Scheduling of Assembly Systems in the Footwear Industry

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Abstract

In the last years, the paradigm of the Portuguese footwear industry has improved drastically to become one of the main world players. In fact, a lot has changed, from low-cost mass production to serving clients consisting of small retail chains, where orders are small and models are varied. In order to deal with such modifications, the footwear industry started investing in technological solutions. The industrial case presented in this paper fits that purpose. The goal is to contribute to the solution of complex scheduling problems arising in the new mixed-model flexible automatic stitching systems of an important footwear factory. The project starts by building an optimization model. Although the model has its own usefulness, the CPLEX program is only capable of reaching optimal solutions for small problem instances. Therefore, a recent metaheuristic, the Imperialist Competitive Algorithm (ICA), has been chosen to tackle larger problems. The ICA is capable of finding optimal results for smaller instances and achieving adequate solutions for real problems in short periods of time. Moreover, ICA improves the results obtained so far by the method currently used in the factory.

Keywords

Footwear Industry, Scheduling, Optimization, Imperialist Competitive Algorithm, Metaheuristics

1. Introduction

The Portuguese footwear industry has remarkably improved its quality and international competitiveness over the last years. Creative design, the achievement of a technological leadership in the type of materials and productive equipment, the progress in management solutions and skilled labor, among other aspects, have been crucial for this improved performance. Nowadays, production flexibility, both in volume and variety, and fast response times are key factors for a company to succeed. This is because demand is increasingly consisting of small orders with a great variety of models. As a consequence, many factories need to transform or adapt their production systems to answer to the new production paradigm and simultaneously handle mixed models.

That is evident in the important footwear factory considered in this work, whose production is almost entirely for export. The company invested (and participated in their design) in completely new flexible automated assembly systems, which can transport boxes, with components of different models, from and to warehouses, and visiting, in any order, the convenient workstations with specialized operators.

These flexible assembly systems, namely the stitching systems, open up many potentialities. However, they require complex scheduling problems to be solved involving large dozens of boxes and workstations. Automatic optimized solutions to these problems not only avoid a permanent and difficult human planning, but are also expected to increase productivity, decrease cycle times, smooth workloads and, naturally, promote the competitive advantages of the factory. Although the modelling of the scheduling problems and the solution approaches to be develop are completely new, in particular due to the novel assembly equipment, the authors are confident that they may be easily adapted to other industries.

In summary, this work addresses the scheduling of production systems in the footwear industry using the following approach: Firstly, an optimization model of the problem is developed and then programmed in CPLEX in order to validate the correspondence of the model with the industrial case. Due to the large dimension of the problems, a relatively recent method is selected, an Imperialist Competitive Algorithm (ICA), which will be suitably adapted to the specificities of this industrial case.

The ICA (Atashpaz-Gargari and Lucas 2007) is a populational metaheuristic which was inspired by the social-political process of imperialist competition. As in other populational metaheuristics, this algorithm maintains a population of solutions throughout the optimization process.

After this introduction to the footwear industry and the problem in study, Section 2 presents relevant literature on planning problems in the footwear industry and respective solution methods. Section 3 illustrates the footwear industry scheduling problem addressed in this paper in more detail, describing the production system and the scheduling approach to be implemented. Section 4 comprises the optimization model for the scheduling problem. Section 5 describes the ICA and the details of its adaptations to the industrial case. Section 6 introduces the computational results, including the solutions obtained by the ICA for a set of test problems and for real data, and also an analysis of a series of KPIs. Finally, some conclusions are drawn in Section 7.

2. Literature Review

The footwear manufacturing process generally involves a complex series of operations that must be sequentially performed to create the final product. This means that several decision problems regarding different levels of planning approaches in this industry have arisen, an idea that is proved by the publications found in our literature. To facilitate its understanding, this section is organized by the level of planning problems, from higher-level to lower-level decisions. In this sense, the section is ordered as follows: first, layout designs problems are addressed; then, some references on line balancing are introduced; finally, important articles on scheduling and sequencing of production systems are presented. All the articles refer to problems in the footwear industry.

In terms of layout design, several different approach were found, with different objectives and, subsequently, different solution approaches. Ulutas and Islier (2015) studied a footwear facility as a dynamic facility layout problem that deals with the arrangement of machines in a site as to minimize the sum of materials handling and re-layout costs by considering multi periods. A meta-heuristics based on clonal selection based algorithm was proposed to solve the problem. Lin et al. (2016) modeled a footwear manufacturing system as a network of stations with stochastic capacity to determine the reliability of the system, which was defined as the probability with which it can complete an order within a defined time constraint. Because the completion time of an order could not be computed directly, this study proposed an algorithm involving a branch-and-bound approach to obtain the system reliability.

