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MULTICRITERIA HYBRID FLOW SHOP SCHEDULING PROBLEM: LITERATURE REVIEW, ANALYSIS, AND FUTURE RESEARCH

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ABSTRACT

This research focuses on the Hybrid Flow Shop production scheduling problem, which is one of the most difficult problems to solve. The literature points to several studies that focus the Hybrid Flow Shop scheduling problem with monocriteria functions. Despite of the fact that, many real world problems involve several objective functions, they can often compete and conflict, leading researchers to concentrate their efforts on the development of methods that take this variant into consideration. The goal of the study is to review and analyze the methods in order to solve the Hybrid Flow Shop production scheduling problem with multicriteria functions in the literature. The analyses were performed using several papers that have been published over the years, also the parallel machines types, the approach used to develop solution methods, the type of method develop, the objective function, the performance criterion adopted, and the additional constraints considered. The results of the reviewing and analysis of 46 papers showed opportunities for future research on this topic, including the following: (i) use uniform and dedicated parallel machines, (ii) use exact and metaheuristics approaches, (iv) develop lower and uppers bounds, relations of dominance and different search strategies to improve the computational time of the exact methods, (v) develop other types of metaheuristic, (vi) work with anticipatory setups, and (vii) add constraints faced by the production systems itself.

Keywords: Production Scheduling; Multicriteria Functions; Hybrid Flow Shop; Literature.

1. INTRODUCTION

Production scheduling is one of the most complex activities in the management of production systems. It is closely connected with the firm's performance in terms of speed, reliability, flexibility, quality, and cost.

The theory of production scheduling, that aims to provide guidelines and methods, for efficient use of resources, has been the subject of countless papers, over the past five decades (MORAIS; MOCCELLIN, 2010). Although several features of scheduling problems are still underexplored due to the variety of production environments, the available resources, restrictions may be imposed and there are multiple objectives to be achieved.

Therefore, this research aims to identify and quantify the published papers that present solution methods for scheduling problems in Hybrid Flow Shop with multicriteria. The results, of this research, may be useful for future research, towards the development of new solution methods, and/or for the application of methods investigated in the context of real companies, with this kind of scheduling problem.

In this article, the term multicriteria is used generically to mean two or more criteria (bicriteria, tricriteria, and multicriteria), which are processed simultaneously in the same objective function.

It is noted that this research is dedicated solely to the production scheduling of jobs, not dealing with the production scheduling of batches of jobs.

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This paper is structured in six sections. After the presentation of the context and research objectives, the theoretical framework is explained in Section 2. In Section 3, the research methodology is presented. Then, the papers that present solution methods for the multicriteria Hybrid Flow Shop scheduling problem are cited. An analysis of papers is presented in Section 5; followed by conclusions, and final considerations, in the sixth section.

2. THEORETICAL FRAMEWORK

2.1 Production Scheduling Problem

Production scheduling is one of the activities of the Planning, Programming and Production Control. This is responsible for deciding the allocation of resources (called machines) over time to perform individual items (jobs and/or batch of jobs, called jobs), in order to better meet a predefined set of criteria (BAKER, 1974, MACCARTHY; LIU, 1993, YANG; LIAO, 1999, and PINEDO, 2008).

One can understand the production scheduling as a set of functions of decision-making, involving: i) allocation decisions machines to process jobs over time (Baker, 1974), called schedule (PINEDO, 1995); ii) decisions sequencing jobs (Baker, 1974), called sequence, which correspond to the order in which jobs are processed on a given machine (PINEDO, 1995).

Therefore, a scheduling problem is “a problem of n jobs $\{J_1, J_2, ..., J_j, ..., J_n\}$ that must be processed on m machines available $\{M_1, M_2, ..., M_k, ..., M_m\}$” (FRENCH, 1982, p. 5). I.e., a scheduling problem “…consists of determining the order or sequence in which the machines will process the jobs so as to optimize some measure of performance” (JOHNSON; MONTGOMERY, 1974, p.322).

