, D13, D15 D16, D22, D24 D25, D26, D27 D29, D31, D32 D33, D35, D37 D39, D40, D41 D44, D45, D46 D48, D49, D50
Print05	8,03	1	D07	30	4	D01 D04 D17 D18	53,63	7	D04, D06, D07 D14, D17, D21 D43
Finsh01	2,42	1	D01	8,19	1	D06	10,56	6	D11, D17, D23 D24, D27, D35
Finish02	18,08	3	D03 D04 D05	30	5	D01 D05 D07 D08 D09	90	11	D04, D08, D14 D16, D18, D19 D20, D21, D28 D33, D34
Finish03	2,6	1	D02	18,28	4	D02 D03 D04 D10	89,61	18	D01, D02, D03 D05, D06, D07 D09, D10, D12 D13, D15, D22 D25, D26, D29 D30, D31, D32
Total Time (h)	78,4			173,7			427,85		
Total consumption (kWh)	4261,65			8231,35			21301,68		
Total cost (R$)	3665,03			7078,96			18319,45		
CPLEX time (sec)	0,156			3,734			0,281		

When the objective was to minimize energy consumption, Table 5 shows that the items are assigned in greater numbers to printing machines 1, 4 and 5 and to finishing machines 1 and 3, as these are the machines with the lowest energy consumption. Table 6, whose objective was to minimize production operating time, shows the items are also assigned in greater numbers to printing machines 1, 4 and 5 but to finishing machines 2 and 3, which are the machines with the highest operating speeds. Regarding the execution time (CPLEX) for solving Portfolios I, II and III using the model proposed in Section 4, Portfolio II used more time for both objectives, approximately 10 seconds (Table 5) and 3.7 seconds (Table 6), for minimizing consumption cost and operating time, respectively. The times presented show a good performance of the software used to solve the order portfolios considering the proposed model. The tests carried out showed that the proposed method performed well.

Section 6.2 presents the application of the production adjustment heuristic considering steps i) to iv) seen in Section 5.1, with the aim of sequencing the items (demands) into daily production shifts, respecting the assignments already determined when solving the optimization model (results determined in Tables 5 and 6).

6.2 Results of applying the production adjustment heuristic

The production adjustment heuristic is based on the assignment of the items to the machines determined by solving the models proposed in Section 4. For Objective Function (1), the results shown in Table 5 were considered and, for Objective Function (16), the results shown in Table 6 were used.

Table 7 shows the working days (shifts) considering the eight normal working hours, as well as the possible two extra hours needed to make the items in each shift. In addition, the results of applying the production adjustment heuristic using Steps i) to iv) and the assignments from objective (1) or objective (16) are shown in Tables 5 and 6 respectively, taking into account the number of items and the rounding in the hours for the scheduling sequencing carried out. For example, Table 7 shows the results for the sequencing carried out for Portfolio III, considering objectives (1) and (16), respectively.

In the representation, the operating time is approximated to the real time by considering whole hours using the decimal 0.5 as a rounding criterion. For example, if the production time is between 4.1 and 4.4 hours, it will be rounded up to 4 hours, and if the production time is between 4.5 and 4.9 hours, it will be rounded up to 5 hours. Table 7 shows the production costs (Consumption and Time) for the horizon proposed by PSC and, in the last row, the costs obtained from solving the mathematical model (ideal cost).

For Portfolios I, II and III, using the solution methodology seen in Section 5, inequalities (2) and (3) considered a planning horizon of 20 days (monthly, disregarding Saturdays and Sundays), which were transformed into machine operating hours/days (8 hours/day plus 2 hours/day of possible overtime multiplied by 20 days). Thus, the values of T_m and T_n for operating the printing and finishing machines were, respectively, T_m = 200 hours and T_n = 200 hours.

Table 7 was drawn up based on the assignment of items to machines made by the model proposed in Section 4, respecting the production sequencing defined by the adjustment heuristic. Gantt charts were constructed, available in Menezes (2021), as well as in the repositor GitHub (2023), which also contains the data from order portfolios I, II and III, used in the computer tests.