Several approaches relying on simulation were found to tackle layout design problems. Chen et al. (2014) created a simulation model of a footwear factory and used it to justify the usage of 2-lines over 4-lines in the stitching area. The study was made by comparing the performance (represented by the unit per man hour) in 72 different scenarios. Dang and Pham (2016) used an adaptive large neighborhood search integrated with a simulation model to define the buffer size and the number of resources in a footwear assembly line with uncertain task times and parallel workstations, with the objective of maximizing the number of pairs produced per person per hour. More recently, Paucar et al. (2020) proposed an approach to optimize and streamline production processes in the footwear industry, considering Covid-19-related safety protocols. Simulation was also used in that study to access the impact in productivity and percentage of defective goods with the approach.

A commonly addressed problem in the footwear industry is balancing, which correspond to the decision problem of optimally partitioning the assembly work among workstations with respect to some objective. For this problem, solution methods mostly recur to metaheuristics. This is the case of Chen et al. (2014), which used an hybrid genetic algorithm to balance stitching lines in real footwear manufacturing facilities, and Quyen et al. (2017), who applied an adaptation of the same metaheuristics to solve a resource constrained balancing problem in the sewing line of a footwear manufacturing plant. For mixed-model line balancing, where different types of product are produced, Sadeghi et al. (2017) proposed a new metaheuristics (ASBsm) which takes inspiration in tabu search. Later, for this same problem, the same authors devised a method based on the variable neighbourhood descent metaheuristic and applied it on the stitching systems of a footwear company (Sadeghi et al. 2018). Exact solution approaches were also found, as was the case of Quyen et al. (2017), which used a dynamic programming algorithm to solve the resource constrained balancing problem for real-world cases in footwear manufacturing.

Finally, the problem of scheduling (deciding the execution times of each operation to be performed) was also studied in the specific scope of the footwear industry. Given the complexity of the problem, most studies rely on heuristics as a solution approach. This is the case of Reyes et al. (2017a), who proposed a finite progressive planning model in the area of footwear assembly, and Costa and Ferreira (1999), who implemented job sequencing rules for a flexible flowline scheduling problem and analyzed their impact in a simulation model. Furthermore, some of the scheduling methods based on heuristics found were applied in industrial software applications ((Barnett et al. 2004), (Zangiacomi et al. 2004) and (Reyes et al. 2017b)). The only exact method found for scheduling in footwear manufacturing was Caicedo et al. (2019), who created a mathematical model to minimize the makespan in a small footwear manufacturing company with characteristics of a flow shop machine environment.

From our literature review, methods based in metaheuristics were not yet applied to scheduling problems in the footwear industry, a gap that we hope to fill with this paper.

3. Problem Description

The main purpose of this work is to devise and implement a new production scheduling method for a footwear factory. However, it should be mentioned that its production system is unique, especially designed for the factory, and for that reason substantially different from the ones discussed in the literature. A thorough study and gathering of requirements had to be performed in order to clearly understand how the production system operates, and to structure and adequately model the scheduling problem.

This section describes the production system and its main characteristics. Then, the scheduling solution currently used by the company is presented, as well as the base structure, objective and features of the proposed new scheduling method.

3.1 Production system

The factory production system under analysis consists of two independent stitching lines. Each of these stitching lines has a warehouse and two linked production lines. Each production line has a set of workstations and two conveyors, which transport the boxes with the components between the workstations and the warehouse. This layout is illustrated by the scheme in Fig. 1. The stitching operations are performed after the different pieces of shoes already cut are received (in boxes), which result in shoes uppers. Shoes uppers are then sent to another factory that assembles the uppers with the soles, thus concluding the manufacturing of the shoes.

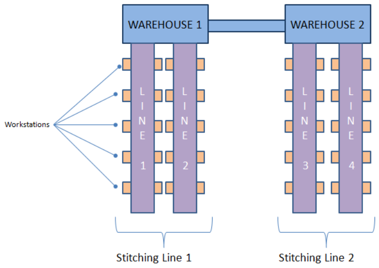

Figure 1. Production system scheme

The raw materials, i.e. the components of the shoes to be stitched, move through the factory in boxes. Each of these boxes has the materials required to produce several pairs of shoes, all of the same model, color and size. The number of pairs inside a box is variable, being frequently of ten pairs, but may be between five and fourteen pairs.