Due to the complexity related to obtaining and maintaining production schedules in firms, this activity is a major obstacle in the search for a good performance of production processes. In fact, the scheduling problem is among the most difficult problems of resolution (MORAIS; MOCCELLIN, 2010).

Based on MacCarthy; Liu (1993), Allahverdi; Cheng; Kovalyov (2008), and Pinedo (2008), lists the following types of scheduling environments: single machine; parallel machine; flow shop; permutational flow shop; job shop; hybrid flow shop or

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flow shop with multiple machines; hybrid job shop or job shop with multiple machines, and; open shop. Figure 1 presents the relationship between these environments.

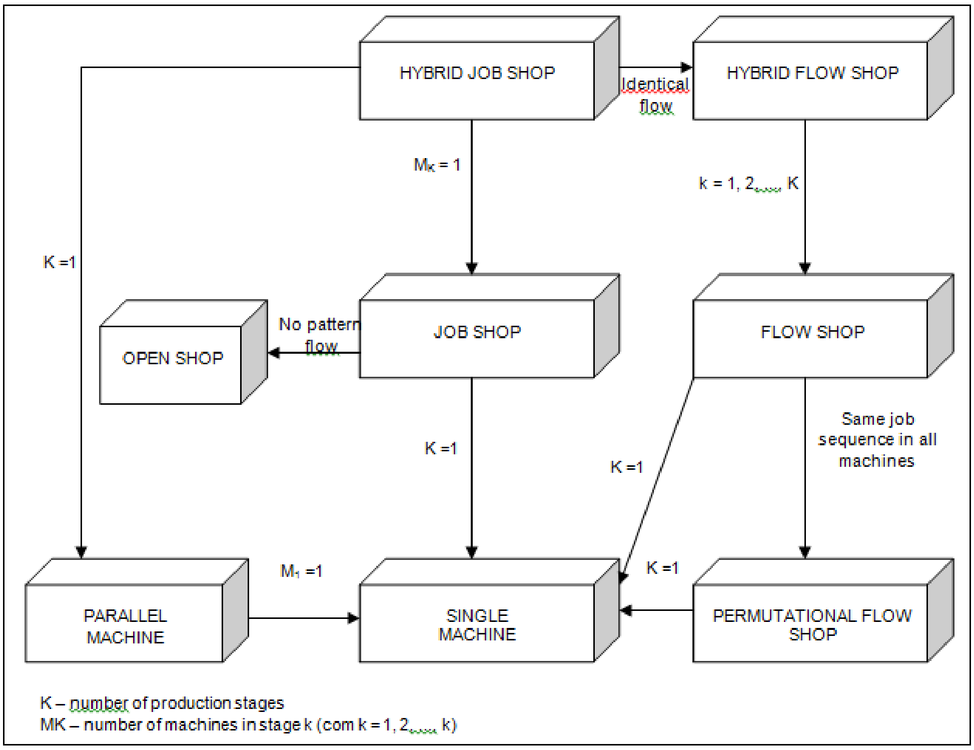

Figure 1: Environments of scheduling and their relationships
Source: MacCarthy; Liu (1993)

This research is dedicated to the Hybrid Flow Shop.

2.2 Hybrid Flow Shop

It is difficult to find a general definition for Hybrid Flow Shop; however, for the purposes of this research, presented by Sethanan (2001) the following is appropriated.

The Hybrid Flow Shop is a type of flow shop in which, at least one of the *k* stages of production, the number of machines is greater than 1 (k < m). In the stages that the number of machines is greater than 1, there are *k* machines or processors in parallel, and each jobs is processed on only one machine stage (SETHANAN, 2001). Figure 2 illustrates the Hybrid Flow Shop scheduling environment.

