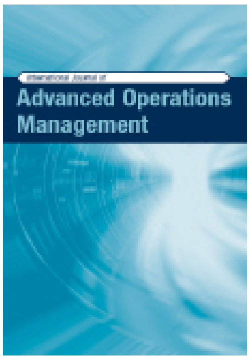

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Optimising production scheduling decisions in flowshop manufacturing cells for a sportswear manufacturing case

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Abstract: This paper aims to reduce makespan and total weighted tardiness (TWT) by applying a cellular manufacturing system (CMS) approach based on formulations for the flowshop group-scheduling problem (FSGSP) to the sewing area of a sportswear manufacturing company in Colombia. The main contribution of this paper is the application of recent FSGSP models to a novel case study in the apparel industry. As part of the methodology, two FSGSP models framed in a CMS environment were proposed based on the literature review. In addition, a genetic algorithm (GA) was developed to evaluate this application in terms of makespan and TWT. The results showed that the proposed approach completely reduced the total tardiness penalty costs and 56.23% for makespan compared to the current state. These results seek to promote the application of models and techniques for addressing the lack of productivity, high waste, and customer dissatisfaction in this Colombian industry.

Keywords: flowshop group scheduling; cellular manufacturing; genetic algorithm; apparel industry; total weighted tardiness; TWT; makespan.

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1 Introduction

The need to satisfy the changing demands of the markets has made today's industrial organisations focus on implementing strategies that allow them to achieve flexibility in their production systems while positively impacting their productivity and finances. This need is even more prevalent in the apparel industry, which is considered very changeable due to customer demands and the so-called 'fast fashion' concept. Among the strategies to respond to these demands, cellular manufacturing system (CMS) have stood out for fulfilling these requirements of flexibility and waste reduction, *mudas*, of the lean manufacturing philosophy (Cáceres-Gelvez et al., 2022a; Ham et al., 1985; Khouzani and Shahraki, 2020; Kia, 2020; Mansour et al., 2022; Sharma and Sharma, 2018; Wemmerlöv and Hyer, 1989). Similarly, production scheduling becomes a pivotal decision in meeting customers' needs, including compliance with due dates for order delivery (Azizi and Hu, 2020; Dolgui et al., 2019; Hajibabaei and Behnamian, 2021; Mollaei et al., 2019; Parente et al., 2020).

Production scheduling decisions in flowshop/flowline CMS environments are known in the research literature as the flowshop group-scheduling problem (FSGSP). The FSGSP consists of finding a sequence for both the product families and the jobs belonging to each product family to be processed on each machine of a flowshop manufacturing cell to optimise one or more performance measures (França et al., 2005; Lin et al., 2009a; Neufeld et al., 2016; Schaller et al., 2000). CMS are considered a key approach to decreasing waste related to unnecessary movements, setup times, and work-in-process (WIP) inventory while increasing throughput and product quality (Cáceres-Gelvez et al., 2022b; Irani, 1999; Nikoofarid and Aalaei, 2012; Wemmerlöv and Hyer, 1989). For this reason, recent literature has been focused on addressing the decisions concerning the implementation of effective manufacturing cells, including their formation, layout, and scheduling in industrial environments (Ebrahimi et al., 2021; Esmailnezhad and Saidi-mehrabad, 2021; Rafiei et al., 2016; Salimpour et al., 2021; Saraçoğlu et al., 2021).

Despite its importance to the industry, production scheduling decisions in flowshop (F_j) manufacturing cells have not been widely addressed in real company cases in the manufacturing sector. According to recent literature, the technology sector has been the primary beneficiary of production scheduling approaches in CMS. These cases include the manufacturing of semiconductor wafers (Celano et al., 2010), printed circuit boards (Gelogullari and Logendran, 2010; Yazdani Sabouni and Logendran, 2018), thin film transistor-liquid crystal displays (TFT-LCD) (Yang, 2002), and honeycomb sandwich panels (Qin et al., 2016). Additional case studies from the metallurgy (Sekkal and Belkaid, 2020) and automotive (Khalid et al., 2019) industries have also been considered in flowshop group scheduling literature; however, the number of applications to real cases in the industrial sector is scarce for the importance of the approach.

The objective of this paper is then to propose FSGSP formulations for applying group technology, i.e., the formation of product families for CMS environments, as well as sequence-dependent setup times and permutation characteristics to minimise *makespan* ($C_{\max}$) and total weighted tardiness (TWT) ($\Sigma w_j T_j$) objectives. The application context is a novel real manufacturing industry case, the sewing department of a sportswear manufacturing company located in Cúcuta, Colombia. The apparel industry is a global industry with a significant role in a country's economy (Das and Patnaik, 2015; Sharama, 2020). In Colombia, the industry is considered one of the most important in the manufacturing sector; in Cúcuta, it represents more than 30% of the local industry (García Bautista and Jauregui Mancipe, 2016).

The consideration of this case study in the apparel industry seeks to propose FSGSP formulations and CMS for other industrial contexts apart from the technological sector. Additionally, this application aims to reduce gaps between research and real-world applications for this Colombian industry. Companies in this sector struggle to compete in international markets due to their lack of productivity, high waste ('*mudas*' in the lean manufacturing terminology), and precarious use of state-of-the-art technological /engineering approaches for solving traditional problems, such as production scheduling. Additionally, the literature on the FSGSP has mentioned the benefits of implementing flowshop manufacturing cells to improve productivity and efficiency, but no publication has measured the impact on key performance indicators for a real industrial context.

In this sense, the definition of product families (*fmls*), i.e., grouping a wide variety of products into similar 'families' to be processed in groups of machines to take advantage of group technology benefits (Ham et al., 1985; Wemmerlöv and Hyer, 1989) is selected in this application. Additionally, keeping a permutation policy (*prmu*) conditions the manufacturing cells to maintain the first-in-first-out flow of materials, as required in lean manufacturing approaches (Abdullah et al., 2018; Abele et al., 2012; Böllhoff et al., 2015; Dennis, 2015). Finally, the sequence-dependent setup times feature (s_{tki}) aims to reduce setup times and other preparation '*mudas*' due to differences between families by grouping jobs belonging to the same family in the schedule (Neufeld et al., 2016; Pinedo, 2016). The *makespan* and TWT objective functions were selected in this application since *makespan* is a machine-utilisation-based objective function, which is important for sewing departments in the apparel industry. At the same time, TWT is a customer-satisfaction-focused objective, which has been related to lean manufacturing schedules (Keshavarz et al., 2019). Using the $\alpha \mid \beta \mid \gamma$ notation, this paper addresses the $F_m \mid s_{tki}, prmu, fmls \mid \Sigma w_j T_j$ and the $F_m \mid s_{tki}, prmu, fmls \mid C_{\max}$ for the same case study.

