Production planning and scheduling with applications in the tile industry

Armindo Soares

Grés Panaria Portugal,
S.A. Zona Industrial de Aveiro, Apartado 3002,
3801-101 Aveiro, Portugal
Email: armindo.soares@hotmail.com

Carina Pimentel*

GOVCOPP,
DEGEIT,
University of Aveiro,
Campus Universitário de Santiago,
3810-193 Aveiro, Portugal
and
UNIDEMI,
Faculty of Science and Technology,
Universidade NOVA de Lisboa,
2829-516 Caparica, Portugal
Email: carina.pimentel@ua.pt
*Corresponding author

Ana Moura

GOVCOPP,
DEGEIT,
University of Aveiro,
Campus Universitário de Santiago,
3810-193 Aveiro, Portugal
Email: ana.moura@ua.pt

Abstract: In this paper we consider the medium to short-term production planning and scheduling (PPS) process of a ceramic tile industry. The PPS process encompasses three problems: 1) the development of a master production plan that determines the medium-term production needs; 2) the development of a biweekly production scheduling plan that minimises the production time required to complete the set of products, so as to meet customer orders within agreed due dates and ensure the filling of connected firing kilns; 3) the available-to-promise problem (or jobs order acceptance/order selection, and delivery date establishment problem). The production scheduling problem (PSP) was addressed as an identical parallel machine problem, with machine eligibility constraints, family and subfamily setups and minimum production lot sizes. A specific heuristic and a mixed integer programming model are proposed to solve the PSP. A model-driven decision support system, applying and manipulating quantitative models, that improves the quality and time expenditure of the PPS process, is also presented.

Keywords: production planning and scheduling; PPS; constructive heuristic; decision support system; DSS; mixed integer programming; MIP; tile industry; master production schedule; MPS; available to promise; ATP; production scheduling.

Reference to this paper should be made as follows: Soares, A., Pimentel, C. and Moura, A. (2022) 'Production planning and scheduling with applications in the tile industry', *Int. J. Operational Research*, Vol. 44, No. 1, pp.58–79.

Biographical notes: Armindo Soares obtained his MSc in Industrial Engineering and Management at the University of Aveiro, Portugal. He works in the Logistics and Production Planning Department of a ceramic tile industry performing production planning functions, being also responsible for the external subcontracting process of the company.

Carina Pimentel is an Industrial Engineering Assistant Professor at the Department of Economics, Management, Industrial Engineering and Tourism of the University of Aveiro. She is a researcher at the Decision Support Systems Group of the Research Unit on Governance, Competitiveness and Public Policies (GOVCOPP). She is also the Director of the Master's in Industrial Engineering and Management at the same university. Her main research interests include the development of solution approaches for supply chain management and operations management decision problems, namely in the production planning and scheduling, lean manufacturing, supply chain strategic decisions and urban logistics areas.

Ana Moura is an Assistant Professor in the Department of Economics, Management, Industrial Engineering and Tourism of the University of Aveiro (UA) and a researcher in the Institute of Systems Engineering and Computers of Coimbra (INESC Coimbra) and in GOVCOPP – (Systems for Decision Support Research Group). She received her PhD from the Faculty of Engineering of the University of Porto (FEUP) in 2005. Her primary area of interest is the application of decision support systems and optimisation methods into industrial problems. Her main application areas have been vehicle routing problems and three-dimensional packing problems.

1 Introduction

The beginning of the 21st century saw a surge in the growth of the construction industry. This led to the growing demand of ceramic tiles (Sangwan et al., 2017). Leading the way to innovation and technology, ceramic manufacturers from the EU-27 account for 23% of global ceramic production, with a production value in Europe of €28 billion (Cerame-Unie, 2012). Portugal is a country with a long tradition in ceramics, both in production and consumption, and is ranked as one of the top European manufacturers of ceramic products due to the high quality of raw materials. Portugal is also the fourth largest producer in Europe and the fifth largest world exporter of floor and wall tiles, after China, Italy, Germany and Spain (Almeida et al., 2016).

In the past, ceramic tile industries were characterised by the large scale production of a limited range of products (Rowley, 1996). However, over the last few decades, consumer demands for tiles has changed, becoming more sophisticated (Davoli et al., 2010). This led to an increase in the variety of products offered and to the shortening of the products' life-cycle. Nowadays, this industry's offer is characterised by highly customised products with high levels of innovation, in an environment with high levels of demand uncertainty (Bonavia and Marin, 2006). Furthermore, the increased demand for specialised products has led to a large growth in the number of make to order companies, leading to greater competition amongst these companies and the increasing strategic importance of lead times (Stevenson et al., 2005) and promotion tools to improve their sales (Farsijani et al., 2018).

In recent years, the incorporation of high technology to production systems brought the advent of a fourth industrial revolution (Rossit et al., 2019). With the digital transformation process, companies have adopted automation technologies that enhance control of task parameters and access to online operational data, providing an opportunity to potentiate its use to support decision-making, and thus, substituting inefficient manual spreadsheets with analytical tools (Vieira et al., 2019). In this work, we present a decision support system (DSS) to support the production planning and scheduling (PPS) process of a ceramic tile company. The DSS supports the decision maker in the development of master production plans, in tackling the available to promise (ATP) function, and also in the development of production scheduling (PS) plans. Thus, the study contributes to the planning and scheduling literature in the tile industry.

The company under study is in Portugal and belongs to one important Italian group. In Portugal, the group has an installed capacity of 8 million m^2 per year and approximately 515 employees and offers a very wide variety of products (currently 8,000 different final products), posing significant challenges to the production planning process and dictating an operation on a jointly 'make to order' and 'make to stock' environment.

The development of the PS plan comprises the allocation of a set of production lots on a set of forming and glazing lines (FGLs), respecting:

1. the machine eligibility constraints between the lines and the products
2. the minimum production lot sizes
3. the orders' promised dates; while maximising the filling of the kilns and, if possible, minimising family and subfamily setup times during the exchange of products.

Furthermore, due to the high times and costs incurred with changeovers, and due to the minimum production lot sizes, the marketing and operations strategy simultaneously includes the production to order and for stock. According to the three-field notation (Allahverdi, 2015), the scheduling problem under consideration can be classified as $P|STs_{i,f}|\sum C_j, TST$, where P represents a set of identical parallel machines, $STs_{i,f}$ represents the sequence-independent family setup time and $\sum C_j, TST$ denotes the total completion time plus total setup time. Moreover, it is a strongly NP-hard problem (Webster, 1997; Dunstall and Wirth, 2005a). For that reason, a constructive heuristic was developed and incorporated within the DSS. The heuristic was strongly inspired on the current procedures used by the production planner in the development of the scheduling plan, in an attempt to achieve similar to higher quality solutions, although at a much lower cost/shorter time. Nonetheless, a mixed integer programming (MIP) model was also devised to evaluate the heuristic solutions quality and performance.

The primary objective of this study was to develop PPS tools, incorporated in a DSS, to support the PPC process of a ceramic tile industry. This objective could be broken down into the following secondary objectives:

- reduce the time required to tackle PPC decision making process
- minimise response times to customer orders enquiries/customer order acceptance process
- decrease production planners' workload
- increase PPC data availability.