According to Burtseva; Yaurima; Parra (2010), the possible machine set environments in stage *i* of a Hybrid Flow Shop are the following:

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- Identical (ID) machines in parallel: the m_i machines in the set have the same speed; therefore, job *j* may be processed on any of m_i machines, since the job processing time is the same for all machines;
- Uniformed (UN) machines in parallel: the m_i machines in the set have different speeds; a job *j* may be processed on any machine of a set; however, its processing time is proportional to the machine speed;
- Unrelated (UR) machines in parallel: the m_i machines in the set have different speeds; a job *j* may be processed on any machine of a set; however, its processing time, reveals not to be proportional to the speed of the machine;
- Dedicated (DED) machines in parallel: the m_i machines in the set are dedicated to perform specific jobs, performing specific jobs.

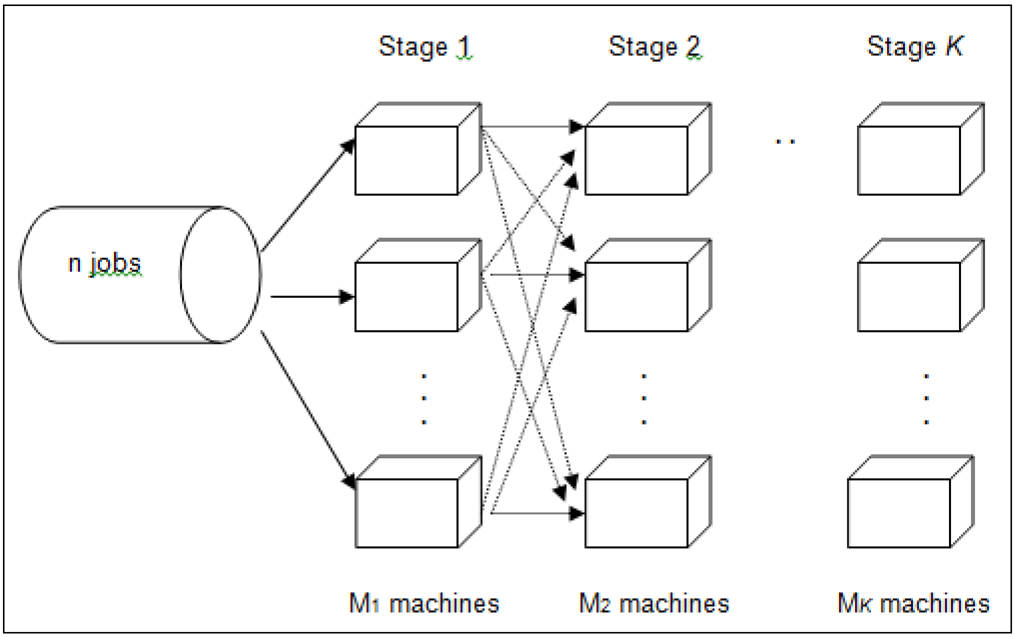

Figure 2: Hybrid Flow Shop scheduling environment
Source: Morais (2008)

2.3 Performance Criteria in Scheduling Problems

The production scheduling is always carried out in order to reach a criterion or set a performance criteria that characterize the nature of the scheduling problem (BOIKO; MORAIS, 2009). Based on French (1982), Bedworth; Bailey (1987), MacCarthy; Liu (1993), Morton; Pentico (1993), and Pinedo (2008), the Table 1 presents the performance criteria, adopted in scheduling problems.

These different performance criteria, according to Baker (1974), relate to three types of decision-making:

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i) Efficient use of resources;

ii) Rapid response to demand, and;

iii) Adaptation to prescribed deadlines of a job that, if reached, cancels the processing that has already been accomplished.