The main contribution of this paper is the application of FSGSP with sequence-dependent family setup times and permutation formulations to the case of the apparel industrial sector for the minimisation of both *makespan* and TWT objective functions. Furthermore, due to the NP-completeness of this problem, a simple genetic algorithm (GA) is developed and validated for the solution of the proposed formulations (Schaller et al., 2000; Tavakkoli-Moghaddam et al., 2010). The choice to use the GA over other metaheuristics is made because of the recognised ability of the GA to solve complex problems of a combinatorial nature, such as the FSGSP (Sivanandam and Deepa, 2007; Zapata-Cortés et al., 2023). Additionally, the GA was selected over an exact method due to the complexity of the problem and the need of the case study company to obtain good solutions in practical times. Finally, an evaluation of the *makespan* and TWT objective functions is carried out compared to the area's current state.

This paper is then divided as follows: Section 2 presents a literature review of the FSGSP models and applications, Section 3 describes the methodology used for defining the FSGSP models and their application to the case study, and Section 4 presents the application results to the case study, and finally, Section 5 concludes and gives future insights for the topic.

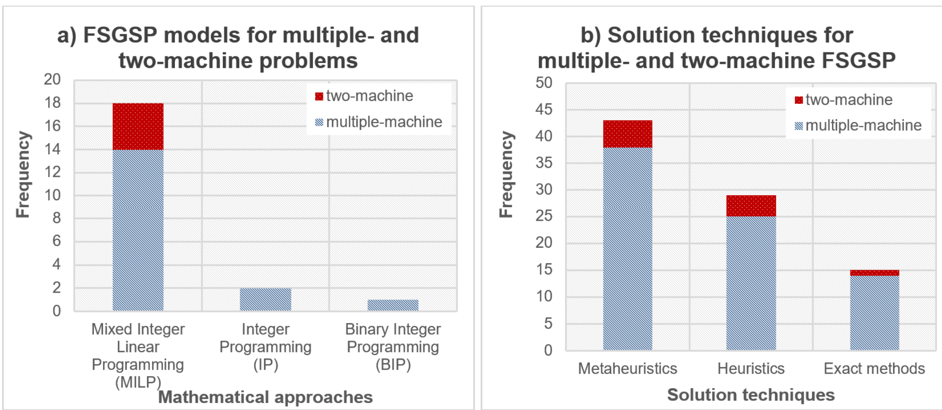
2 Literature review

In this section, a brief literature of mathematical models, solution techniques and real-world applications for the FSGSP is presented. Section 2.1 shows the results of the review process for academic publications that proposed or used mathematical formulations and/or applied solution techniques for the problem, whereas Section 2.2 presents the literature addressing the problem in real-world situations.

2.1 *Mathematical models and solution techniques for the FSGSP*

The FSGSP has been addressed using either constructive algorithms, heuristics or metaheuristics and exact mathematical methods. Figure 1 shows an analysis of the mathematical approaches [Figure 1(a)] and solution techniques [Figure 1(b)] found in the literature for the FSGSP.

Figure 1 Results of the literature review on (a) FGSGP models (b) solution techniques for FSGSP (see online version for colours)



The first approaches to solve the FSGSP considered construction algorithms used in the solution of different production scheduling problems, such as the Campbell-Dudek-Smith (CDS) (Neufeld et al., 2015; Schaller, 2000; Schaller et al., 2000), the Nawaz-Enscore-Ham (NEH) (Celano et al., 2010; Neufeld et al., 2015; Schaller, 2000; Schaller et al., 2000), the Gupta-Darrow (Schaller, 2000; Schaller et al., 2000), the CDS-NEH-Descend (CMD) (Neufeld et al., 2015; Schaller, 2000; Schaller et al., 2000), among other heuristics, as well as hybrids among them. However, more recent approaches have been directed toward the formulation of mathematical programming models and advanced techniques for solving the problem, such as metaheuristic algorithms, as well as towards the application to real-life industrial cases (Gelogullari and Logendran, 2010; Khalid et al., 2019; Qin et al., 2016; Yazdani Sabouni and Logendran, 2018). Table 1 shows the recent mathematical formulations for the FSGSP found in the literature.

Relevant models for the FSGSP include those by Salmasi et al. (2010), Naderi and Salmasi (2012), Costa et al. (2020), whereas more recent models were proposed by Ghorbanzadeh and Ranjbar (2023), Sekkal and Belkaid (2022) and Saraçoğlu et al. (2021) for specific case studies. Additionally, metaheuristics were found to be frequently applied to solve the problem. These include GAs (Celano et al., 2010, 2011; Costa et al., 2017; França et al., 2005; Keshavarz et al., 2014; Lin et al., 2009b; Liou and Hsieh, 2015), tabu search (TS) (Celano et al., 2010; Lin et al., 2009b; Lu and Logendran, 2013; Salmasi et al., 2010), and simulated annealing (SA) (Lin et al., 2009a; Naderi and Salmasi, 2012; Ying et al., 2010, 2012), among others.

Table 1 Relevant mathematical models for the FSGSP in the literature

Authors	*Problem*	*Formulation*			*Solution technique*
		MIP	*IP*	*BIP*	
Yuan et al. (2020)	$F_2 \mid prmu, fmls, block, t_j \mid C_{\max}$	x			CPLEX, Co-evolutive GA
Salmasi et al. (2010)	$F_m \mid s_{rf}, fmls, prmu \mid \Sigma C_j$	x			B&P, CPLEX, TS, ACO-NEH
Salmasi et al. (2011)	$F_m \mid s_{rf}, fmls, prmu \mid C_{\max}$	x			Hybrid ACO
Naderi and Salmasi (2012)	$F_m \mid s_{rf}, fmls, prmu \mid \Sigma C_j$	x			CPLEX, GSA
Solimanpur and Elmi (2011)	$F_m \mid fmls, block \mid C_{\max}$		x		TS-NEH
Lin and Ying (2019)	$F_m \mid s_{rf}, fmls, nwt \mid C_{\max}$			x	LKH
Keshavarz et al. (2014)	$F_m \mid s_{rf}, fmls, prmu \mid \Sigma C_j$	x			B&B, B&P, modified GA
Keshavarz et al. (2019)	$F_m \mid s_{rf}, fmls, prmu \mid \Sigma(w_j E_j + w_j T_j)$	x			B&P, CPLEX, sequencing rules, HPSO
Costa et al. (2020)	$F_m \mid srf, block \mid C_{\max}$	x			CPLEX, parallel self-adaptive GA
Ghorbanzadeh and Ranjbar	$F_m \mid srf, fmls, TOU, re, ca \mid TEC$	x			Decomposition-based heuristic
Sekkal and Belkaid (2022)	$F_m \mid s_{rf}, learn \mid C_{\max}, TEC$	x			LP-metric method
Saraçoğlu et al. (2021)	$Fm \mid fmls \mid C_{\max}$ $F_m \mid fmls \mid \Sigma F_j$	x	x	x	GA, LINGO

Notes: Conventions: B&P: branch and price, NEH: Nawaz-Enscore-Ham, GA: genetic algorithm, TS: tabu search, ACO: ant colony optimisation, GSA: hybrid GA and simulated annealing, HPSO: hybrid particle swarm optimisation LKH: Lin-Kernighan-Helsgaun.