Table 7. Allocation of items to machines according to the Production Adjustment Heuristic.

Machine	Order Portfolio I - 10 Items				Order Portfolio II - 20 Items				Order Portfolio III - 50 Items			
	OF (1)		OF (16)		OF (1)		OF (16)		OF (1)		OF (16)	
	Num. Items	Hours	Num. Items	Hours	Num. Items	Hours	Num. Items	Hours	Num. Items	Hours	Num. Items	Hours
Print01	2	10	3	20	4	30	4	30	8	64	11	91
Print02	1	6	1	6	1	5	1	5	1	4	1	4
Print03	1	2	1	2	2	23	2	23	1	2	1	6
Print04	4	20	4	21	9	31	9	31	28	95	30	97
Print05	2	20	1	8	4	31	4	31	12	95	7	57
Finsh01	1	3	1	2	5	30	1	8	20	100	6	20
Finish02	1	2	3	18	1	6	5	29	3	26	11	84
Finish03	3	20	1	3	4	29	4	20	12	90	18	87
Total Time (h)	83		80		185		177		476		446	
Total consumption (kWh)	3038,4		4338		7025,8		8271,8		17007,4		21394,6	
Total cost (R$)	2613,02		3730,68		6042,19		7113,75		14626,36		18399,36	

To illustrate how the sequencing and scheduling of production in daily shifts was carried out in the company, consider Portfolio III and the minimization of consumption cost (OF (1)), for which, respecting the designations made in Table 5, according to the 5th column of Table 7, the production of Portfolio III was completed in a total of 476 hours, distributed over 11 days (shifts) of production. In this case, printing machines 01, 02 and 03 operate without the need for overtime. Printing machines 04 and 05 include 7 hours of overtime each. Finishing machine 01 uses 12 hours of overtime while finishing machines 02 and 03 need 2 hours of overtime each. The highest concentration of items was on printing machines 04 and 05 and finishing machines 01 and 03 due to their low energy consumption.

Similarly, to illustrate the sequencing and scheduling done for the machines, consider Portfolio III and the minimization of operating time (OF (16)), for which, respecting the designations made in Table 6, according to column 6 of Table 7, the production was completed in a total of 446 hours, spread over 10 days. In this case, printing machines 02 and 03 work without any need for overtime. Printing machines 01, 04 and 05 need 11, 17 and 9 hours of overtime, respectively. Finishing machines 01 and 02 include 4 hours of overtime each while finishing machine 03 uses 7 hours of overtime. The highest concentration of items was on printing machine 04 and finishing machines 02 and 03 due their high speed.

Portfolio I with 10 items was adjusted to a planning horizon of 3 days, while Portfolio II with 20 items was adjusted to 4 days and Portfolio III with 50 items was adjusted to 11 days, to minimize consumption costs and 10 days to minimize operational time.

From the production adjustment made by the PSC following Steps i) to iv), it can be seen that, in relation to the solutions obtained by the optimization model, considering the minimization of consumption cost (OF (1)) or operational time (OF (16)), there was an increase in the total cost of the operation in both cases. For Portfolio I, there was an increase of R$55.43 (2613.02 (Table 7) - 2557.59 (Table 5) = 55.43), which corresponds to an increase of 2.2% for minimizing the cost of consumption and R$65.70 (1.8%) for minimizing operational time. For Portfolio II, the increase was R$150.70 (2.6%) and R$34.80 (0.5%). For Portfolio III there was a reduction of R$151.00 (1%) for the consumption cost but an increase of R$79.90 (0.44%) for operational time. The greatest increase in operational time occurred in relation to Portfolio III, from 462 hours to 476 hours, for minimizing the consumption cost, whose variation was approximately 3.0% in relation to the solutions obtained by the mathematical model (Section 4), according to Table 5, as well as from 427.85 hours to 446 hours, for minimizing operational time, whose variation was approximately 4.2% in relation to the solutions obtained by the mathematical model, according to Table 6.

The PSC can, at any time, if necessary, change the sequence in which the items are allocated to the machines, as long as the assignment of items to the printing and finishing machines is not altered.