Between conducting the different operations in a box, the box is placed in a warehouse. Warehouses function by gravity and have sixteen cells, each with capacity for four boxes, which means it can keep sixty four boxes simultaneously. Although the stitching lines are independent, there is a conveyor which allows the passage of boxes between warehouses.

The workstations are arranged along the production lines. The boxes' transportation between warehouses is assured by a conveyor. When it gets to a workstation, the box is deposited in a buffer, which is a space where the box remains until the workstation is free to work on that box. After operating the box, the workstation's operator puts the box on another conveyor, which transports the box back to the warehouse.

Each workstation can only perform the set of operations that both its operator and machine are able to execute.

Each box to be worked on is associated with a routing. The routing defines which operations must be done in the components of the box and the precedence relations between them, that is, the order by which they should be done. Routings can be represented by graphs. In a linear routing the operations will be executed in a fixed sequence. In the example represented in Fig. 2a., the sequence of operations must be: 1-2-3-4. Fig. 2b. represents a more general situation, also occurring in the factory, where the sequence of operations can be 1-2-3-4 or 1-3-2-4.

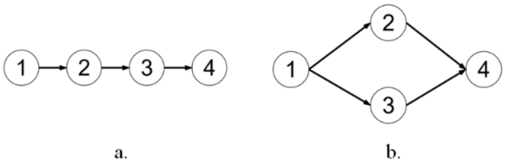

Figure 2. a. Linear Routing b. Routing in graph

Each operation has an associated operation time, which is the time it takes for that operation to be executed. Furthermore, as previously mentioned, only some workstations are eligible to perform a certain operation.

From the analysis of the characteristics of this production system, the most important conclusion one can draw is that it has a unique operation mode, considerably different from the most common production systems. The main difference is the fact that a box can be moved between any two workstations, despite having to go through the warehouse. Unlike the traditional lines, where all the boxes follow the same route, sequentially passing by the workstations in the same order, in this system the route followed by each box is independent. Moreover, it is important to mention that it became clear that the scheduling method to be implemented must not only define the sequence of operations to be executed in each workstation, but also define at which workstation each operation should be conducted, when it can be performed by several workstations. This way, besides the production scheduling itself, the method will also affect the system balancing, by defining the tasks to be executed in each workstation.

3.2 Scheduling approach to be implemented

The analysis of the production system characteristics and functioning, the observation of the current scheduling method, and the discussions with the interested party, made it possible to conceive a new scheduling approach to be developed and implemented. Such approach, contrarily to the current scheduling method, should benefit from a global vision of the planning horizon and the higher level of information used. In fact, by knowing the characteristics of the lines and the boxes to be produced, it should be possible to determine a complete production schedule a priori and, therefore, improve the production by achieving higher quality solutions, in a short period of time. The current practice in the company is an ad hoc scheduling method which verifies, at each time, if there are workstations without waiting boxes. If that is the case, the method ascertains which box to send to that workstation, based on some practical criteria to avoid bottlenecks or to attend to box priority, box position in the warehouse or lower number of operations in the routing still to be performed. This scheduling method is, obviously, limited, for it only uses the information of the current state of the boxes and of the production line to decide which box to send next to a certain workstation.

The new scheduling approach can be seen as a system which receives a set of inputs, performs a series of operations, and returns an output. As inputs, the system will receive all the information referring to the production line necessary to proceed to the operations' scheduling. This information includes the list of available workstations, the list of boxes to be produced, as well as the data: the number of pairs of shoes in the box, the routing and the set of operations already performed (if the box has already started being operated) should be provided to the system. For each routing, the precedence relations between the different operations are needed, as well as the duration time of each operation and the set of workstations which are available to perform it. With these inputs, the system will determine, for each workstation, which operations will be executed on each box, as well as their starting times. Such final production scheduling should minimize the makespan, which is the total time to produce all the boxes.

The details of the approach followed are discussed in the following sections, based on an optimization model and on the ICA metaheuristic.

4. Optimization Model

A mixed linear integer optimization model was developed taking into consideration the scheduling case described previously. It was advantageous to better understand the situation, to solve small instances and to validate the solutions. The optimization model was programmed in IBM ILOG CPLEX Optimization Studio, version 12.6. This software takes the model and the parameters of the problem and applies an exact optimization-based method.
Due to the significant dimension of the real problems under study, the CPLEX had to employ too much time to find solutions, and sometimes it was not able to find them. Consequently, a metaheuristic was devised, the ICA, in order to obtain adequate solutions for such problems in a time interval that is viable for the industrial application.