Source: Authors

2.2 Real-world applications of the FSGSP

The literature review allowed the identification of some applications of the FSGSP to real industrial contexts, especially in the technology sector. As mentioned above, the production of high-technology products has been addressed the most for the FSGSP (Celano et al., 2010; Gelogullari and Logendran, 2010; Ghorbanzadeh and Ranjbar, 2023; Qin et al., 2016; Yang, 2002; Yazdani Sabouni and Logendran, 2018). Other real case applications include cases in the automotive industry (Khalid et al., 2019), the metalworks industry (Sekkal and Belkaid, 2022) and shoe manufacturing (Saraçoğlu et al., 2021). Table 2 compares the application addressed in this paper and other FSGSP applications retrieved from the literature. The table includes the authors, the characteristics of the problem using Graham's notation $\alpha \mid \beta \mid \gamma$, the solution techniques used (e.g., heur., for heuristics and metaheur., for metaheuristics), and finally, the industrial context.

Table 2 Comparison between the present article and other FSGSP applications in the literature

Authors	*Problem*	*Solution Technique*			*Application*
		Exact	*Heur.*	*Metaheur.*	
Celano et al. (2010)	$F_j \mid s_{tki}, prmu, block \mid C_{\max}$		NEH	GA, TS	Semiconductor wafer production
Yang (2002)	$F_j \mid s_{ki}, prmu \mid C_{\max}$	B&B	Heuristic		TFT-LCD production
Qin et al. (2016)	$F_j \mid gta, prmu \mid C_{\max}$ $F_j \mid gta, prmu \mid \Sigma C_j$ $F_j \mid gta, prmu \mid \Sigma w_j C_j$ $F_j \mid gta, prmu \mid L_{\max}$		Sequencing rules	GA, QDEA	Aluminium honeycomb sandwich panels production
Gelogullari and Logendran (2010)	$F_j \mid prmu, fmls \mid \Sigma C_j$	Column generation B&P		TS	Printed circuit boards production
Yazdani Sabouni and Logendran (2018)	$F_j \mid fmls \mid \Sigma w_j F_j$ $F_j \mid fmls \mid \Sigma w_j T_j$	CPLEX, B&P	CFIM1, CFIM2	TS	Printed circuit boards production
Khalid et al. (2019)	$F_j \mid prmu, fmls \mid WIP$ $F_j \mid prmu, fmls \mid Av.utiliz.$		Sequencing rules, NEH	GA, PSO, NEPSO	Automotive industry
Ghorbanzadeh and Ranjbar (2023)	$F_m \mid s_{rf}, fmls, TOU, re, ca \mid TEC$		Decomposition-based heuristic		TFT-LCD production
Sekkal and Belkaid (2022)	$F_m \mid s_{rf}, learn \mid C_{\max}, TEC$	LP-metric method			Forged connecting rod production
Saraçoğlu et al. (2021)	$F_m \mid fmls \mid C_{\max}$ $F_m \mid fmls \mid \Sigma F_j$	LINGO		GA	Shoe manufacturing
This paper	$F_j \mid s_{tki}, prmu, fmls \mid \Sigma w_j T_j$ $F_j \mid s_{tki}, prmu, fmls \mid C_{\max}$			GA	Sportswear manufacturing

Notes: Conventions: B&B: branch and bound, B&P: branch and price, NEH: Nawaz-Enscore-Ham, CFIM1/2: cycle forward improving algorithms, GA: genetic algorithm, TS: tabu search, QDEA: quantum differential evolutionary algorithm, PSO: particle swarm optimisation, NEPSO, NEH-PSO hybrid algorithm, TFT-LCD: thin-film transistors/liquid crystal displays.

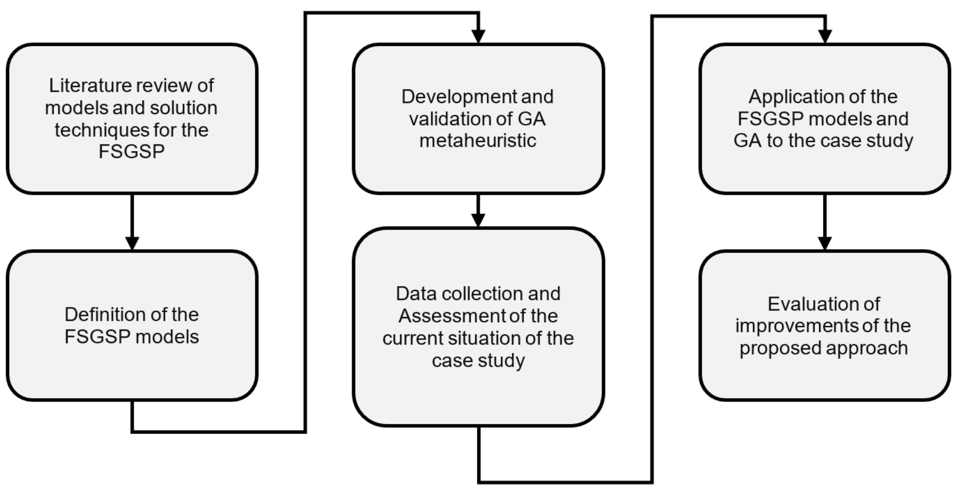
Source: Authors

The literature review results allowed identifying two models presented by Naderi and Salmasi (2012) for total completion time minimisation. Their Model 1 was adapted in this paper for the TWT objective, whereas their Model 2 was changed to minimise the makespan objective function, as mentioned in Section 3.1. Additionally, it was found that metaheuristic algorithms are more frequent when solving the FSGSP due to its NP-completeness. Genetic and TS algorithms are the most frequently used metaheuristics for multiple and two-machine problems. GAs are considered robust when solving combinatorial problems such as FSGSP (Kia, 2020; Sivanandam and Deepa, 2007). In this sense, the two FSGSP formulations and a GA are presented in the following sections for the apparel case study.