Table 1: Performance Criteria adopted in scheduling problems

Notation	**Description**
C_j	Completion Time of Job
C_{max}	Makespan
$\sum C_i/n$	Mean Completion Time
$\sum C_j$	Completion Time
$\sum w_j C_j$	Weighted Completion Time
E_j	Earliness of JobTotal
$\sum E_j$	Total Earliness
E_{max}	Earliness Maximum
$\sum Ej/n$	Mean Earliness
$\sum w_j E_j$	Weighted Total Earliness
F_j	Flow Time of Job
$\sum F_j/n$	Mean Flow Time
$\sum w_j F_j$	Weighted Total Flow Time
$\sum Lj$	Total Lateness
L_j	Lateness of Job
L_{max}	Lateness Maximum
$\sum L_j/n$	Mean Lateness
$\sum w_j L_j$	Weighted Total Lateness
T_j	Tardiness of Job
$\sum T_j$	Total Tardiness
T_{max}	Tardiness Maximum
$\sum T_j/n$	Mean Tardiness
$\sum w_j T_j$	Weighted Total Tardiness
$\sum U_j$	Number of Late Jobs
$\sum U_j/n$	Mean Number of Late Jobs
W_j	Time to Wait
ΣW_j	Total Time to Wait
W_{max}	Wait Time Maximum
$\sum W_j/n$	Mean Time to Wait
$\sum w_j W_j$	Weighted Total Time to Wait

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Regarding the optimization criteria Lateness and Tardiness, Pinedo (2008) explains the delay of job j (Lateness - L_j) the difference between the completion time of job and its due date, is defined as $L_j = C_j – d_j$, while the delay of job j (Tardiness - T_j) corresponds to the delay in completing the job in relation to its due date. According to Pinedo (2008) Tardines of job is defined as $T_j = max(C_j – d_j, 0) = max(L_j, 0)$. The difference between Tardiness and Lateness lays on the fact that Tardiness is never negative.

In addition to performance criteria, mentioned above, according to Godinho Filho et al. (2013) other criterias have been reported in the literature: Due Date Cost ($\Sigma c_j d_j$); Bottleneck Utilization Rate (BTK); Capacity Utilization Rate (CPT); Inventory Costs (IC); Number of Families (NF); Overtime (OT); Size Buffer (SB); Time Blocking of the Machines (MBT); Total Cost of Opportunity (TCO); Total Cost of Setup (TSC); Total Cost Utility (TCU); Total Idle Time (MIT); Total Setup Time (TST ou ΣSj); Transportation Costs (TC); Work In Process (WIP).

2.4 Constraints in Scheduling Problems

Regarding to the assumptions of scheduling problems, these can be divided into hypotheses about jobs and/or job groups, about machinery and policy operations (GUPTA; STAFFORD, JR., 2006). These assumptions determine the constraints of a specific scheduling problem, in order to make the problem as similar as possible to a real situation.

Based on Allahverdi et al. (1999), Allahverdi et al (2008), and Pinedo (2008), Table 2 presents the constraints that may be incorporated in scheduling problems; as well as the notation adopted in this article to describe these constraints.

In addition to these constraints, single machine is a special case in which many stages (not all) in a Hybrid Flow Shop can have only one machine (BURTSEVA; YAURIMA; PARRA, 2010); this environment is termed as Hybrid Flow Shop with a dominant stage (MORAIS; GODINHO FILHO; BOIKO, 2013).

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Table 2: Constraints incorporated in scheduling problems.

Notation	Description
Batch	Batch jobs
Bfr	No intermediate buffers
Bkdwn	Breakdown
Block	Blocking
Btlck	Bottleneck resource
Com_d_j	Common due dates
Diff_d_j	Different due dates
Diff_r_j	Different release dates
Dyn_arr	Dynamics arrivals of jobs
H_Fin	Finite planning horizon
L_WT	Limited waiting time
$Lost_{op}$	Lost operations
Lrem	Level of remaining resources
Maint	Maintenance
Ntw	No-Wait
Prec	Precedence
Prmp	Preemptions
Reentrant	Reentrant flow
Removal	Removal times
Skp	Skip stages
Stoc_dj	Stochastic due dates
ST_{sd}-AS	Sequence-dependent setup and anticipatory
ST_{sd}-NS	Sequence-dependent setup and non-anticipatory
Stsi-AS	Sequence-independent setup and anticipatory
St_{si}-NS	Sequence-independent setup and non-anticipatory
Transport	Transport times

2.5 Solution Methods

Since the pioneering work of Johnson, published in 1954 (JOHNSON, 1954), many solution methods have been developed to solve the scheduling problems in many different types of scheduling environments.