The production plans devised by the DSS help to streamline the production planners' responsibilities, by releasing a significant part of their working time, and by highlighting alternative production plans. These two aspects constitute two main contributions of this work. Moreover, another important contribution is the automation of the ATP process that allows a significant improvement in response time and in the determination of the best production lead times.

The remainder of this paper is structured as follows: in Section 2 we present a literature review and in Section 3 the company production process and the PPS problem are described. Section 4 is focused on the description of the DSS as well as of the heuristic and the MIP model developed to solve the production scheduling problem (PSP). In Section 5, some computational results are presented, where the heuristic and the MIP model are tested, using two real instances. In Section 6, we present the managerial implications of the DSS implementation in the company. Finally, in Section 7, the main conclusions of this work are summarised.

2 Literature review

To remain competitive in a fierce market, companies in the ceramic tiles sector are challenged to produce in smaller batches in order to increase responsiveness. The current conditions pose great complexities to the production planning and control (PPC) process. In such an environment the PPC is a demanding job being mandatory to achieve high quality production plans. In the ceramic tile industry an effective PPC system, supported by a DSS, can provide substancial competitive advantage in the market.

The DSS presented in this paper tackles medium to short-term PPC decisions, providing:

1. information about expected delivery times of customers' requests (order promising process)
2. information about which end items to manufacture in the future (master production schedule – MPS)
3. a detailed scheduling of resources to meet production requirements (PS).

The order promising process includes the set of business activities that are triggered to provide a response to customer order requests (quantity, delivery date, etc.). In this process, it is necessary to compute if there are enough real or planned products available that have not been previously committed (ATP) (Boza et al., 2014). Order promising typically includes activities related to the acceptance/rejection of jobs (order acceptance or order selection), and setting the delivery date (Framinan and Leisten, 2010). A classification of ATP systems and a general framework for ATP-related decisions can be found in Framinan and Leisten (2010).

MPS is the process of developing plans for identifying which quantities of products should be manufactured during certain periods (Jonsson and Ivert, 2015). Thus, daily/weekly production lot sizes for the various products are determined such that end customers' demand over the planning horizon is fulfilled at a minimal total cost (As'ad et al., 2015). MPS is a key decision-making activity, in which strategic goals from business planning are translated into an anticipated statement of production, from which all other schedules are derived at lower levels (Vieira and Favaretto, 2006). The same authors point out that it contains a statement of the volume and timing of the end products to be made, driving the whole operation in terms of what is assembled, what is manufactured, and what is bought. The MPS additionally provides the information to the sales function on what can be promised to customers and when delivery can be made. Therefore, the sales function can load known sale orders against the MPS and keep track of what is ATP (Slack et al., 2001).

PS aims at generating detailed production schedules for the shop-floor over a relatively short interval of time, which indicate, for each order, the start and completion times of the required resources for processing (Stadtler, 2015). According to the literature, the PS problem that we are dealing with falls within the category of identical parallel machines scheduling (PMS) problems, with family sequence-independent setup times. When family setup times exist, a number of job families are considered where each family is a set of jobs that have similar characteristics in terms of setups, tooling and operation sequence. Furthermore, the number of job families is fixed, as well as the number of jobs in each family (Allahverdi, 2015). A family sequence-independent setup time is needed when switching from the processing of family i jobs to those of another family j, $i \neq j$, being the duration of this setup equal to the sequence-independent setup time for family j (Dunstall and Wirth, 2005b). A recent literature review about PS problems with setup times/costs can be found in Allahverdi (2015). Moreover, Potts and Kovalyov (2000) revise scheduling with batching decisions. The literature on PMS problems is very extensive and this topic is studied from many points of view (Ravetti et al., 2007). However, comparing the number of contributions reported in Allahverdi (2015) considering PMS problems with family sequence-independent setup times with the other classes of PS problems considered in the same paper, we may conclude that the problem under consideration in our work seems to have been much less explored in the literature than other PS problems. Allahverdi (2015) mentions three contributions for this problem: one from Schaller (2014) for problem $P|STs_{i,f}|\sum T_j$, in which several versions of tabu search and genetic algorithms are proposed, other from Bettayeb et al. (2008) for problem $P|STs_{i,f}|\sum w_j C_j$, proposing a branch and bound algorithm and a constructive heuristic, and a third one from Tavakkoli-Moghaddam and Mehdizadeh (2007) considering a MIP model for the $P|STs_{i,f}|\sum w_j F_j$ problem. Note that $\sum T_j$ denotes total tardiness, $\sum w_j F_j$ represents the total weighted flowtime and that $\sum w_j C_j$ corresponds to the total weighted completion time. To the best of our knowledge a MIP model for a problem with similar characteristics to the one considered in this paper has not yet been proposed in the literature.

Some contributions dealing with heuristic approaches for the identical parallel machine scheduling problem with family sequence-independent setup times, can be found (Shin and Leon, 2004; Dunstall and Wirth, 2005b; Liao et al., 2012). Dynamic programming approaches (Webster and Azizoglu, 2001) and branch and bound approaches can also be found (Azizoglu and Webster, 2003; Chen and Powell, 2003; Dunstall and Wirth, 2005a).

Contributions integrating several PPC problems can also be found in the literature. In a recent paper Fazeli-Kebria et al. (2019) proposed a mathematical programming model, a branch and bound, and an efficient heuristic algorithm for the order acceptance (ATP) and scheduling problem. Furthermore, Ramezanian et al. (2017) present an integrated approach determining lot sizing and scheduling decisions in a tile manufacturing.

In a recent paper, Ardjmand et al. (2016) reviewed the application of DSS to PPS and concluded that there are a variety of DSS applications in the literature that address the subject. Moreover, the authors conclude that most practices use model-driven (applying and manipulating quantitative models) and knowledge-driven DSSs (specialised in solving problems by applying person-computer systems).

A few contributions can be found in the literature regarding the development of DSSs to support ATP, MPS and PS in the ceramic tiles industry. As an example, in Alemany et al. (2015) a model-driven DSS is presented to deal with the ATP process; Mundi et al. (2013) develop a model-driven DSS for the MPS of ceramic supply chains; and Framinan et al. (2014) present a specific PS system developed and deployed in the Spanish ceramic tile sector. Framinan et al. (2014) argue that despite the enormous size of the scheduling literature, papers dealing with real problems, like the ceramic tile production problem tackled in their work, are much more scarce.

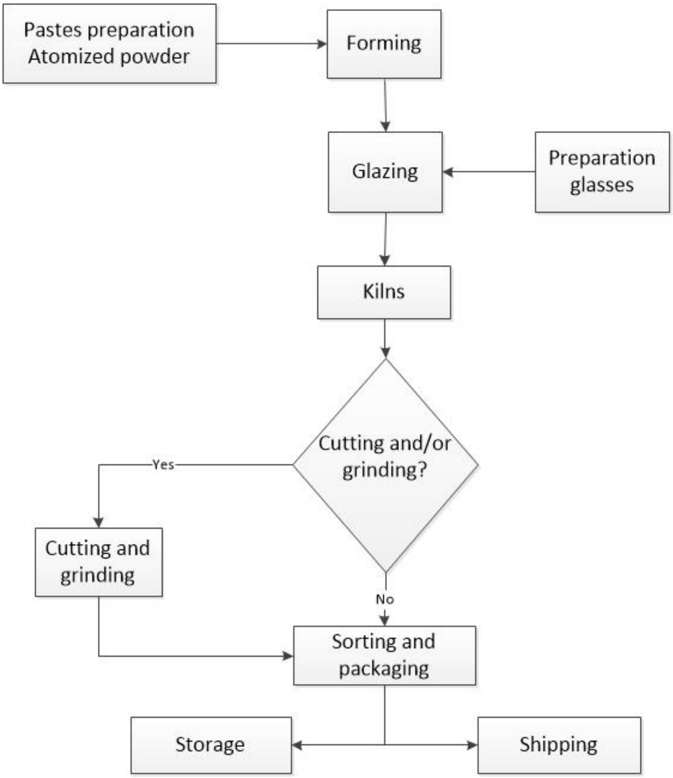
3 Problem description

Considering the company manufacturing process types, its production can be characterised as a hybrid flow shop. The production plant is divided into four main sections (forming, glazing, kiln and classification) in a layout organised by process. Moreover, the production is sorted into lots. The main productive processes are depicted in the flowchart presented in Figure 1, as well as the sequential stages from raw materials to final products. In Framinan et al. (2014) a detailed description of the tile production process can be found.