3 Methodology

In this section, the methodology followed to apply the FSGSP for the case of the sportswear manufacturing company is presented. Section 3.1 shows the use of models 1 and 2 by Naderi and Salmasi (2012) for minimising TWT and makespan. Section 3.2 presents the development and validation of the proposed GA, and Section 3.3 presents the case study.

Figure 2 Proposed methodology for applying the FSGSP and GA to the case study



Source: Authors

The methodology followed in this paper is shown in Figure 2. The methodology first considered a review of the FSGSP models and solution techniques used in the research literature. The next step consisted of defining the FSGSP models and developing and validating a GA to be applied to solving the formulations. The following steps included collecting the necessary input information and assessing the current situation to determine the current measures of TWT and *makespan*. The final steps consisted of implementing the proposed FSGSP-CMS approach and applying the GA to evaluate *makespan* and TWT compared to the company's current state.

3.1 Flowshop group scheduling models

The FSGSP was described mathematically by Schaller et al. (2000) and has been largely addressed in recent years in the academic literature due to its importance to the effective implementation of CMS (Irani, 1999; Neufeld et al., 2016; Wemmerlöv and Hyer, 1989). The problem consists of finding a sequence for a given set of n jobs to be processed on m machines arranged in a flow line (flowshop) manner, where each job belongs to one of g product families ($K = \{1, 2,\dots, g\}$, where K is the set of g families) and G_k is the set of jobs belonging to the k^{th} family (França et al., 2005; Schaller et al., 2000). The processing time of each job j on each machine i is represented by p_{ij}. Additionally, if a machine i is processing a product family t, the machine may need a setup time before processing a product family k, defined as s_{tki}, where $s_{tti} = 0$, i.e., jobs belonging to the same product family do not require significant setup times.

As mentioned in the previous subsection, Naderi and Salmasi's (2012) Model 1 and Model 2 were used in this application in the case of sportswear manufacturing to obtain exact solutions for the optimisation of TWT and *makespan* objective functions. Since the interest of this paper is not to propose a new mathematical model for the FSGSP and no constraints were modified or eliminated, the equations for the constraints of the models presented by Naderi and Salmasi (2012) are not shown in this paper. However, TWT and *makespan* objective functions are defined with the inclusion of a new set of constraints regarding these measures.

Model 1 was adapted to include the TWT objective, as shown in (1). Additionally, a new set of constraints was included for defining jobs' tardiness, as shown in (2). In these expressions, T_j is the tardiness of job j, defined as the positive difference between the completion time of job j on the last machine m, (C_{jm}) and the due date for job j (e_j) while w_j is the weight or cost per unit of tardiness for job j.

$$Minimise\ TWT = \sum_{j \in G_k} w_j T_j \tag{1}$$

$$T_j \geq C_{jm} - e_j, \qquad \forall j \in G_k \tag{2}$$

Similarly, Model 2 was used to compute the makespan, or maximum completion time of jobs objective function, as shown in (3), where $C_{gn_k m}$ is the completion time of the last job slot (n_k) in the last product family (g) processed on the last machine (m).

$$Minimise\ Makespan = C_{gn_k m} \tag{3}$$

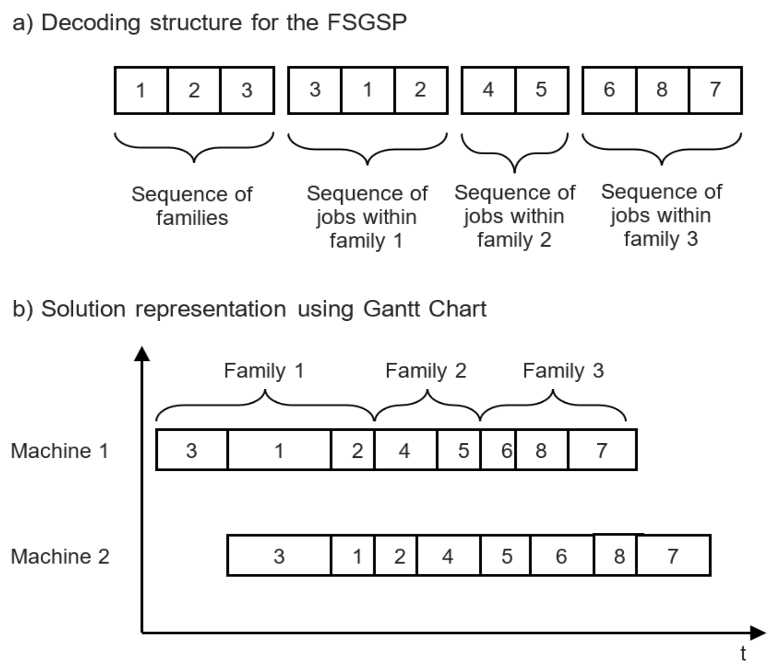
3.2 Development and validation of the GA

Since the FSGSP is considered a combinatorial problem of the NP-Complete class (França et al., 2005; Lin et al., 2009b; Schaller et al., 2000), a GA is developed for its optimisation in this application. The GA is selected for this application as it resembles Darwin's theory of evolution, where the fittest individuals survive from generation to generation (Sivanandam and Deepa, 2007). Additionally, it is considered one of the most robust algorithms to optimise complex combinatorial problems (Sivanandam and Deepa, 2007). The proposed GA considers the basic operators of a simple GA, i.e., selection, crossover, and mutation operators. In this metaheuristic, individuals are measured according to fitness functions consisting of the objective functions presented in (1) and (3) for TWT and *makespan*, respectively. The characteristics of the GA developed for the optimisation of the FSGSP for the case study are presented below.

3.2.1 Encoding structure and solution representation for the FSGSP.

Figure 3 shows the encoding structure [Figure 3(a)] and solution representation [Figure 3(b)] for the FSGSP, as used by França et al. (2005) and Lin et al. (2009b), among other authors and as embodied by Neufeld et al. (2016) in their comprehensive review of the problem.