According to Yenisey; Yagmahan (2014), the solution methods for scheduling problems can be categorized into:

- Optimum or exact methods: methods that generate an optimal schedule, according to the performance criterion adopted; mathematical models and specific algorithms are used to solve problems, and obtain an optimal solution, as it adds Pereira (2011);

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- Approximate methods: methods that seek to achieve a feasible solution close to the optimum in a reasonable computational time; can be classified, according to Yenisey; Yagmahan (2014), into heuristic and metaheuristic.

The use of optimum methods is justified when dealing with small problems; the solution for problems, using optimum methods, usually demand high computational time, making the search for optimal solutions not viable (PEREIRA, 2011). Thus, Yenisey; Yagmahan (2014) add that, the optimum methods become inefficient for large problems, since they have many jobs, machines and goals, and are combinatorial optimization problems from NP-hard problems class. Arenales et al. (2007) emphasize that the development of integer programming softwares, such as CPLEX, XPRESS, and LINDO, has improved their ability to solve large problems. The Branch-and-Bound (B&B) method is the approach, according to Yenisey; Yagmahan (2014), most commonly, used to obtain optimal solutions. Arenales et al. (2007) also points the Branch-and-Cut (B&C), Gomory, Benders, Dantzig-Wolf, and Lagrangian Relaxation to obtain optimal solutions.

Heuristics are methods that generate a schedule of good quality at a reasonable computational time, with no guarantee of optimality. Solutions obtained by heuristics can be used as an initial solution in improving heuristics and metaheuristics. According to Souza; Moccellin (2000) heuristics can be subclassified into:

- Constructive heuristic: the schedule, adopted as the problem solution, is obtained: i) directly from the ordering of jobs by priority indexes, calculated according to the processing times of the jobs; ii) by sorting the best schedule jobs, from a set of schedules obtained, also using priority indexes associated with the jobs, or; iii) from the successive generation of partial schedules jobs, to obtain a complete schedule through some criterion insertion of jobs, and;
- Improvement heuristic: the schedule, adopted as the problem solution, is obtained from initial solutions that, through some iterative procedure (usually involving exchanges of positions jobs in original schedule), are improved, seeking to achieve a better solution, than the current one, according as the performance criterion adopted.

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- Metaheuristics are procedures that coordinate local search strategies at a higher level, creating a process to avoid local minimum, conducting a search of the most robust solution to a problem (GLOVER; KOCHENBERGER, 2003); although there is no consensus in the literature concerning a standard subclassification of metaheuristic, this can be used (PEREIRA, 2011; OLIVEIRA, 2008; and SERAPIÃO, 2009):

- Metaheuristics of relaxation: "…procedures to solve problems with modifications to the original model, the generated solution provides the solution to the original problem." (PEREIRA, 2011, p. 6). This kind of metaheuristics simplifies the real problem, removing and modifying some restrictions of it (OLIVEIRA, 2008).

- Metaheuristics of neighborhood search: "… procedures that run search spaces, which should be considered at each step, the neighborhood of the solution obtained in the previous interaction." (PEREIRA, 2011, p. 16); e.g., according to Blum; Roli (2003), Dreo et al. (2007) and Yenisey; Yagmahan (2014) are: Greedy Randomized Adaptive Search Procedure (GRASP); Tabu Search (TS); Guided Local Search (GLS), Iterated Local Search (ILS), Local Search (LS), and, Variable Neighborhood Search (VNS).