The parameters, decision variables, constraints and objective function of the model are presented below.

The sets and parameters of the model are the following:

C: set of the boxes to be produced

P: set of the workstations

N_i: set of operations of box i

T_{trans}: time it takes for a box to be transported between the warehouse and a workstation, or vice versa

t_{ik}: duration of the operation k of box i

λ_{ikl}: binary parameter: 1 if operation k of box i is done after operation l of box i, 0 otherwise

ρ_{ikp}: binary parameter: 1 if operation k of box i can be executed in workstation p, 0 otherwise

M: "very large" number

The decision variables of the model are the following:

s_{ik} : starting time of operation k of box i

α_{ikp} : binary variable: 1 if operation k of box i is executed in workstation p, 0 otherwise

$\delta_{ik\tilde{\imath}\tilde{k}}$: binary variable: 1 if operation k of box i is performed after operation $\tilde{k}$ of box $\tilde{\imath}$, 0 otherwise

$\varphi_{ik\tilde{\imath}\tilde{k}p}$: binary variable: 1 if operation k of box i and operation $\tilde{k}$ of box $\tilde{\imath}$ are performed in workstation p, 0 otherwise

$\omega_{ik\tilde{\imath}\tilde{k}}$: binary variable: 1 if operation k of box i is performed in the same workstation as operation $\tilde{k}$ of box $\tilde{\imath}$, 0 otherwise

T: variable which represents the makespan

The proposed mathematical model considers the following problem constraints:

- A workstation can only perform one operation at a time.

$$s_{ik} + (1 - \delta_{ik\tilde{i}\tilde{k}}) * M + (1 - \omega_{ik\tilde{i}\tilde{k}}) * M \geq s_{\tilde{i}\tilde{k}} + t_{\tilde{i}\tilde{k}}, \forall i \in C, k \in N_i, \tilde{i} \in C\colon \tilde{i} \geq i, \tilde{k} \in N_{\tilde{i}}\colon (\tilde{i} > i \vee \tilde{k} > k)$$

$$s_{\tilde{i}\tilde{k}} + (1 - \delta_{ik\tilde{i}\tilde{k}}) * M + (1 - \omega_{ik\tilde{i}\tilde{k}}) * M \geq s_{ik} + t_{ik}, \forall i \in C, k \in N_i, \tilde{i} \in C\colon \tilde{i} \geq i, \tilde{k} \in N_{\tilde{i}}\colon (\tilde{i} > i \vee \tilde{k} > k)$$

- A workstation can only perform an operation for which it is qualified.

$$\alpha_{ikp} \leq \rho_{ikp}, \forall i \in C, k \in N_i, p \in P$$

- An operation of a box is executed in one and only one workstation.

$$\sum_{p \in P} \alpha_{ikp} = 1, \forall i \in C, k \in N_i$$

- Auxiliary constraints to define the value of $\varphi_{ik\tilde{i}\tilde{k}p}$.

$$\phi_{ik\tilde{i}\tilde{k}p} \geq \alpha_{ikp} + \alpha_{\tilde{i}\tilde{k}p} - 1, \forall i \in \{1, \ldots, C\}, k \in \{1, \ldots, N_i\}, \tilde{i} \in C\colon \tilde{i} \geq i, \tilde{k} \in N_{\tilde{i}}\colon (\tilde{i} > i \vee \tilde{k} > k), p \in P$$

$$\phi_{ik\tilde{i}\tilde{k}p} \leq \frac{\alpha_{ikp} + \alpha_{\tilde{i}\tilde{k}p}}{2}, \forall i \in C, k \in N_i, \tilde{i} \in C\colon \tilde{i} \geq i, \tilde{k} \in N_{\tilde{i}}\colon (\tilde{i} > i \vee \tilde{k} > k), p \in P$$

- Auxiliary constraints to define the value of $\omega_{ik\tilde{i}\tilde{k}}$.

$$\omega_{ik\tilde{i}\tilde{k}} * M \geq \sum_{p \in P} \phi_{ik\tilde{i}\tilde{k}p}, \forall i \in C, k \in N_i, \tilde{i} \in C\colon \tilde{i} \geq i, \tilde{k} \in N_{\tilde{i}}\colon (\tilde{i} > i \vee \tilde{k} > k)$$

$$\omega_{ik\tilde{i}\tilde{k}} \leq \sum_{p \in P} \phi_{ik\tilde{i}\tilde{k}p}, \forall i \in C, k \in N_i, \tilde{i} \in C\colon \tilde{i} \geq i, \tilde{k} \in N_{\tilde{i}}\colon (\tilde{i} > i \vee \tilde{k} > k)$$