Figure 3 (a) Encoding structure (b) solution representation for the FSGSP



Source: Authors

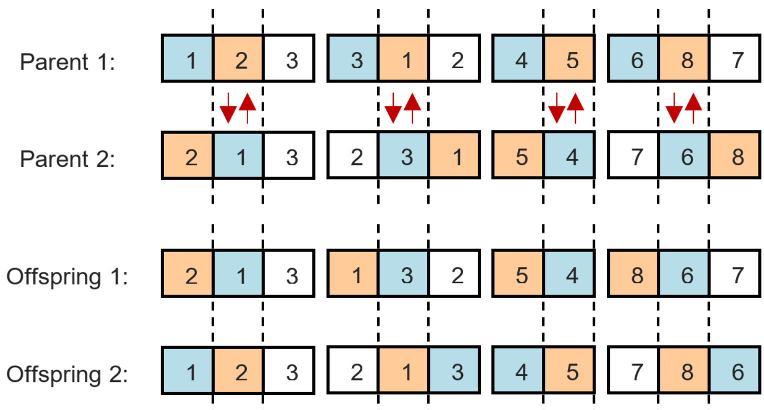
Figure 3(a) shows an encoding structure consisting of a chromosome of g + 1 parts, where g is the number of product families, whose sequence is defined in the first part of the chromosome. The sequence of the jobs belonging to each family is determined by the other components of the chromosome (França et al., 2005; Neufeld et al., 2016). Figure 3(b) shows the decoded solution represented by the chromosome in Figure 3(a). The sequence of families is 1-2-3, and the jobs belonging to each family are processed in groups to avoid sequence-dependent family setup times. In this sense, the sequence of jobs within the first family, i.e., family 1, is 3-1-2, the sequence of jobs within family 2 is 4-5, and the sequence of jobs within family 3 is 6-8-7. Since the permutation policy is considered, the sequence of families and jobs does not change from machine to machine.

3.2.2 Selection, crossover, and mutation operators

The operator to select the individuals from the population for the combination process consists of a selection tournament, whose size can be defined through the parameter 'tournament_size'. Then, the operator randomly considers the number of individuals designated by the parameter for the tournament and selects the fittest individuals according to the fitness function.

The crossover operator is carried out using the partially matched crossover (PMX) method for each chromosome division (Sivanandam and Deepa, 2007). Figure 4 shows an example of the application of the PMX method where a crossover section is randomly generated between two points of each segment to subsequently perform an exchange between the allele values found within this section. Similarly, the same values within the crossover section are exchanged outside the crossover section so that they are not repeated in the same chromosome segment. For example, Figure 4 shows how the PMX mechanism swaps 2 and 1 values within the dotted area for the first segment of the chromosome.

Figure 4 An example of the application of the PMX method (see online version for colours)



Source: Authors

Table 3 Sets of parameters used for the GA tuning process

Set of parameters	*Population size*	*Number of generations*	*Tournament size*	*Crossover probability*	*Mutation probability*
1	100	100	3	0.7	0.2
2	200	200	4	0.8	0.3
3	100	300	2	0.9	0.1
4	200	400	3	0.8	0.2

Source: Authors

Table 4 Results of the validation and parameterisation processes of the GA for the *makespan* fitness function

Number of machines	*Family size*	*Number of data instances*	*Set of parameters 1*		*Set of parameters 2*		*Set of parameters 3*		*Set of parameters 4*	
			Instances solved	*Avg. % error*	*Instances solved*	*Avg. % error*	*Instances solved*	*Avg. % error*	*Instances solved*	*Avg. % error*
2 machines	Small	18	18	0.001	18	0.000	18	0.001	18	0.000
	Medium	18	12	0.010	12	0.004	12	0.004	12	0.011
3 machines	Small	54	54	0.001	54	0.001	54	0.000	54	0.000
	Medium	54	18	0.004	18	0.001	18	0.001	18	0.004
6 machines	Small	18	18	0.006	18	0.005	18	0.004	18	0.003
			Average:	0.012	Average:	0.006	Average:	0.005	Average:	0.006

Source: Authors

Table 5 Results of the validation and parameterisation processes of the GA for the TWT fitness function

Number of machines	*Family size*	*Number of data instances*	*Set of parameters 1*		*Set of parameters 2*		*Set of parameters 3*		*Set of parameters 4*	
			Instances solved	*Avg. % error*	*Instances solved*	*Avg. % error*	*Instances solved*	*Avg. % error*	*Instances solved*	*Avg. % error*
Loose due dates										
2 machines	Small	18	12	0.327	12	0.202	12	0.186	12	0.755
	Medium	18	6	0.418	6	0.755	6	0.071	6	0.571
3 machines	Small	54	18	0.077	18	0.057	18	0.049	18	0.037
6 machines	Small	18	8	0.034	8	0.056	8	0.010	8	0.014
			Average:	0.184	Average:	0.167	Average:	0.082	Average:	0.273
Tight due dates										
2 machines	Small	18	12	0.084	12	0.062	12	0.169	12	0.116
	Medium	18	6	0.047	6	0.028	6	0.026	6	0.048
3 machines	Small	54	18	0.008	18	0.025	18	0.018	18	0.036
6 machines	Small	18	8	0.022	8	0.005	8	0.009	8	0.000
			Average:	0.037	Average:	0.032	Average:	0.059	Average:	0.053

Source: Authors

3.2.3 Validation and parameter tuning

The validation process consisted of comparing the best result of the *GA* with the optimal solution (*OPT*) for small data instances of the FSGSP as proposed by Salmasi et al. (2010) and Keshavarz et al. (2019). These results were compared according to a percentage error (% *error*) as shown in (4). The optimal solution of these data instances was obtained using Python 3.8, the PuLP package (https://pypi.org/project/PuLP/) and the IBM ILOG CPLEX solver via the formulations adapted from Naderi and Salmasi's (2012) models.