3.1 PPS problem statement

The company's PPS process is a time consuming and exhausting task for the production planners because it is focused on a set of 900 catalogued products without any kind of automation. This task is highly repetitive and time consuming, representing approximately 80% of the time currently spent in the execution of the PPS process. The remaining 20% corresponds to the time needed to schedule the products. In addition to this, the PPS process is currently strongly conditioned by human intuition. As a recent production strategy, the company has been adjusting its production strategy to a pull philosophy. In practice, a stock out is the trigger to a production and when this occurs, production is fixed to a quantity that enables meeting the orders currently placed and the foreseen needs. This production strategy aims at achieving a high level of customer service in terms of order fulfilment time.

Figure 1 Production process flowchart



The PPS process is supported by the Microsoft Excel tool and is focused on the forming and glazing processing steps, having two main purposes:

1 to provide a holistic view of the present and near future production requirements to balance the supply with the future demand needs

2 to define and deliver to the production department a biweekly PS plan.

In addition to this, the PPS process is also used to establish ATP dates to the customer's requests.

For planning purposes, the forming and glazing steps are aggregated and considered as one integrated system, denominated in the remainder of this paper by FGLs.

In order to determine the production requirements and to balance the near future production loads with the forming and glazing/kilns capacities the company develops a MPS.

The biweekly PS plan comprises the distribution of the several products to be produced in the near future over a set of ten FGL, taking into account several operational and capacity constraints. For scheduling purposes, six days per week are available (from Monday to Saturday) and in each line only one product (lot) can be produced per day. Moreover, in each line there is a forming process in which a major setup occurs whenever there is an exchange in the product format (product dimensions or product family). The mean time needed to execute this setup is one day, so a full working day is assigned to this setup. Furthermore, this setup time is independent of the production sequence. There are also two other types of setups, which are not formally considered in the production plan, because the time needed to perform them is insignificant compared to the major setup. The first type occurs when there is an exchange in the class (or in the collection) of the product in which the products' characteristics are very similar differing only in the colour; and the second type, when there is an exchange in the thickness or in the relief of the product.

In the biweekly PSP the (single-operation) jobs are partitioned into mutually exclusive families and a batch corresponds to a contiguous series of scheduled jobs (or lots) belonging to the same family (Dunstall and Wirth, 2005b). Families are given and batches are constructed in the scheduling process. The structure of families is such that a batch can be processed on a FGL without major setup times being incurred between jobs.

The assignment of the production lots to the several days are attributed to a line considering the characteristics of the product and the FGL, for example the shape, the graphical technology and the applications to incorporate in the tile. In this assignment, if there are products with close deadlines, belonging to the same class, they must be produced sequentially in the same line, from the lighter colour ones to the darker ones.

The production volume of the set of lines is conditioned by the weekly kilns' capacity, estimated in approximately 23,500 square metres per kiln. Regardless of the number of kilns connected, their full load must be guaranteed with a tolerance of 5% of their estimated capacity. Another important constraint is related to the production loads. Each product has a minimum grinding glass load associated, dictating not only the minimum production lot size but also its processing time. The production lot size must be multiple of the minimum lot size. Typically, a glass load (or minimum lot size) corresponds to the daily production capacity of a line. In addition to this, each lot should be fully processed in one of the lines and should not be split amongst the set of available lines.

The set of ten FGL may be considered identical regarding their production speed, although they are not suitable to process all the product types. Moreover, each line cannot process more than one product at the same time.

The planning horizon of the PS plan corresponds to two weeks (12 working days) partitioned into a set of equal length intervals with a minimum length period equal to one day. Moreover, the PS plan is delivered to the production team one week in advance of the beginning of the production, to allow on time knowledge about the raw materials and other resources that will be needed.

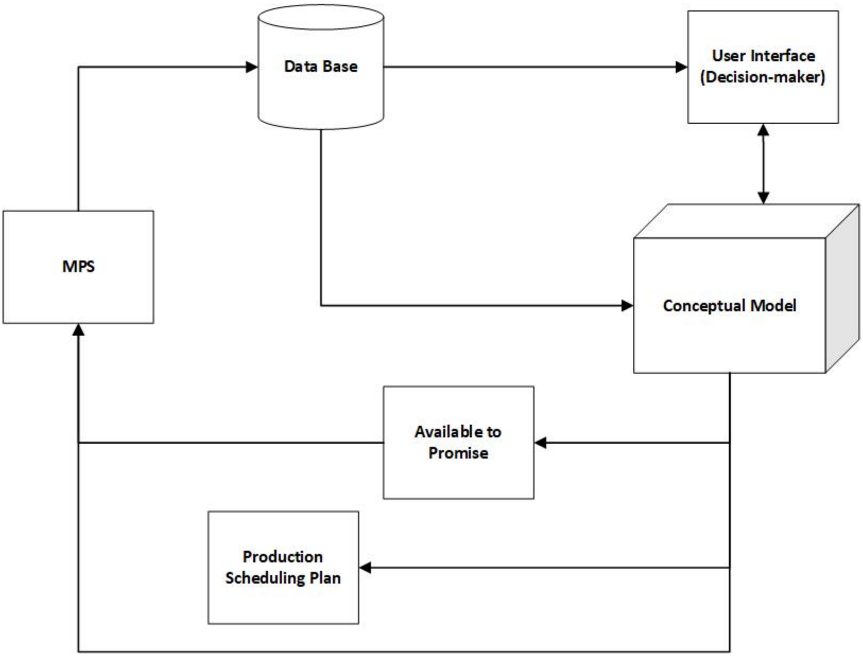
During this project the ATP process was also recognised as a process with strong opportunities for improvement. The company is committed to provide an answer to the ATP requests within a period of 48 hours and the order lead time is fixed to a maximum of six weeks. Nonetheless, the aim of the company is to assure minimum lead times for all the orders. The production planners receive on average 50 ATP enquiries per day and the decision-maker must be able to answer these requests on the same day. Otherwise, the 48 hours company commitment of customer's response may be at risk.

4 Decision support system

To fulfil all the company's needs, a DSS was designed and developed. The proposed DSS is composed by a data base (DB), a user interface and a conceptual model (CM)

(Figure 2). The CM is composed by a MIP model and a Heuristic that is powered by the information available in the DB system and the data introduced by the decision-maker (input interface). It is also composed by a so called, pre-processing heuristic that allows the user to define the production priority of each reference. The major output of the CM is the PS plan and a related MPS that will determine the short-term production needs. Another output is the ATP process that allows not only the determination of the best production lead times, but also an improvement in the response time to the client's enquiries.