- For every box, all the precedence constraints between two operations must be respected.

$$s_{ik} + (1 - \lambda_{ikl}) * M \geq s_{il} + t_{il}, \forall i \in C, k \in N_i, l \in N_i \setminus k$$

- Each box can only execute one operation at a time and there is a transport time of $2 * T_{trans}$ between two consecutive operations.

$$s_{ik} + (1 - \delta_{iki\tilde{k}}) * M \geq s_{i\tilde{k}} + t_{i\tilde{k}} + 2 * T_{trans}, \forall i \in C, k \in N_i, \tilde{k} \in N_i\colon \tilde{k} > k$$

$$s_{i\tilde{k}} + \delta_{iki\tilde{k}} * M \geq s_{ik} + t_{ik} + 2 * T_{trans}, \forall i \in C, k \in N_i, \tilde{k} \in N_i\colon \tilde{k} > k$$

- The starting times of the operations cannot be lower than the time it takes to transport a box from the warehouse to the workstation.

$$s_{ik} \geq T_{trans}, \forall i \in C, k \in N_i$$

- The makespan is greater than or equal to the finishing time of all the operations.

$$T \geq s_{ik} + t_{ik}, \forall i \in C, k \in N_i$$

The objective of this model is to minimise the makespan, which is the total production time, and is given by:

$$min \quad T$$

5. Imperialist Competitive Algorithm

An Imperialist Competitive Algorithm (ICA), a population-based metaheuristic, was developed to deal with large scheduling problems. As briefly presented in Section 1, the ICA consists of performing a series of steps, which are now described in detail. As will be explained, there are problem-dependent and problem-independent steps.

Initial population creation: Each individual is a country, which is generated randomly or using heuristic rules.

Initial empire construction: The countries of the initial population are classified as being imperialists or colonies, based on the value of the objective function. Initially, some of the best countries are selected as imperialists and the remaining become their colonies. Then, an imperialist is attributed to each colony. The group of an imperialist with its colonies constitutes an empire. The number of individuals N_{pop} and the number of imperialists N_{imp} of the initial population are parameters of the algorithm.

Assimilation and mutation: The assimilation is done in each empire at each iteration of the algorithm. It refers to the process by which an imperialist tries to influence its colonies to be more similar to itself. After the assimilation, a mutation is performed to each of the colonies in order to increase the population's diversity. If after these two processes a colony is better than its imperialist, then it becomes the imperialist and vice versa.

Imperialist competition: In this step, the weakest colony of the weakest empire is freed and all the empires compete to conquer this colony. Each empire has a conquest probability that is proportional to its total power. The imperialist competition makes some empires stronger and others weaker.

Elimination: The imperialist competition may lead to empires without colonies, since these were conquered by other empires. In this case, the empire without colonies is eliminated from the population.

Both the initial population creation and the assimilation and mutation steps are problem-dependent, which means that their application has to be specific to the characteristics of the problem.

First, the problem-independent, more general steps of the ICA, are delineated and, only after, the problem-dependent steps, which are specific to the industrial case and have to be created from scratch due to the unique characteristics of the problem, will be considered.

5.1 Problem-independent steps

5.1.1 Initial empire construction

After creating the initial population, some of the best countries are selected to be the imperialists. The size of the initial population is N_{pop}, the number of imperialists is N_{imp} and the number of colonies is N_{col}. To distribute the colonies by the imperialists, it is necessary to calculate the normalized cost of each imperialist, using the following formula:

$$C_n = \max_{i=1,\ldots,N_{imp}} c_i - c_n$$

where c_n is the cost of the n-th imperialist and C_n is its normalised cost. The colonies are distributed by the imperialists based on their normalised power. The normalised power p_n of each imperialist is defined as:

$$p_n = \left| \frac{C_n}{\sum_{i=1}^{N_{imp}} C_i} \right|$$

The number of colonies of empire n, NC_n, is then given by:

$$NC_n = round(p_n \times N_{col})$$

Finally, each colony is randomly assigned to an imperialist until the number of colonies of each empire is reached.

5.1.2 Imperialist competition

In the ICA, every empire competes to conquer more colonies other than the ones it already owns. The imperialist competition gradually results in an increase in the power of the stronger empires and a decrease in the power of the weaker empires. To model this competition, the weakest colony of the weakest empire is liberated from its current imperialist. The empires then compete to conquer this colony, with the more powerful empires having a higher probability of conquest.