$$\%\, error = \frac{GA - OPT}{OPT} \tag{4}$$

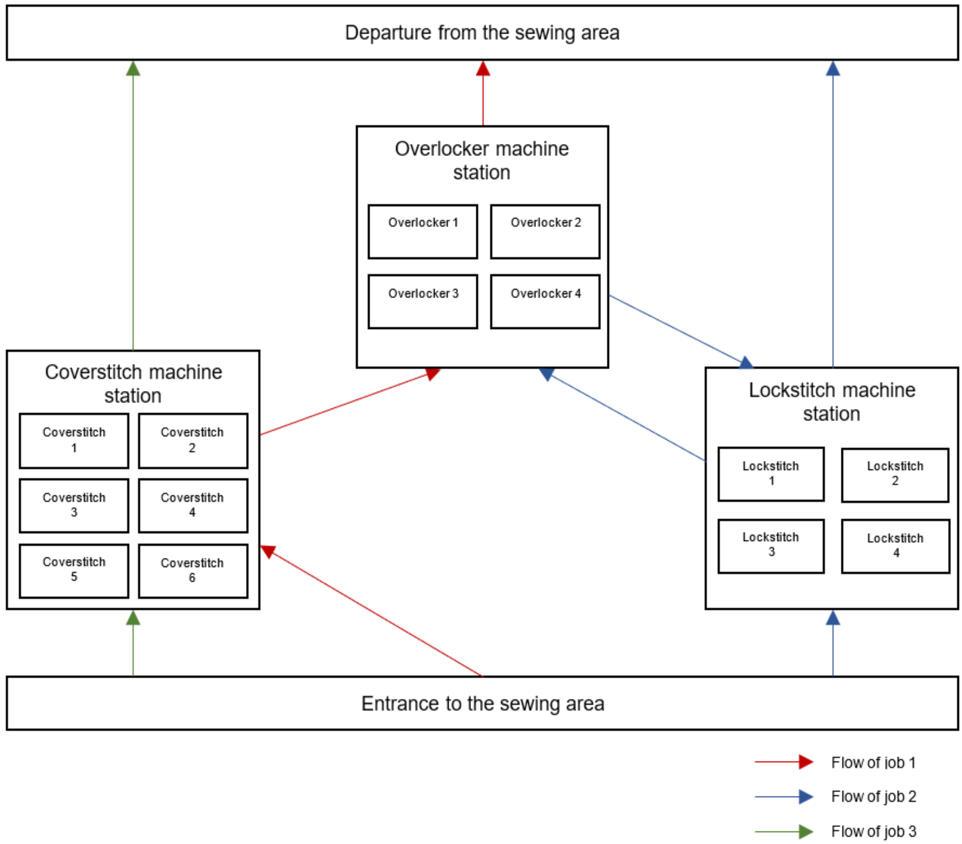
The tuning process of the GA parameters was performed simultaneously with the validation process, using the same data instances for the FSGSP, where four sets of five parameters were considered, as presented in Table 3. Table 4 and Table 5 show the results of the GA validation and parameterisation processes, where the characteristics of the resolved data instances are described according to the levels established by Salmasi et al. (2010) for the number of machines/families, as well as the tightness of the due dates as proposed by Keshavarz et al. (2019). The tables also show the average percentage error achieved by the GA compared to the optimal results that the CPLEX solver could reach for specific instances. The results of the tuning process indicate that both sets of parameters 2 and 3 performed the best for solving the FSGSP for the *makespan* and TWT objective functions; however, the set of parameters 3 gave better results on average than the set of parameters 2. Therefore, the set of parameters 3 is used in the GA application for both *makespan* and TWT optimisation.

3.3 The sportswear manufacturing case study and data collection process

The case study used in this application of the FSGSP is the sewing area of a small company that manufactures sportswear for men and women that is located in the city of Cúcuta, Colombia. The company manufactures T-shirts, sweatpants, pants, leggings, and tank tops. Its operations are organised into a residential house divided into six departments, including reception and dispatch, sewing, printing, finishing, storage areas, and an administrative office.

The focus of this application is the sewing area, which is composed of three similar machine workstations, including the coverstitch, the overlocker, and the lockstitch machine workstations, each with six, four, and four machines, respectively. Figure 5 presents a scheme of the current state of the sewing area for the case study. This arrangement of machines resembles a flexible job shop environment, where jobs are processed on one of the machines at each workstation, according to their sequence of operation. However, this arrangement has created efficiency problems for the company since jobs have very long lead times, increasing WIP inventory. At the same time, machines require frequent and longer setup times due to the wide variety of product families. The aforementioned has generated low machine utilisation in the area and non-compliance with customer order delivery due dates, so the *makespan* and TWT objectives were selected for this FSGSP application.

Figure 5 Scheme of the current state for the sewing area of the case study company (see online version for colours)



Source: Authors

In this application, one of the company's customers requested an order to be delivered within one working day (10 hours = 36,000 seconds), which is described in Table 6. The table shows the types of products, the product families (references), the number of jobs, and their due date in seconds. In this sense, the T-shirts include 156 jobs; the pants have 108 jobs; the sweatpants include 132 jobs; the leggings include 60 jobs, and the top tanks include a total of 60 jobs. In total, 516 jobs were included in this application, where processing times for each job on each machine and machine setup times for each product family are presented as Supplementary Material of this paper. The company defines a penalty cost for the delivery of tardy jobs as COP 2.5 (≈ USD 0.0006) per second per job.

The sewing area of the case study was proposed to be transformed to meet the due delivery dates and avoid tardy jobs. Therefore, a system of three flowshop manufacturing cells was proposed to produce the product families, as shown in Figure 6 and Table 7. The figure shows a scheme of the proposed cellular manufacturing approach for the sewing area. The table presents the types of products assigned and the machines that compose each manufacturing cell, according to the sequence of operations required to process each product type in the sewing department, as presented in the Supplemental Material. In this sense, the manufacturing cells #1 (MC1), #2 (MC2), and #3 (MC3) are composed of machines belonging to the current workstations: coverstitch, overlocker, or lockstitch, and are shown in the table in the technological order necessary to process each product family in a flowshop manner.

Table 6 Description of the jobs for the application of the proposed approach

Type of products	*Product families (references)*	*Quantity*	*Job due dates (seconds)*	*Product families (references)*	*Quantity*	*Job due dates (seconds)*
T-shirts	W057-C01	48	36,000	W057-C03	48	36,000
	W057-C02	36	36,000	W057-C04	24	36,000
Pants	A034-P01	36	36,000	A034-P03	24	36,000
	A034-P02	48	36,000			
Sweatpants	S082-S01	36	36,000	S082-S03	36	36,000
	S082-S02	12	36,000	S082-S04	48	36,000
Leggings	P021-L01	24	36,000			
	P021-L02	36	36,000			
Top tanks	P021-F01	36	36,000			
	P021-F02	24	36,000			
				Total jobs:	516	