Figure 2 DSS components



4.1 User interface

The user interface (Figure 2) allows the user or the decision-maker to interact directly with the CM and to consult information of the DB. The decision-maker or user has access to two main menus:

1 View information

This menu is composed by two submenus:

- fixed production (FP)
- products priority (PP).

This first menu allows the user to consult all the information related to the FP and PP. In the first submenu, the FP, the user can consult the fixed part of the production plan over a given time period and the available stock of a given product. The available stock is the difference between the actual stock and the product quantity currently allocated to the sales orders. This submenu shows all the previously computed and valid PS plan. Here, the user has a macro vision of the future production needs, over a given time horizon, this is, the MPS information. It is possible to visualise the list of products with production needs, in the present period, as well as over the next 30, 60 and 90 days. The other information available in this 'view information' menu is the PP, which is a categorisation (with colours) of the products according to their stock levels (Subsection 4.1.1). So, the submenu PP, allows the user to consult the list of products of a same colour where it could not only see the reference code and description, but also the stock levels (or stock outs), the quantities to produce and the related due dates.

2 Production scheduling

This option has three menus:

- available-to-promise
- PS plan
- set production (SP).

This second main menu allows the decision-maker to interact directly with the CM. The decision-maker can select one of three different submenus. The first one, ATP, allows to obtain the client demands delivery dates, through the execution of the ATP process (Subsection 4.2). With the second submenu, the user can compute a valid PS plan through the execution of a MIP model (Subsection 4.4) or a heuristic approach (Subsection 4.3). The third one, SP submenu, allows to set the production (or to firm the production), for the *n* following days, according to the results obtained by the heuristic approach. The decision maker can choose the best production plan and the number of days to be set.

The CM of the DSS is supported by a set of auxiliary functions and algorithms that are called prior to the execution of each of the above-mentioned menus. These functions and algorithms are presented in the next two sections.

4.1.1 PP determination

After the compilation of all relevant data, each product is classified according to a given colour. The product colour code is a mechanism to enable a better visual management of the production needs, each colour being associated with an 'ideal production lead time', considering the firmed orders and the sales forecasts. The colour descriptions are presented in Table 1.

For MPS purposes all the products to be included in the PSP must have an agreed due date. In this phase, only the products classified as red and orange have an established due date that is computed through the ATP process (Subsection 4.2).

Table 1 Colours symbology attributed to the products

Class	*Description*
Red	Product out-of-stock (orders' quantity is higher than the available stock). Production already firmed and production order released. Production quantity and due date already established.
Orange	Product out-of-stock (orders' quantity is higher than the available stock). Product needs to be produced, but production is not firmed yet.
Green	Product will run out-of-stock within the next 30 days (considering its stock coverage).
Yellow	Product will run out-of-stock in between the next 30–60 days (considering its stock coverage).
Blue	Product will run out-of-stock in between the next 60–90 days (considering its stock coverage).
White	Product stock coverage > 90 days.

For the remaining products, produced using a make to stock strategy, the due date of a given product *i* is determined taking into account the product stock coverage and its replenishment time, using equations (1)–(3).

$$Stock\ coverage_i = \frac{Available\ stock_i\ (m^2)}{Sales\ along\ the\ last\ 90\ days_i\ (m^2)} \times 90\ (days) \tag{1}$$

$$Available\ stock_i = Physical\ stock_i - cumulative\ sales\ orders_i \tag{2}$$

$$Due\ date_i = '\,zero\ point\,' + stock\ coverage_i + replenishment\ time_i \tag{3}$$

Note that, in equation (2), the physical stock, is the current stock on-hand at the 'zero point' day (the zero point is the starting date to the production planning horizon) and the cumulative sales orders represent the total sales orders also in the 'zero point' day. Moreover, in equation (3) the replenishment time of a given product is the time between the date in which the product will run out-of-stock and the date in which it must be available to the customer.

4.1.2 Quantity to produce

After determining the products' due date, the quantity to produce must be computed. This is determined considering the provisional needs and the minimum lot size. This information is obtained from the DB. The quantity to be produced should be a multiple of the minimum lot size, which satisfies the product needs. The number of days required to produce this quantity is computed in this step. So, the time needed for the production is the total quantity to be produced divided by the minimum lot size, with the achieved value rounded up. The aim is to ensure that the obtained lot sizes are an integer number of days.

4.2 Available-to-promise algorithm

The ATP submenu allows the user to obtain a due date for a product being required in a customer order request (prior to the order acceptance). The decision-maker must input some required data like: the product code, the quantity required, and the maximum date required for delivery. After determining the quantity to produce (Subsection 4.1.2), based on the quantity required and the minimum production lot sizes, the algorithm tries to schedule the production of the product under analysis, for a date as close as possible to the current calendar date. The algorithm also tries to allocate the product production between the productions of the products already programmed, without detriment to the already FP. If it is possible to schedule the product within the maximum required date for delivery, a message is sent with information of the proposed due date and FGL to which it was allocated. If not, an alert message pops up and new parameters are requested to rerun the ATP algorithm.

4.3 The PS heuristic

The PS heuristic is one of the components of the CM. The decision maker can choose the heuristic approach or the MIP model (Subsection 4.4).

The PS heuristic begins by requesting that the decision-maker introduces the schedule's starting date (or 'zero point') and the FP plan (the list of products scheduled prior to the zero point). After setting the 'zero point', information about the products to be included in the PSP is collected. This information is the heuristic approach input, related to the products' characteristics and productive needs. All the data and information are consulted from the DB of the company information system, like the relevant products characteristics to the development of the PSP (product code number; description; collection and shape format; FGL in which the product can be produced; minimum lot size; and the minimum lot size processing time). Another information, also consulted from the DB, is the cumulative sales, the orders placed and not yet delivered, the physical stock, the forecasted needs and the products due dates.

After all the input data is gathered, the heuristic approach is applied. The PSP heuristic is divided in three steps (Figure 3).

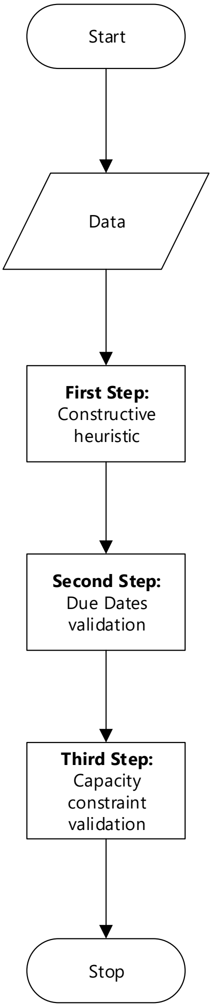
The aim of the first step of the constructive heuristic is to determine a myopic solution and is divided into two phases. In the first phase the decision-maker chooses the highest priority products (red and/or orange) and these products are assigned to the FGL. This way, the products are initially assigned to the lines capable of producing them. After that, the approach checks if a given product is assigned to more than one line and the number of products per line. If there is more than one line with the same assigned product, the algorithm removes the product from the line that has the biggest number of allocated products. This procedure will be called until each product is allocated to only one production line.