- Metaheuristics based on evolutionary methods: "…procedures focused on sets of solutions that evolve in this space." (PEREIRA, 2011, p. 16); e.g., according to Dreo et al. (2007), Simon (2013) and Yenisey; Yagmahan (2014) : Genetic Algorithm (GA); Estimation of Distribution Algorithm (EDA); Differential Evolution (DE); Memetic Algorithm (MA); Simulated Annealing (SA); Scarter Search (SS); Artificial Immune System (AIS); Colonial Competitive Algorithm (CCA);.and Harmorny Search Optimization (HSO),

- Metaheurisitcs based on swarm intelligence: procedures based on swarm intelligence include any attempt to design algorithms in order to solve problems inspired by the collective behavior of social insects and other animal societies (BONABEAU; DORIGO; THERAULAZ, 1999). Examples of methods based on swarm intelligence are: Ant Colony Optimization (ACO); Particle Swarm Optimization (PSO); Artificial Bee Colony (ABC); Firefly Algorithm (FA);

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Shuffled Frog-Leaping (SFL); and Bacterial Foraging Optimization (BFO) (SERAPIÃO, 2009 and RUIZ-VANOYE, 2012);

- Hybrids metaheuristics: "…procedures that combine two or more metaheuristics and uses search strategies." (PEREIRA, 2011, p. 16).

Boschetti et al. (2009) adds and emphasizes the use of hybrid methods or matheuristics, algorithms that are developed from the interoperation of metaheuristics and mathematical programming techniques.

3. RESEARCH METHODOLOGY

The methods qualitative and quantitative were used in this research. For the purpose, this research was classified as descriptive, explanatory, methodological, and as bibliographical.

The databases used in the literature review were: Compendex; Digital Library of Theses and Dissertations; DOAJ; Emerald; Hindawi, Open J-Gate; IEEE Xplore; Science Direct; Web of Knowledge; Scielo and; Brazilian Digital Library (BDTD); Scirus, and; Scopus. The keywords used were: flow shop; hybrid flow shop; flexible flow shop; multiple machines flow shop; flow shop with multiple machines; bi-objective; tri-objective, multi-objective; bicriteria; tricriteria, and; multicriteria. An extensive combination of keywords was also used to identify the published papers. A time limitation has not been established.

For each paper, the following topics were reviewed:

i) The machine set environments in Hybrid Flow Shop considered: identical (ID); uniform (UN); unrelated (UR), or; dedicated (DED);

ii) The performance criteria adopted;

iii) The considered constraint(s);

iv) Objective function used: bicriteria; tricriteria; multicriteria;

v) Solution method(s) developed, in terms of:

- Methods categories: optimum methods; approximate methods;
- Approximate methods classification: heuristic; metaheuristic;
- Heuristics subclassification: constructive; improvement;

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- Metaheuristics subclassification: neighborhood search; evolutionary; swarm intelligence; hybrids;
- Optimum method type developed;
- Metaheuristic type developed.

Analyses were made based on the number of publications and percentage of occurrence.

In the review, only papers that consider the performance criteria simultaneously, in the same objective function, were reviewed.

4. MULTICRITERIA HYBRID FLOW SHOP SCHEDULING PROBLEM: LITERATURE REVIEW

A literature review on the development of solution methods for the bicriteria, and multicriteria scheduling problem was presented by Nagar, Heragu & Haddock (1995); but, the authors did not identify the publications addressing the Hybrid Flow Shop scheduling problem.

Several papers that address the Hybrid Flow Shop scheduling problem with two or more performance criteria have been identified, however, many of these papers deal with the development and analysis methods for each criterion separately.