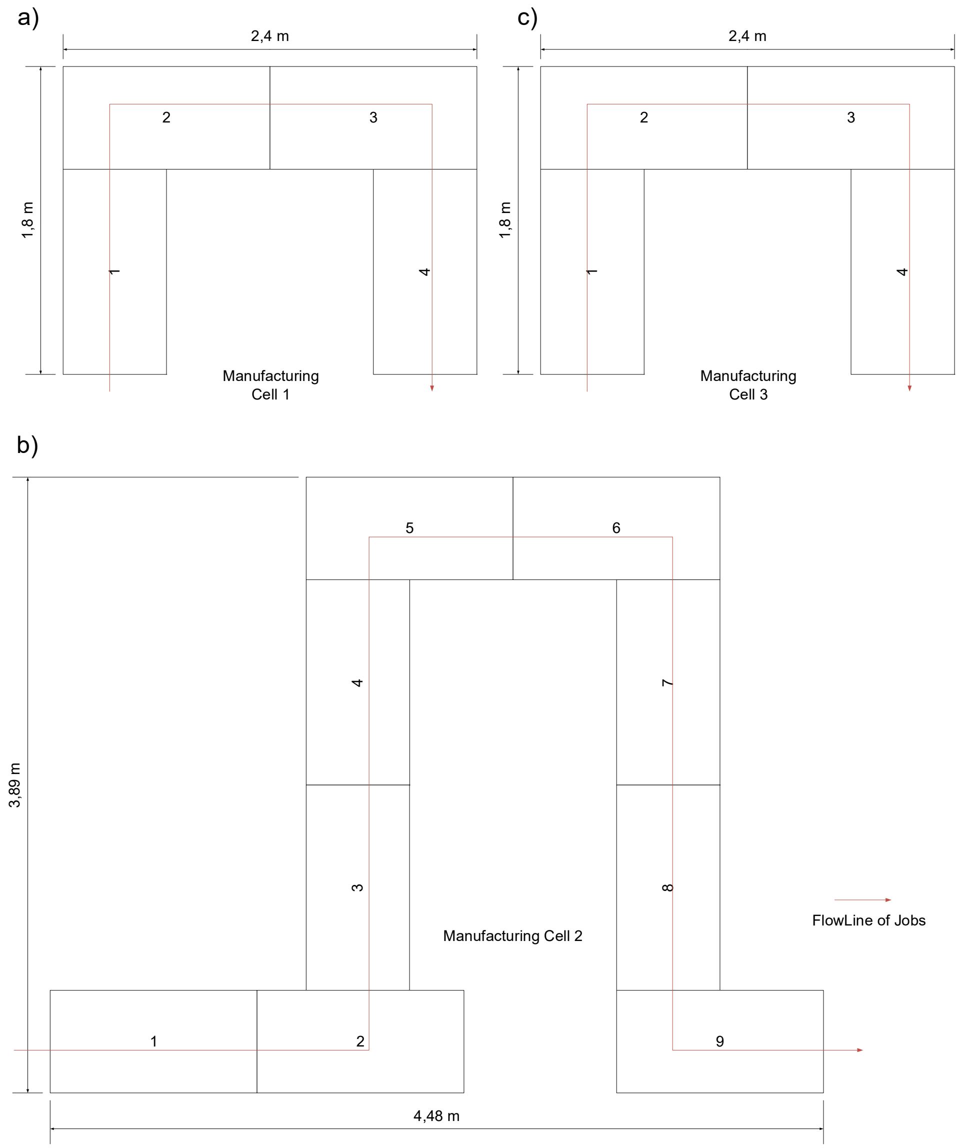
Source: Authors

Table 7 Description of the proposed manufacturing cell approach

	Manufacturing cell # 1	*Manufacturing cell # 2*	*Manufacturing cell # 3*
Types of products assigned	T-shirts	Pants	Sweatpants, leggings, and top tanks
Machines within each manufacturing cell	1 Coverstitch	1 Lockstitch	1 Coverstitch
	2 Overlocker	2 Overlocker	2 Coverstitch
	3 Coverstitch	3 Lockstitch	3 Coverstitch
	4 Coverstitch	4 Overlocker	4 Coverstitch
		5 Lockstitch	
		6 Coverstitch	
		7 Lockstitch	
		8 Coverstitch	
		9 Lockstitch	

Source: Authors

Figure 6 Scheme of the proposed cellular manufacturing state for the sewing area of the case study company (see online version for colours)



Source: Authors

4 Results and discussion

Since one of the objectives of this article is to compare the company's current situation with the proposed manufacturing cell approach, the research results are focused on evaluating the impact on *makespan* and TWT objectives.

4.1 Assessment of the current situation of the company's sewing department

As mentioned in previous sections, the sewing area of the sportswear manufacturing company is organised in a flexible job shop machine environment. Jobs are processed on machines at each workstation in batches of 12 units, according to their operations sequence. Thus, for example, a T-shirt reference needs to be processed at the coverstitch machine station once it enters the sewing area and if there is a machine available at this station. Once it finishes its process in this station, it must go to the overlocker machine station, to later return to the coverstitch machine station to finally leave the sewing area.

According to the above mentioned, and to assess the *makespan* and TWT values for the current state, the completion time of each job j in each workstation w (C_{jw}) must be computed as shown in the expression (5), where $\min\{C_w\}$ is the minimum completion time among the machines within workstation w, s_{tki} is the sequence-dependent family setup time on machine i, and P_{ji} is the processing time of job j on machine i. The expression defines the C_{jw} as the maximum between the completion time of each job at the previous workstation and the sum of the minimum completion time among the machines within the current workstation and the setup time on any machine at the current workstation, the processing time of jobs on the machines at the workstation must be added.

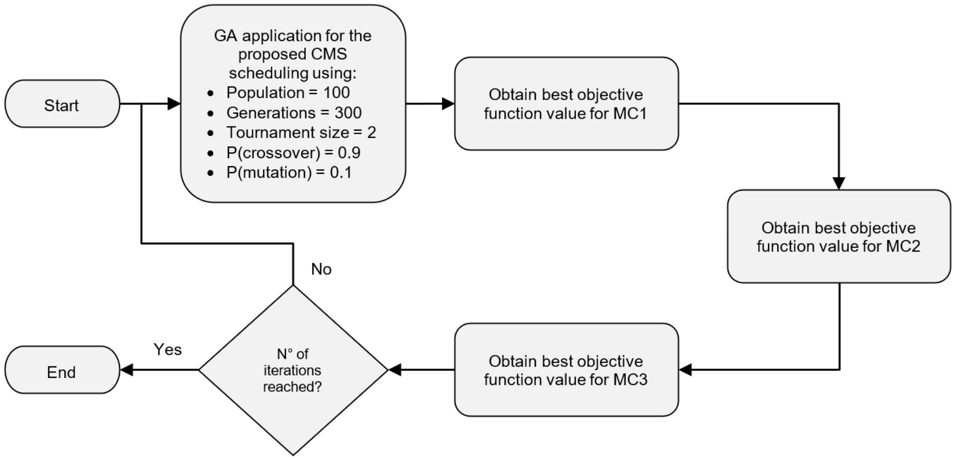
$$C_{jw} = \max\left\{C_{j(w-1)}; \min\left\{C_w\right\} + s_{tki}\right\} + P_{ji} \tag{5}$$

Using the input information from the orders, as mentioned in subsection 3.3, the TWT and *makespan* values were then calculated for the current state, according to the expressions (1) and (3), respectively, considering the computation of the C_{jw} as defined in (5). The results showed a total tardiness penalty cost of COP 180,100 (≈ USD 44.47) and a *makespan* of 60,690 seconds. These results indicate that the current situation in the sewing area of the company causes tardy deliveries of orders, which will eventually impact customer satisfaction, corporate image, and finances, which can be detrimental in the future, especially for a small company. For example, if on an order of 516 jobs, as used in this case, the company loses USD 44.47, and assuming the company processes 100,000 jobs in a year, it could be losing over USD 8,600 in a year in tardy deliveries alone, which is significant, considering the devaluation of the local currency.