In the second phase of the first step the algorithm makes groups (or batches) of products, aiming to minimise minor and major setups, and afterwards determines a production sequence per line. The following sequential grouping is performed:

1. group products by class (or collection)
2. group products by format
3. group products by thickness.

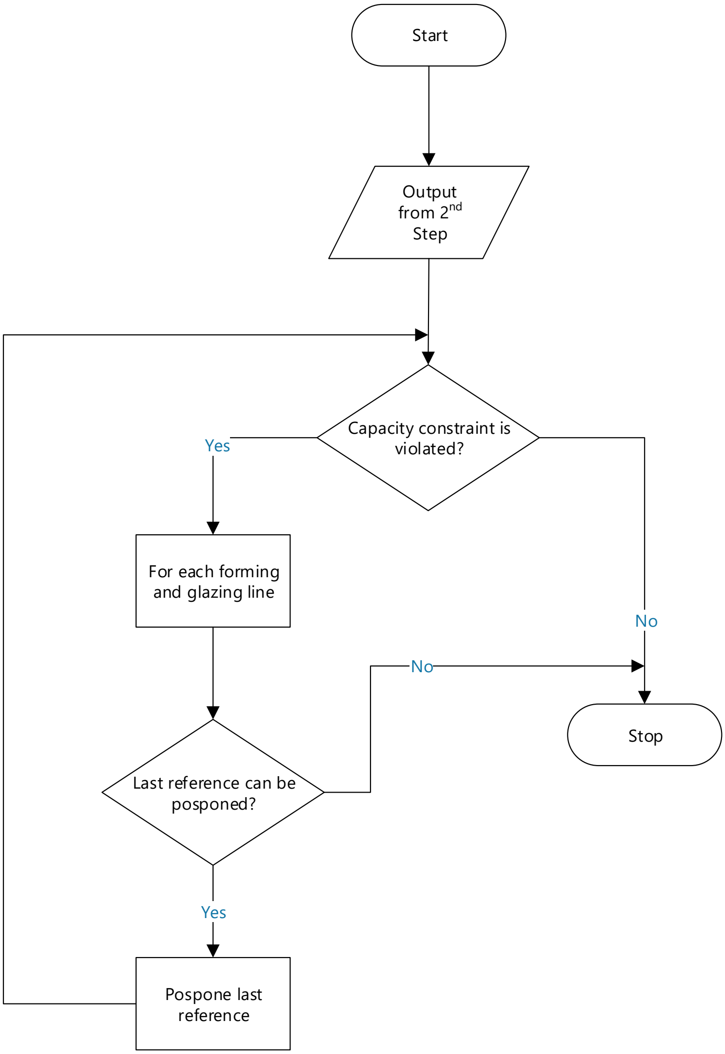
Afterwards, the sequence is established considering the format batches. The batches' order is organised in increasing order of the critical product belonging to each batch. The critical product of the batch is the one with the smallest due date. A second step of the PS heuristic is made to verify if all the due dates are meet. If there are some due dates that are not meet, then the associated products are removed from the solution and the heuristic tries to insert them into other production lines and/or on different days. If that is not possible, the product will go to a products not programmed list.

Figure 3 PSP heuristic flow chart



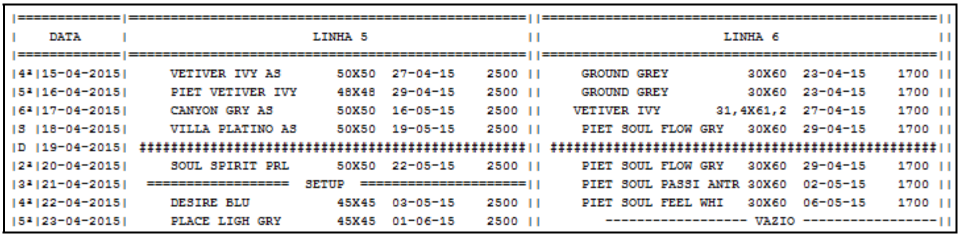
The production bottleneck is the kilns sector, so their maximum capacity must be considered in the PS process. The current market demand is much higher than the company's supply, so the minimum loads compliance with the minimum kiln's capacity is not analysed by the heuristic. If the supply becomes higher than the demand, the heuristic will include less urgent products into the plan, e.g., products belonging to classes green, yellow, blue and white considered in this order. So, the third step is the validation of the kiln's maximum capacity (Figure 4).

Figure 4 Third step algorithm (see online version for colours)



In this step, the heuristic verifies if the capacity is exceeded and, in that case, the algorithm attempts to delay the productions of the last day of the planning horizon in each line, until the number of square meters of ceramic material respects the maximum capacity of the kilns, with a tolerance of 5%. Specifically, what happens is that until the kilns' maximum capacity is not exceeded, the approach will sequentially scan all lines and for each one, checks if it is possible to postpone the product that will be produced in the last day, without compromising its due date. If it is not possible to postpone any products from all the lines, then the PS solution is not valid. In this case, the PSP must be rerun after the adjustment of some input parameters. An example of a partial schedule obtained with the PS heuristic is presented in Figure 5.

Figure 5 Production schedule



```
|=============|===================================================||==================================================||
|    DATA     |                       LINHA 5                     ||                      LINHA 6                     ||
|=============|===================================================||==================================================||
|4ª|15-04-2015|     VETIVER IVY AS        50X50  27-04-15    2500 ||    GROUND GREY          30X60  23-04-15    1700 ||
|5ª|16-04-2015|     PIET VETIVER IVY      48X48  29-04-15    2500 ||    GROUND GREY          30X60  23-04-15    1700 ||
|6ª|17-04-2015|     CANYON GRY AS         50X50  16-05-15    2500 ||   VETIVER IVY       31,4X61,2  27-04-15    1700 ||
|S |18-04-2015|     VILLA PLATINO AS      50X50  19-05-15    2500 ||    PIET SOUL FLOW GRY   30X60  29-04-15    1700 ||
|D |19-04-2015| ##################################################|| ################################################||
|2ª|20-04-2015|     SOUL SPIRIT PRL       50X50  22-05-15    2500 ||    PIET SOUL FLOW GRY   30X60  29-04-15    1700 ||
|3ª|21-04-2015|  ==================  SETUP  =====================||    PIET SOUL PASSI ANTR 30X60  02-05-15    1700 ||
|4ª|22-04-2015|     DESIRE BLU            45X45  03-05-15    2500 ||    PIET SOUL FEEL WHI   30X60  06-05-15    1700 ||
|5ª|23-04-2015|     PLACE LIGH GRY        45X45  01-06-15    2500 ||       ------------------ VAZIO -----------------||
```

4.4 Mathematical model

As stated in the beginning of Section 4, the CM is composed by a MIP model and a Heuristic. In this section the MIP model developed for the biweekly PSP is presented. The aim is to develop a biweekly production plan, to a set of FGLs taking into account weekly furnaces capacity, demands and due dates per product, huge family independent setup times, minimum lot sizes (in full working days) and a compatibility matrix between machines and products, while minimising total production completion times plus family setup times. As already stated, the scheduling problem under consideration is a strongly NP-hard problem, so for big problem instances it is not reasonable to solve it using an exact approach. However, it allowed to test and validate the quality of the heuristic solutions, since it was not possible to compare it with other published works. Nonetheless, in some instances it is possible to achieve a solution in a reasonable computational time, so the model was incorporated in the DSS (Section 4).