The total power of an empire is determined by the imperialist and the power of its colonies. The total cost of empire *n* is given by the following expression:

$$CT_n = c_n(imperialist_n) + \alpha \times average\big(c_n(colonies\ of\ empire_n)\big)$$

where CT_n is the total cost of empire *n* and α is a number between 0 and 1, which reflects the weight of the colonies in the total cost of the empire. The value of α is a parameter of the algorithm. The total normalised cost of empire *n*, CT_n, is given by:

$$CTN_n = \max_{i=1,\dots,N_{imp}} C\,T_i - CT_n$$

Finally, the conquest probability for empire *n* is given by:

$$p_{q_n} = \frac{CTN_n}{\sum_{i=1}^{N_{imp}} CTN_i}$$

5.2 Problem-dependent steps

In order to apply the ICA, its general characteristics have to be adapted to the specific characteristics of the problem. In relation to the parameters, **N_{pop}, w**as defined as 100, **N_{imp}** as 7 and α as 0.6. The initial solutions were randomly generated without violating the precedence constraints of the problem. The objective function was calculated by scheduling every operation and then finding the maximum finishing time, which corresponds to the makespan.

Moreover, it was necessary to define a solution codification and the solutions' assimilation and the mutation operators. Graphical examples of the solution codification and the solutions' assimilation and mutation operators are available in www.inescporto.pt/~jsoeiro/Footwear_Sequencing. These engendered operators can be used further on future research projects on scheduling, through their incorporation in other metaheuristics that make use of them, such as genetic algorithms.

5.2.1 Solution codification

The first step to apply the ICA was defining the following codification for the representation of a solution: each solution has a matrix including the operations sequence for each box and the workstation where they will be executed, which is the global sequence matrix.

Each set of two consecutive lines of the matrix refers to a given box. In this case, the first two lines refer to box 1 and the other two to box 2. The first and third lines define the sequence of the operations to be performed for the respective box. The cells of the second and fourth lines define the workstation that will execute the operation referred in the cell immediately above them.

Moreover, each solution also has a vector which characterizes the global sequence of operations. Each element of this vector indicates the only box associated with the operation to be performed, since the sequence of operations for each box was already defined by the previous matrix.

5.2.2 Assimilation with the imperialist

A colony assimilates with its imperialist through a two-point crossover operator. Two elements of the imperialist global operations sequence matrix are randomly chosen to be the crossover points. The elements before the first crossover point and after the second crossover point are copied from the imperialist to the new colony, and erased from the old colony. The remaining elements from the old colony are then copied to the new colony.

The same procedure is followed for each set of two consecutive lines of the global sequence matrix.

5.2.3 Solution mutation

The solution mutation was accomplished by switching the sequence of operations, always assuring that a solution obtained by mutation respects the operations' precedence constraints. Furthermore, a mutation is also executed in the workstations by randomly choosing a new workstation for an operation, which is also randomly chosen. The mutation procedure is the following:

1. Randomly choose two elements from the global sequence matrix and switch them.
2. Randomly choose a box operation and assign it to a new workstation, randomly chosen from the set of admissible workstations.
3. Randomly choose a box to change its operations sequence.
4. Save the operations sequence of this box in an auxiliary vector.
5. Randomly choose two elements from the auxiliary vector and switch them.
6. Create a vector which will keep the elements that could not be scheduled due to precedence constraints.
7. While the box's operations sequence is incomplete:
    a. If there are elements in the vector of operations that could not be scheduled due to precedence constraints, check for every element if it is now possible to schedule it in the new operations sequence (this means checking if its direct precedents have already been scheduled). If so, schedule the operation.
    b. If in step 7.1. it was not possible to schedule any operation, then read the next element from the auxiliary vector. If the direct precedents have already been scheduled, then schedule this operation. Otherwise, save the operation in the vector of operations that could not be scheduled due to precedence constraints.

6. Computation Results

This section presents the computational results obtained both by the optimization model using CPLEX and by the metaheuristic ICA, for a set of test problems and for the industrial case. It is important to mention that test problems of different dimensions were considered in order to make it possible to analyze the performance of the optimization methods. This set of problems was randomly generated, meaning that their data was generated automatically by a program. Even so, it was assured that the problems obtained represented the reality of the industrial case. This means all the problems simultaneously have boxes with diverse graph routings and operations that can be executed by multiple workstations. The characterization of the problems is in Table 2.