The results obtained when considering the minimization of consumption cost or operational time show the difficulty of defining a priority criterion in the production at the printing factory, since prioritizing consumption cost increases operational production time and prioritizing operational time increases the consumption cost.

7 Conclusions

In this study, a mathematical model of integer linear programming was proposed to help in the optimization of the PSC of a printing factory, through the assignment of items to be produced on printing and finishing machines, aiming to minimize the consumption cost of electricity or the operational time of production and subject to operational constraints and meeting demand. In its formulation, the proposed assignment model for decision making by the PSC sector was simplified by disregarding internal factors of the production process relating to production sizing, such as long production planning periods, stock, long-term dammed demands, deadlines for fulfilling order portfolios, labor costs (scalability) and production control.

For the computational tests, the GAMS-CPLEX programming language was used, considering a portfolio of items to be produced and the machine data provided by the printing company, such as setup times, processing speeds and respective energy consumption. The results showed the efficiency of the proposed model to assist PSC, enabling the company to reduce its expenditure on energy consumption for the given case study, for example when energy tariffs become more expensive. On the other hand, the reduction of operational time can be considered when the customer order portfolio increases and the industry wants to speed up its production process, in return increasing its energy consumption. The results showed that, when prioritizing the energy consumption reduction, the model assigned the items to the machines with the lowest energy consumption, not taking into account their respective operating speeds, which resulted in an increase in operational time. On the other hand, when the priority was given to reducing the operational time, the model allocated the items to the machines with the highest speed, resulting in higher energy consumption and, consequently, a higher energy consumption cost to meet the demand. After the assignment made from the solution of the proposed mathematical model, the proposed production adjustment heuristic was applied in order to sequence and schedule the production of the items in predefined daily production shifts over the planning horizon. The model allows the planning horizon to be extended and, for example, a weekly or monthly production can be considered instead of daily production.

The contribution of this study is in proposing an optimization approach dealing with energy efficiency in rotary offset printing and finishing machines, a topic that is not widely covered in the literature. Even taking into account the limitations and simplifications in the development of the model and the production adjustment heuristic, the objectives proposed in this study, to optimize energy and to assist the PSC of a printing company, were achieved. Its importance is exclusively related to trying to improve the productive sector of the printing company, specifically in reducing energy consumption costs, investigated with two objectives: minimizing the consumption cost or minimizing the operational time of production, which also affects the energy consumption. Future work could help other industries in the production planning sector that are interested in reducing their energy costs, or their operational production time. Specific suggestions are: (i) work with larger portfolios of customer items, for a weekly or monthly planning horizon; (ii) investigate the trade-off between consumption cost and operational production time, which are conflicting objectives, defining a multiobjective model and solving it using multiobjective optimization methods; (iii) to develop a general model for PSC, which takes into account constraints related to production sizing, long production planning periods, stocks and surpluses, long-term demands, deadlines for fulfilling orders and labor cost limits (scalability), as well as including production control in the printing company.

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Authors contribution

Lucas Farias de Menezes was responsible for conceptualization of the work and of the solution methodology, methodology and the proposition of the model, software learning and aplication, validation of results, writing—original draft preparation, writing—review and editing, and supervision and project administration. Antonio Roberto Balbo was responsible for conceptualization of the work and of the solution methodology, methodology and the proposition of the model, software learning and aplication, validation of results, writing—original draft preparation, writing—review and editing, and supervision and project administration. Adriana Cristina Cherri was responsible for conceptualization of the work and of the solution methodology, methodology and the proposition of the model, software learning and aplication, validation of results, writing—original draft preparation, writing—review and editing, and supervision and project administration. Sônia Cristina Poltroniere was responsible for conceptualization of the work and of the solution methodology, methodology and proposition of the model, validation of results, writing—original draft preparation, writing—review and editing, supervision and project administration. Carla Taviane Lucke da Silva Ghidini was responsible for methodology and proposition of the model, validation of results, and writing—review and editing. Edilaine Martins Soler was responsible for software learning and aplication, and validation of results.