This MIP is based on a discretisation of the time horizon into several periods (days). In each period, a single product is produced, or the machine is setup, or there is no production at all. In addition to this, a given product may be produced in an integer number of periods depending on the lot size dimension and in each period a setup state is preserved to the next period.

Next, we formally present the proposed MIP model. Consider the following sets, parameters and decision variables:

Sets

N	number of products: $i, j, s \in 1, \dots, N$
K	number of glazing lines: $k \in 1, \dots, K$
T	number of periods belonging to the planning horizon: $t \in 1, \dots, T$
F	number of families: $f \in 1, \dots, F \wedge q \in 1, \dots, F$
W	number of programming weeks: $w \in 1, \dots, W$.

Parameters

d_i	due date of product i
e_{ik}	compatibility index between product i and glazing line k - $e_{ik} = 1$ if product i can be processed on glazing line k

- $e_{ik} = 0$ if product *i* cannot be processed on glazing line *k*

L_i	product *i* minimum lot size (in m^2 and corresponds approximately to one day of production)
P_i	number of required days of production of product *i*
Cap_w	weekly kilns capacity (in m^2)
S_k	family to which glazing line k is setup at the beginning of the planning horizon
$R[f]$	matrix that contains the products belonging to each family *f*.

Decision variables

$$x_{iftk} \begin{cases} 1 & \text{if product } i \text{ of family } f \text{ starts its processing on period } t \text{ on glazing line } k \\ 0 & \text{otherwise} \end{cases}$$

$$y_{ftk} \begin{cases} 1 & \text{if there is a setup of family } f \text{ on period } t \text{ on glazing line } k \\ 0 & \text{otherwise} \end{cases}$$

$$z_{ftk} \begin{cases} 1 & \begin{array}{l} \text{if the setup state of family } f \text{ on glazing line } k \text{ is} \\ \text{preserved from period } t \text{ to period } t+1 \end{array} \\ 0 & \text{otherwise} \end{cases}$$

The MIP model is:

$$Min \sum_{f} \sum_{i \in r[f]} c_{if} + \sum_{f} \sum_{t} \sum_{k} y_{ftk} \tag{4}$$

Subject to:

$$\sum_{k:e_{ik}=1} \sum_{t} x_{iftk} = 1, \forall f, \forall i \in r[f] \tag{5}$$

$$\begin{gathered} x_{iftk} + x_{jqhk} \leq 1, \forall f, \forall q : q \neq f, \forall i \in r[f], \forall t, \forall j \in r[q], \forall k : e_{ik} = 1 \wedge e_{jk} = 1, \\ \forall h : h \geq t \wedge h \leq t-1+P_i \end{gathered} \tag{6}$$

$$x_{iftk} + y_{qhk} \leq 1, \forall f, \forall i \in r[f], \forall t, \forall q : q \neq f, \forall k : e_{ik} = 1, \forall h : h \geq t \wedge h \leq t-1+P_i \tag{7}$$

$$x_{iftk} + y_{nhk} \leq 1, \forall f, \forall i \in r[f], \forall t, \forall k : e_{ik} = 1, \forall h : h \geq t \wedge h \leq t-1+P_i \tag{8}$$

$$\begin{gathered} x_{iftk} + x_{sfhk} \leq 1, \forall f, \forall i \in r[f], \forall t, \forall s \in r[f] \wedge s \neq i, \forall k : e_{ik} = 1 \wedge e_{sk} = 1, \\ \forall h : h \geq t \wedge h \leq t-1+P_i \end{gathered} \tag{9}$$

$$\sum_{f} \sum_{i \in r[f]:\, e_{ik}=1} x_{iftk} + \sum_{f} \sum_{f} y_{ftk} \leq 1, \forall k, \forall t \tag{10}$$

$$C_{if} - \sum_{k:\, e_{ik}=1} \sum_{t} (t-1+P_i) \times x_{iftk} \geq 0, \forall f, \forall i \in r[f] \tag{11}$$

$$\sum_{f} z_{ftk} = 1, \forall k, \forall t \tag{12}$$

$$x_{iftk} + z_{q,t-1,k} \le 1, \forall f, \forall i \in r[f], \forall q : q \ne f, \forall k : e_{ik} = 1, \forall t \tag{13}$$

$$y_{ftk} + z_{q,t-1,k} - z_{ftk} \le 1, \forall f, \forall q : q \ne f, \forall k, \forall t \tag{14}$$

$$z_{ftk} + z_{q,t-1,k} - y_{ftk} \le 1, \forall f, \forall q : q \ne f, \forall k, \forall t \tag{15}$$

$$z_{ftk} - y_{ftk} - z_{f,t-1,k} \le 0, \forall f, \forall k, \forall t \tag{16}$$

$$C_{if} \le d_i, \forall f, \forall i \in r[f] \tag{17}$$

$$\sum\nolimits_f \sum\nolimits_{i \in r[f]} \sum\nolimits_{t: t \in w} \sum\nolimits_{k: e_{ik} = 1} L_i \times P_i \times x_{iftk} \le cap_w, \forall w \tag{18}$$

$$z_{sk0k} = 1, \forall k \tag{19}$$

$$z_{f0k} = 0, \forall f : f \ne s_k, \forall k \tag{20}$$

$$y_{f0k} = 0, \forall f, \forall k \tag{21}$$

$$x_{if0k} = 0, \forall f, \forall i \in r[f], \forall k : e_{ik} = 1 \tag{22}$$

$$x_{iftk} \in \{0, 1\}, \forall f, \forall i \in r[f], \forall t, \forall k \tag{23}$$

$$y_{ftk} \wedge z_{ftk} \in \{0, 1\}, \forall f, \forall t, \forall k \tag{24}$$

$$C_{if} \in N^+, \forall i \in r[f], \forall f \tag{25}$$

The objective function (4) minimises the schedule total completion times, as well as the total time spent with family setups. Constraint (5) guarantees that in each line and each period only one lot of each product can be processed. Constraints (6), (7), (8) and (9) ensure that during the processing of a given lot (of a product) in a given line, no other product can be processed nor can a family be setup in that line. The set of constraint (10) guarantee that in each period and line, only one of the following states can occur: the line is stopped, the line is processing a lot, or the line is being setup. The lots completion times are determined through constraint (11). Equations (12) ensure that in each machine and each period, exactly one setup family must be preserved for the following period. Moreover, through constraint (13) it is assured that when a new lot of a family begins its processing, no other family setup state can be preserved to the next period, meaning that if at period t in a given machine a new lot is started, then in that machine and period only the setup state associated to the family that started being processed can be preserved. No other alternative family setup state can be preserved. Constraint (14) set guarantees that in each period and each line a change in the family setup state should occur when a setup for another family occurs. Additionally, through the set of constraint (15) it is assured that a setup occurs if the families that are preserved in successive periods are different from each other. The set of constraints (16) establishes that if in a given line a family f setup state is preserved to the next period, a setup occurred for that family in that period or that family was preserved from the previous period. The need to respect due dates is ensured by constraint (17). Constraints (18) guarantee that the weekly capacity of the kilns is respected. Equations (19), (20) and (21) establish the initial conditions, specifying the lines' setup state at the beginning of the planning horizon. More specifically, they provide information about the family for which the lines are setup. Constraint (22) guarantees that lots can only be processed after the beginning of the planning horizon. Finally, the decision variables domain is established though constraints (23), (24) and (25).