Table 2. Characterization of the test problems and the industrial case

Problem	No. of boxes	Average number of operations per box	No. of workstations
1	5	5	5
2	7	7	7
3	9	9	9
4	11	11	11
5	13	13	13
6	15	15	15
7	17	17	17
Industrial case	97	9.42	60

Finally, it is important to mention that the results were obtained in an Acer Aspire E5-521G computer, with 4 GB of RAM memory and an AMD A8-6410 processor (quad-core with 2 GHz clock frequency).

6.1 Test problems

Table 3 shows the CPLEX results, namely the optimal solution and average execution time, and the ICA results for the test problems. Both programs were run 5 times for each problem instance.

Table 3. Results of CPLEX and ICA execution

Problem	Optimal solution	Average execution time of CPLEX (seconds)	Execution time of ICA (seconds)	Average solution value	Average GAP
1	534	0.562	3	534	0%
2	754	1.922	3	754	0%
3	970	15.488	60	970	0%
4	1202	88.394	120	1204.2	0.183%
5	1385	687.222	240	1425.8	2.946%
6	1579	907.164	240	1642.8	4.041%
7	1902	11112.780	240	1942.2	2.114%

The stopping criteria for the ICA was the execution time, with this being adapted according to the dimension of the problem.

The results obtained made it possible to draw some conclusions. Firstly, the solution obtained for the smaller instances was equal to the optimal solution, which validates the correct functioning of the ICA. In fact, the solution proves that the ICA attempts to solve the problem defined by the optimization model. Secondly, it can also be said that the ICA has a good performance, both in terms of efficiency and effectiveness. For the 3 smaller instances, the ICA was able to reach the optimal solution in little time. For the 4 larger instances, the average GAP is less than 5%, and the execution time is within the acceptable for the industrial case (where a maximum execution time of 300 seconds is convenient).

It is also important to state that it was not possible to obtain a solution for the industrial case since the computer's RAM was not enough to keep all the variables generated by the model due to the size of the real problem. Furthermore, even with more RAM, the exponential growth of the execution time with the size of the problem makes it impracticable to use the model in the industrial case. This indicates that using the optimization model in CPLEX directly for the industrial case is not a viable option.

6.2 Industrial case

Since this real problem could not be solved with CPLEX, it was important to find a procedure to evaluate the quality of the solutions attained by the ICA.

In this sense, a simulation program was developed which balanced and scheduled the operations according to the method currently used by the factory. This way, it is possible to obtain the makespan by simulating the factory method and compare the solution with the one obtained by the ICA.

In the case of the ICA, to evaluate the makespan, it was run 5 times and the value of the best solution throughout the execution time was registered for each of the runs.

The makespan value obtained by the simulation is 564.16 minutes. The average value makespan value obtained by the ICA is 546.26 minutes. This means that the ICA was capable of generating solutions that reduce the makespan obtained by the heuristic in 3.173%, approximately. Furthermore, the ICA converged quickly to a solution. In the run with the longest convergence time, the ICA took 92.067 seconds to get to the final value of the solution. This fast convergence is essential due to the need to obtain a solution in less than 5 minutes.

7. Conclusions

This paper addressed the design, development and testing of a new scheduling method for a complicated production problem in a large footwear factory. It should be mentioned that this type of industrial case is unique due to the newly installed automatic flexible transportation systems; moreover, scheduling problems in the footwear industry are not usually considered in the literature.

The project started by building an optimization model for the problem, which was then programmed in CPLEX. The analysis of the results contributed to validating the model, which proved to adequately represent the essential matters of the proposed industrial case. Furthermore, the CPLEX model was also capable of reaching optimal solutions for small problem instances.

A recent metaheuristic was chosen, the Imperialist Competitive Algorithm (ICA), to compensate for the expected limitations of the exact approach to tackle real larger problems. After the indispensable adaptation to the real scheduling case and the validation of its correct functioning, in particular by comparison with the optimal results for smaller instances, the computational tests indicated that the ICA obtains positive results in a short period of time. Furthermore, a solution representation and assimilation and mutation operators were specifically developed for the case study, and can be used on future research projects, by being incorporated in other metaheuristics applied to scheduling.

In addition, and to achieve a more complete appraisal of the advantages of implementing the ICA, a simulator was created from scratch to obtain more results after applying the scheduling method currently in use at the factory.