4.2 Application of the FSGSP model and GA metaheuristic to the proposed cellular manufacturing approach

The GA developed and validated in subsection 3.2 was applied in five iterations following the procedure shown in Figure 7 and using Python 3.8 on a computer with a 2.2GHz Intel Core i5 processor and 6Gb of RAM. According to the validation process, the method was applied for TWT and makespan objective functions separately and using the GA parameters. The proposed approach was applied to the data collected in subsection 3.3.

Figure 7 Procedure for the GA application to flowshop scheduling in the proposed CMS approach



Source: Authors

The results of applying the proposed approach and procedure for the sportswear manufacturing sewing area are presented in Table 8. The table shows the TWT and *makespan* objective function values for each iteration for the three manufacturing cells of the proposed CMS (MC1, MC2 and MC3). Additionally, the total objective function value is calculated as the sum of the values of the manufacturing cells for the TWT and the maximum value of the manufacturing cells for the *makespan*. Finally, a percentage of change with the objective values for the current state is computed to understand the impact of the proposed approach.

Table 8 Description of the proposed manufacturing cell approach

Iteration	*Objective function value for the proposed CMS**				*% change with the current state*
	MC1	*MC2*	*MC3*	*Total*	
Total weighted tardiness, TWT (In COP)					
0	0	0	0	0	–100%
1	0	0	0	0	–100%
2	0	0	0	0	–100%
3	0	0	0	0	–100%
4	0	0	0	0	–100%
Makespan, C_{max} (In seconds)					
0	13,930	14,082	26,570	26,570	–56.22%
1	13,930	14,082	26,564	26,564	–56.23%
2	13,930	14,082	26,564	26,564	–56.23%
3	13,930	14,082	26,564	26,564	–56.23%
4	13,930	14,082	26,564	26,564	–56.23%

Note: *Best result for each iteration

Source: Authors

4.3 Discussion: comparative analysis of the proposed approach with the current situation

The results presented in the previous subsection show the impact of the proposed CMS for the case of sportswear manufacturing in Cúcuta. The system of three manufacturing cells, formed from the similarity in the sequence of operations of the products and the grouping of products in product families, allowed a 100% reduction in the total tardiness cost for the order reviewed in the case.

When applying the developed and validated GA to the case study data, it was found that the formulation through the flowshop group scheduling with sequence-dependent setup times, permutation and product families impacted the process from the first generations reaching a TWT of zero. It was also found that the implementation of CMS increased the capacity of the sewing area, which can provide the company with the efficiency and productivity needed to compete in today's global markets.

Concerning the *makespan* objective, a reduction of 56.23% was found against the company's current status. This result indicates that the company can decrease the completion time of the last job on the last machine by half. This reduction is achieved because the CMS approach allows to process similar products on certain machines in a flowshop manner, and machine setup times are minimised in the CMS approach.

Optimising *makespan* is important to increase machine utilisation in the sewing area. However, minimising TWT is focused on meeting order due dates and customer satisfaction, so a proper balance must be sought in production scheduling when optimising these objectives for CMS approaches.

The results of the application of the FSGSP presented in this paper for the case of a company in the apparel industry demonstrate the capability of applying optimisation techniques in real industrial contexts. For the apparel and industrial sector in Cúcuta and Colombia, these results should encourage the use of more advanced tools or methods for decision-making in the production areas, especially in companies with processes that have been designed in a traditional way and where decision-making is done empirically. For the literature on the FSGSP, these results add to the current evidence of the impact of optimising production scheduling in conjunction with CMS, as previously proven in other studies (Irani, 1999; Wemmerlöv and Hyer, 1989).

5 Conclusions and future research

This paper presented and evaluated an FSGSP proposal, based on a CMS environment, for the sewing area of a company that produces sportswear for men and women in the case study. The case study company was experiencing problems fulfilling customer orders on time due to 'mudas' such as high machine setup times and low confusing flows in the sewing area, which have impacted the efficiency and productivity of its production system. In this sense, the improvement proposal presented to the company sought to change the current production approach, based on the flexible job shop machine environment, to a flowshop CMS, which takes advantage of the benefits of group technology and decreases machine setup times.

According to the literature review results, the FSGSP models for minimising *makespan,* and TWT were defined. Additionally, the development and validation of a GA metaheuristic to be applied to the solution of these models were performed. The collection of data for the current state of the sewing area of a sportswear manufacturing company in Cúcuta was carried out.

The results showed a 100% improvement in tardiness penalty costs (TWT) for the specific order, while the *makespan* was reduced by 56.23% for the case study's sewing area. These results demonstrate that the proposed manufacturing cell approach based on the FSGSP formulation significantly impacted the performance of the case study's sewing area. This is mainly because the proposed formulation considers similar grouping products into product families to be processed in specific manufacturing cells, thus reducing 'mudas' such as jobs waiting for machines to be available, machine setup times, and inadequate flows in product processing. For this reason, these results are promising for the apparel sector in Cúcuta, other countries and similar industries since this approach can significantly impact the efficiency and productivity of the production system of the companies in this sector, which may improve their competitiveness in local and international markets.

This research presented unique contributions to the knowledge related to applying the FSGSP with sequence-dependent family setup times to a real case of the apparel sector through the proposal of a CMS and the optimisation through a GA. Additionally, the proposed approach and application demonstrated its impact on improving efficiency and productivity in industrial environments. Finally, future research is focused on the design, planning and operation of CMS, considering the formation, layout and scheduling decisions, together with other decisions in the area of operations, in environments of uncertainty, which will bring the proposed formulations closer to industrial realities. Additionally, the proposal of metaheuristic, matheuristic and artificial intelligence techniques that perform better in solving these complex problems in real case studies are of interest for future works.

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