5 Computational results and solution methods comparison

For the testing and validation of the mathematical model and the PSP heuristic approach, two real test instances were considered. Those test instances were developed using real data. For that, relevant information was compiled, gathered from the people responsible for the PS process and from the company's information platforms. These tests will measure the responsiveness of the mathematical model and the heuristic, to the company current situation, also allowing the comparison of the solutions obtained by the two approaches. To do so, two biweekly production plans were devised and compared for each of the approaches. The main characteristics of the instances can be found on Table 2. A first test instance – small instance – was created through the random selection of 42 references, in order to facilitate the analysis of the model and heuristic performance. Then, a new instance – a large instance – was built with 100 references, this one depicting a real production planning problem usually dealt by the company.

The aim of this tests was to analyse the behaviour of both approaches using instances like the real ones and to perform a solutions comparison. The mathematical model was implemented in OPL and solved by IBM ILOG CPLEX Optimization Studio 12.6.2 (IBM, 2015), and the PSP heuristic was implemented in NetBeans IDE 8.0.2 (Foundation, 2016). Both approaches were tested using a personal computer with the following characteristics: Intel core i7, processor 2.4 Ghz, and 12 GB of RAM.

Table 2 Instance characterisation

	Small instance	*Big instance*
Number of products	42	100
Number of families	13	14
Average due date	22 days	33 days
Average lot dimension	2,633 m^2	3,068 m^2
Average minimum lot size	2,157 m^2	2,211 m^2
Average lot processing time	1.22 days	1.43 days
Kilns capacity	73,500 m^2/week	

In order to quantify and compare the obtained solutions, the following indicators were used: the number of setups; the makespan; the objective function value; the GAP between the PSP heuristic solution and the MIP model solution; and the computational time.

A computational time limit equal to 10,800 seconds was considered. Moreover, the GAP is defined by equation (26), where $Z_{PSP\ heuristic}$ represents the objective function value of PSP heuristics and $Z_{mathematical\ model}$ represents the objective function value of the MIP model. The results achieved can be found on Table 3.

$$GAP = \frac{Z_{PSP\ heuristic} - Z_{mathematical\ model}}{Z_{mathematical\ model}} \times 100 \tag{26}$$

The scheduling plan obtained with the mathematical model for the small instance corresponds to the optimal solution. However, in the big instance, the mathematical model was not able to solve the problem within the pre-established time limit, corresponding the solution presented on Table 3, to an incumbent solution with a gap of 1.5% from the optimal solution.

Table 3 Solution comparison

	Small instance		*Big instance*	
	PSP heuristic	*Mathematical model*	*PSP heuristic*	*Mathematical model*
Number of setups	15	10	18	22
Makespan (days)	14	13	39	36
Objective function value	254	217	1,297	1,193
Computational time (seconds)	1	337	2	10,800
GAP	17.1%		8.8%	

As can be concluded from Table 3, although the quality of the solutions obtained with the MIP model is superior to the one obtained with the PSP heuristic, due to its huge solution times, it is unlikely that it can be used in the real context. However, its development and testing was beneficial, since it allowed to gauge the quality of the solutions obtained with the heuristic.

Moreover, the computational tests also showed that the real problem instances are difficult to solve optimally, although good quality incumbents are found quickly in the solution process.

6 DSS implementation

In this section the managerial implications and limitations of the DSS implementation in the company under study are discussed.

The DSS was used experimentally in a ceramic industry for a few weeks, with real data, to find alternative planning and programming solutions to those that were obtained through the conventional planning and programming using the Excel tool. Prior to this study, the analysis of the production needs, the determination of the quantities to produce in the near future, the ATP process and the allocation of the references to the glazing lines took approximately ten hours. With the DSS similar solutions could be reached much faster, in less than five seconds, releasing the production planner time to other valuable activities. However, due to the company tight capacities, production planning was heavily influenced by the power of some customers (considered critical to the company) and by the high profit margins of some products, that took higher priority in their insertion into the production plans, leading to changes in the solution proposed by the DSS. Despite this fact, the DSS was used by the company to help them finding an initial solution that was further refined manually to accomplish the production plan exceptions and some particularities of the problem.

7 Conclusions and future developments

This work has given an overview of the PPS area and focused on the industrial applicability of scheduling models and approaches. When solving real problems, the main difficulty is to choose an approach that totally fits the problem at hands. So, the challenge is to develop and adapt the best theoretical methods and approaches that consider all the practical features of the problem.

The main objective of this work was to develop a tool that would help the decision-makers obtain good complementary or alternative solutions for the PPS, in a reduced time. This goal was fulfilled with the development and implementation of a DSS, whose CM is composed by a heuristic approach and a MIP model. The heuristic approach does not guarantee the optimal solution for the problem, but it provides acceptable solutions in a small computational effort and time. With a superior processing time, the MIP model also allows to solve the PPS, providing higher quality solutions.

The DSS was tested with different problem instances, based in real data. It was found that, for large campaign productions, some of the non-added value activities (namely tool change setups) were reduced and sometimes eliminated, improving the production response times of a given set of products. It was also found that the developed heuristic can easily be used to streamline several issues related to PS, which results in significant time-consuming gains in the process.

One of the limitations of the work is due to some of the real problem features. Some of the features of the problem have been simplified, such as, not accounting for serial change setups and tool-dies change setups, in light of what is done in the traditional company scheduling. Nevertheless, this setup simplification does not invalidate the developed model and heuristic.

For future work, there are some improvements that could be considered in this DSS, such as a balancing work on the lines. It would also be interesting to improve the DSS to present suggestions for the PPS when the proposed production volume is higher than the weekly kilns capacity. For example, the DSS should be able to inform the decision-maker of the products whose deadlines should be changed and the related negotiations that could be made with the affected customers. Regarding the MIP model, it would also be interesting to extend it to allow scheduling with variable setup times and the inclusion of sub-family setup times. Finally, the development of an improvement heuristic to reduce the optimality gap of the proposed constructive heuristic would also be another valuable contribution.

References

Alemany, M. et al. (2015) 'A model-driven decision support system for reallocation of supply to orders under uncertainty in ceramic companies', *Technological and Economic Development of Economy*, Vol. 21, No. 4, pp.596–625.

Allahverdi, A. (2015) 'The third comprehensive survey on scheduling problems with setup times/costs', *European Journal of Operational Research*, Vol. 377, No. 2, pp.345–378.

Almeida, M. et al. (2016) 'Environmental profile of ceramic tiles and their potential for improvement', *Journal of Cleaner Production*, Vol. 131, pp.583–593, Elsevier.

Ardjmand, E. et al. (2016) 'Application of decision support systems in scheduling/planning of manufacturing/service systems: a critical review', *International Journal of Management and Decision Making*, Vol. 15, Nos. 3–4, p.248.

As’ad, R., Demirli, K. and Goyal, S. (2015) ‘Coping with uncertainties in production planning through fuzzy mathematical programming: application to steel rolling industry’, *International Journal of Operational Research*, Vol. 22, No. 1, pp.1–30.

Azizoglu, M. and Webster, S. (2003) ‘Scheduling parallel machines to minimize weighted flowtime with family set-up times’, *International Journal of Production Research*, Vol. 41, No. 6, pp.1199–1215.