In conclusion, the new scheduling method for the industrial case, based on the ICA, succeeded in computational tests and practical evaluation. Consequently, it is now in the process of being integrated with the production management and control system. The approach is likely to be adapted for similar systems, in this or other industries.

References

Atashpaz-Gargari, E. and Lucas, C., Imperialist competitive algorithm: an algorithm for optimization inspired by imperialistic competition, *2007 IEEE Congress on Evolutionary Computation*, pp. 4661–4667, 2007.

Barnett, L., Rahimifard, S., and Newman, S., Distributed scheduling to support mass customization in the shoe industry, *International Journal of Computer Integrated Manufacturing*, vol. 17, no. 7, pp. 623–632, 2004.

Caicedo, A.J., Parra, J.W., and Rivera, L., Mathematical model for production sequencing in a manufacturing company, *Journal of Physics: Conference Series*, 2019.

Chen, J.C., Putra, A.P., Anggono, N., Chen, J., and Su, Y.-S., Simulation modeling and analysis for stitching line of footwear industry, *International Conference on Industrial Engineering and Operations Management*, pp. 1099–1106, 2014.

Chen, J.C., Wu, C.W., Thao, T.D.D., Su, L.H., Hsieh, W.H., and Chen, T., Hybrid genetic algorithm for solving assembly line balancing problem in footwear industry, *Advanced Materials Research*, vol. 939, pp. 623–629, 2014.

Costa, M.T. and Ferreira, J.S., A simulation analysis of sequencing rules in a flexible flowline, *European Journal of Operational Research*, vol. 119, no. 2, pp. 440–450, 1999.

Dang, Q.-V. and Pham, K., Design of a Footwear Assembly Line Using Simulation-based ALNS, *Procedia CIRP*, vol. 40, pp. 596–601, 2016.

Lin, Y.-K., Huang, D.-H., and Huang, C.-F., Estimated network reliability evaluation for a stochastic flexible flow shop network with different types of jobs, *Computers & Industrial Engineering*, vol. 98, pp. 401–412. 2016.

Paucar, V., Munive, S., Nunez, V., Marcelo, G.E., Alvarez, J.C., and Nallusamy, S., Development of a lean manufacturing and SLP-based system for a footwear company, *IEEE International Conference on Industrial Engineering and Engineering Management*, pp. 1112–1116, 2020.

Quyen, N.T.P., Chen, J.C., and Yang, C.-L., Hybrid genetic algorithm to solve resource constrained assembly line balancing problem in footwear manufacturing, *Soft Computing*, vol. 21, no. 21, pp. 6279–6295, 2017.

Quyen, N.T.P., Kuo, R., Chen, J.C., and Yang, C.-L., Dynamic programming to solve resource constrained assembly line balancing problem in footwear manufacturing, *Industrial Engineering and Applications (ICIEA), 2017 4th International Conference on*, pp. 66–70, 2017.

Reyes, J., Aldás, D., Salazar, E., Armendáriz, E., Álvarez, K., Núñez, J., and García, M., Finite Progressive Planning for the Assembly Process in Footwear, *IOP Conference Series: Materials Science and Engineering*, vol. 212, pp. 012020, 2017.

Reyes, J., Urvina, R., Ramírez, S., Álvarez, K., Pazmiño, R., Sanchez, L., Benites, M., and Aldas, D., FAPS system: A prototype for lean manufacturing scheduling in footwear 12th Ibero-American Conference on Software Engineering and Knowledge Engineering 2017 - Held Jointly with the Ecuadorian Conference on Software Engineering, CEIS 2017 and the Conference on Software Engineering Applied to Control and Automation Systems, ISASCA, pp. 13–25, 2017.

Sadeghi, P., Rebelo, R.D., and Ferreira, J.S., Balancing a Mixed-Model Assembly System in the Footwear Industry, *IFIP International Conference on Advances in Production Management Systems*, pp. 527–535, 2017.

Sadeghi, P., Rebelo, R.D., and Ferreira, J.S., Balancing mixed-model assembly systems in the footwear industry with a variable neighbourhood descent method, *Computers & Industrial Engineering*, vol. 121, pp. 161–176, 2018.

Ulutas, B. and Islier, A.A., Dynamic facility layout problem in footwear industry, *Journal of Manufacturing Systems*, vol. 36, pp. 55–61, 2015.

Zangiacomi, A., Zhijian, L., Sacco, M., and Boër, C.R., Process planning and scheduling for mass customised shoe manufacturing, *International Journal of Computer Integrated Manufacturing*, vol. 17, no. 7, pp. 613–621, 2004.

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