Bettayeb, B., Kacem, I. and Adjallah, K.H. (2008) ‘An improved branch and bound algorithm for solving the identical parallel machines scheduling problem with family setup times’, *Journal of Systems Science and Systems Engineering*, Vol. 17, No. 4, pp.446–459.

Bonavia, T. and Marin, J.A. (2006) ‘An empirical study of lean production in the ceramic tile industry in Spain’, *International Journal of Operations & Production Management*, Vol. 26, No. 5, pp.505–531, Emerald Group Publishing Limited.

Boza, A. et al. (2014) ‘A model-driven DSS architecture for delivery management in collaborative supply chains with lack of homogeneity in products’, *Production Planning & Control*, Vol. 25, No. 8, pp.650–661, Taylor & Francis.

Cerame-Unie (2012) *Paving the Way to 2050: The Ceramic Industry Roadmap*, 32pp, European Ceramic Industry Association, Brussels.

Chen, Z-L. and Powell, W. (2003) ‘Exact algorithms for scheduling multiple families of jobs on parallel machines’, *Naval Research Logistics*, Vol. 50, No. 7, pp.823–840.

Davoli, G. et al. (2010) ‘A stochastic simulation approach for production scheduling and investment planning in the tile industry’, *International Journal of Engineering, Science and Technology*, Vol. 2, No. 9, pp.107–124.

Dunstall, S. and Wirth, A. (2005a) ‘A comparison of branch-and-bound algorithms for a family scheduling problem with identical parallel machines’, *European Journal of Operational Research*, Vol. 167, No. 2, pp.283–296.

Dunstall, S. and Wirth, A. (2005b) ‘Heuristic methods for the identical parallel machine flowtime problem with set-up times’, *Computers and Operation Research*, Vol. 32, No. 9, pp.2479–2491.

Farsijani, H., Shirmohammadi, Y., Bazazzadeh, S.H. and Eghbal, R. (2018) ‘Identification and prioritisation of AIDA promotion model tools by use of fuzzy AHP approach’, *International Journal of Operational Research*, Vol. 32, No. 1, pp.92–113.

Fazeli-Kebria, M., Moslehi, G., Mollaverdi, N. and Reisi-Nafchi, M. (2019) ‘Customer’s order acceptance and scheduling to maximise total profit’, *International Journal of Operational Research*, Vol. 34, No. 2, pp.301–320.

Foundation, A.S. (2016) *Developing Applications with NetBeans IDE*.

Framinan, J.M. and Leisten, R. (2010) ‘Available-to-promise (ATP) systems: a classification and framework for analysis’, *International Journal of Production Research*, Vol. 48, No. 11, pp.3079–3103.

Framinan, J.M., Leisten, R. and Ruiz García, R. (2014) ‘A case study: ceramic tile production’, in *Manufacturing Scheduling Systems: An Integrated View on Models, Methods and Tools*, pp.371–395, Springer-Verlag, London.

IBM (2015) *IBM ILOG CPLEX Optimization Studio OPL Language User’s Manual*, 155pp.

Jonsson, P. and Ivert, L.K. (2015) ‘Improving performance with sophisticated master production scheduling’, *International Journal of Production Economics*, Vol. 168, pp.118–130, Elsevier.

Liao, C-J., Chao, C-W. and Chen, L-C. (2012) ‘An improved heuristic for parallel machine weighted flowtime scheduling with family set-up times’, *Computers & Mathematics with Applications*, Vol. 63, No. 1, pp.110–117, Pergamon.

Mundi, I. et al. (2013) ‘A model-driven decision support system for the master planning of ceramic supply chains with non-uniformity of finished goods’, *Studies in Informatics and Control*, Vol. 22, No. 2, pp.153–162.

Potts, C. and Kovalyov, M. (2000) ‘Scheduling with batching: a review’, *European Journal of Operational Research*, Vol. 120, No. 2, pp.228–249.

Ramezanian, R., Sanami, S.F. and Nikabadi, M.S. (2017) 'A simultaneous planning of production and scheduling operations in flexible flow shops: case study of tile industry', *International Journal of Advanced Manufacturing Technology*, Vol. 88, Nos. 9–12, pp.2389–2403.

Ravetti, M.G., Mateus, G.R., Rocha, P.L. and Pardalos, P.M. (2007) 'A scheduling problem with unrelated parallel machines and sequence dependent setups', *International Journal of Operational Research*, Vol. 2, No. 4, pp.380–399.

Rossit, D.A., Tohmé, F. and Frutos, M. (2019) 'Production planning and scheduling in cyber-physical production systems: a review', *International Journal of Computer Integrated Manufacturing*, Vol. 32, Nos. 4–5, pp.385–395.

Rowley, C. (1996) 'Flexible specialisation: some comparative dimensions and evidence from the ceramic tile industry', *New Technology, Work and Employment*, Vol. 11, No. 2, pp.125–136.

Sangwan, K.S., Choudhary, K. and Batra, C. (2017) 'Environmental impact assessment of a ceramic tile supply chain – a case study', *International Journal of Sustainable Engineering*.

Schaller, J. (2014) 'Minimizing total tardiness for scheduling identical parallel machines with family setups', *Computers & Industrial Engineering*, Vol. 72, pp.274–281.

Shin, H.J. and Leon, V.J. (2004) 'Scheduling with product family set-up times: an application in TFT LCD manufacturing', *International Journal of Production Research*, Vol. 42, No. 20, pp.4235–4248, Taylor & Francis.

Slack, N., Chambers, S. and Johnston, R. (2001) *Operations Management*, 3rd ed., Prentice Hall, Englewood Cliffs, New Jersey.

Stadtler, H. (2015) 'Production planning and scheduling', in Stadtler, H., Kilger, C. and Meyr, H. (Eds.): *Supply Chain Management and Advanced Planning: Concepts, Models, Software, and Case Studies*, pp.195–211, Springer, Germany.

Stevenson, M., Hendry, L.C. and Kingsman, B.G. (2005) 'A review of production planning and control: the applicability of key concepts to the make-to-order industry', *International Journal of Production Research*, Vol. 43, No. 5, pp.869–898, Taylor & Francis.

Tavakkoli-Moghaddam, R. and Mehdizadeh, E. (2007) 'A new ILP model for identical parallel-machine scheduling with family setup times minimizing the total weighted flow time by a genetic algorithm', *IJE Transactions A*, Vol. 20, No. 2, pp.183–194.

Vieira, G.E. and Favaretto, F. (2006) 'A new and practical heuristic for master production scheduling creation', *International Journal of Production Research*, Vol. 44, Nos. 18–19, pp.3607–3625, Taylor & Francis.

Vieira, M., Pinto-Varela, T. and Barbosa-Póvoa, A. (2019) 'A model-based decision support framework for the optimisation of production planning in the biopharmaceutical industry', *Computers and Industrial Engineering*, Vol. 129, pp.354–367.

Webster, S. (1997) 'The complexity of scheduling job families about a common due date', *Operations Research Letters*, Vol. 20, No. 2, pp.65–74, North-Holland.

Webster, S. and Azizoglu, M. (2001) 'Dynamic programming algorithms for scheduling parallel machines with family setup times', *Computers & Operations Research*, Vol. 28, No. 2, pp.127–137, Pergamon.