In the review, 46 articles that simultaneously consider the performance criteria found: Hayrinen et al. (2000); Liu; Chang (2000); Janiak; Lichteinsten (2001); Gupta et al. (2002); Tang et al. (2002); Lin; Liao (2003); Jungwattanaki et al. (2005); Quadt; Kuhn (2005); Sawik (2005); Akrami; Karimi; Hosseini (2006); Torabi; Fatemi-Ghomi; Karimi (2006); Janiak et al. (2007); Jenabi et al. (2007); Jungwattanaki et al. (2007); Quadt; Kuhn (2007); Sawik (2007); Xuan; Tang (2007); Fakhrzad; Heydari (2008); Jungwattanaki et al. (2008); Khalouli; Ghedjati; Hamzaoui (2008); Mahdavi et al. (2008); Behnamian; Fatemi Ghomi; Zandieh (2009); Davoudpour; Ashrafi (2009); Jungwattanaki et al. (2009); Naderi; Zandieh; Roshanaei (2009); Naderi et al. (2009), Weng; Fujimura (2009a); Weng; Fujimura (2009b); Behnamian; Zandieh; Fatemi Ghomi (2010); Dugardin; Yalaoui; Amodeo (2010); Karimi; Zandieh; Karamooz (2010); Khalouli; Ghedjati; Hamzaoui (2010); Li; Wang; Huo (2010); Rashidi; Jahandar; Zandieh (2010); Behnamian; Zandieh (2011); Cho et al. (2011); Li et al.

(2011); Mousavi; Zandieh; Amiri (2011); Pereira (2011); Zandieh; Karimi (2011); Han et al. (2012); Weng; Wei; Fujimura (2012); Bozorgirad; Logendran (2013); Ebrahiny; Fatemi Ghomi; Karimi (2013); Fadaei; Zandieh (2013); and Jolai et al. (2013).

In addition to what was related above, Sang (2013) points out problems on the mixed integer programming model to Hybrid Flow Shop scheduling proposed by Behnamian; Zandieh (2011). Tables 3: summarizes the main points reviewed in every paper.

Table 3: Papers that presents solution methods for multicriteria Hybrid Flow Shop scheduling problem – Review Summary

Papers	**The machine set environments**	**Performance Criterions**	**Constraints**	**Objective Function**	**Solution methods**	
					Category and Classification	**Sub Classification or Type**
Hayrinen et al. (2000)	UR	$\sum T_j$; $\sum W_j$; IBS; NF	ST_{sd}-NS $Lost_{op}$	Multicriteria	- Approximate: i) Heuristic	i) Improvement
Liu; Chang (2000)	ID	TST; TSC	ST_{sd}-NS	Bicriteria	- Optimum	MIP and Rel_Lag
Janiak; Lichteinsten (2001)	ID	$\sum w_jE_j$; $\sum w_jT_j$; $\sum w_jW_j$	-	Tricriteria	- Approximate: i) Heuristic	i) Constructive
Gupta et al. (2002)	ID	$\sum E_j$; $\sum T_j$; C_{max}; $\sum c_jd_j$	-	Multicriteria	- Approximate: i) Heuristic; ii) Metaheuristic	i) Constructive; ii) Neighborhood Search: LS
Tang et al. (2002)	ID	$\sum w_jE_j$; $\sum w_jT_j$	Batch Prec ST_{si}-NS Removal	Bicriteria	- Optimum; - Approximate: i) Heuristic	MIP and Rel_Lag/PD i) Improvement
Lin; Liao (2003)	DED	$\sum W_j$; $\sum OT$	Batch ST_{sd}-NS	Bicriteria	- Approximate: i) Heuristic	i) Improvement
Jungwattanaki et al. (2005)	UR	C_{max}; $\sum U_j$	ST_{sd}-NS	Bicriteria	- Approximate: i) Heuristic; ii) Metaheuristic	i) Constructive; ii) Evolutionary: GA and SA
Quadt; Kuhn (2005)	ID	TSC; IC; $\sum c_jU_j$; $\sum F_j/n$	Batch	Multicriteria	- Approximate: i) Heuristic	i) Constructive
Sawik (2005)	ID	$\sum U_j$; $\sum T_j$; T_{max}; TWR	Batch Zbfr H_Fin	Multicriteria	- Optimum	MIP
Akrami; Karimi; Hosseini (2006)	ID	TSC; $\sum F_j/n$	Batch ST_{si}-NS Zbfr H_Fin	Bicriteria	- Optimum - Approximate: i) Metaheuristc	MIP i) Neighborhood Search: TS; and Evolutionary: GA
Torabi; Fatemi-Ghomi; Karimi (2006)	ID	TST; TC; WIP; IC	Batch ST_{si}-NS H_Fin	Multicriteria	- Optimum - Approximate: i) Metaheuristc	MIP i) Evolutionary: GA
Janiak et al. (2007)	ID	$\sum w_jE_j$; $\sum w_jT_j$; $\sum w_jW_j$	-	Tricriteria	- Approximate: i) Metaheuristc	MIP i) Neighborhood Search :TS; Evolutionary:

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						SA; and Hybrid: TS/SA
Jenabi et al. (2007)	UR	TST; CE	Batch ST_{si}-NS H_Fin Skp_Stage	Bicriteria	- Optimum - Approximate: i) Heuristic; ii) Metaheuristc	MIP i) Constructive ii) Hybrid: GA/SA
Jungwattanaki et al. (2007)	UR	C_{max}; $\sum U_j$	ST_{sd}-NS	Bicriteria	- Approximate: i) Heuristic;	i) Constructive
Quadt; Kuhn (2007)	ID	TSC; $\sum F_j/n$	Batch ST_{si}-AS Skp_Stage	Bicriteria	- Approximate: i) Metaheuristc	i) Evolutionary: GA
Sawik (2007)	ID	$\sum U_j$; CPT	Zbfr H_Fin	Bicriteria	- Optimum - Approximate: i) Heuristc	MIP i) Contructive
Xuan; Tang (2007)	ID	$\sum w_jC_j$; $\sum w_jW_j$	ST_{si}-NS Transport $Lost_{op}$ Prec	Bicriteria	- Optimum	Rel_Lag
Fakhrzad; Heydari (2008)	ID	$\sum c_jE_j$; $\sum c_jT_j$	ST_{si}-NS Btlck Lrem	Bicriteria	- Optimum - Approximate: i) Heuristc; ii) Metaheuristic	MIP i) Constructive ii) Neighborhood Search: TS; Evolutionary: SA; and Hybrid: SA/TS
Jungwattanaki et al. (2008)	UR	C_{max}; $\sum U_j$	ST_{sd}-NS Diff_rj	Bicriteria	- Approximate: i) Heuristc; ii) Metaheuristic	i) Constructive ii) Evolutionary: GA
Khalouli; Ghedjati; Hamzaoui (2008)	ID	$\sum w_jE_j$; $\sum w_jT_j$	-	Bicriteria	- Approximate: i) Metaheuristic	i) Swarm Intelligence: ACO
Mahdavi et al. (2008)	ID	$\sum w_jT_j$; $\sum w_jL_j$	Batch ST_{si}-NS	Bicriteria	- Optimum - Approximate: i) Metaheuristic	MIP i) Evolutionary: GA
Behnamian; Fatemi Ghomi; Zandieh (2009a)	ID	C_{max}; $\sum L_j$; $\sum T_j$	ST_{sd}-NS	Tricriteria	- Approximate: i) Metaheuristic	i) Hybrid: GA/LS/SA/VNS
Behnamian; Zandieh; Fatemi Ghomi (2009b)	ID	$\sum E_j$; $\sum T_j$	Batch ST_{sd}-NS Window_dj	Bicriteria	- Approximate: i) Metaheuristic	i) Neighborhood Search: VNS; and Evolutionary: SA; and Swarm Intelligence: PSO
Davoudpour; Ashrafi (2009)	ID	T_{max}; $\sum C_j$; L_{max}; $\sum w_jT_j$	ST_{sd}-NS Diff_r_j	Multicriteria	- Approximate: i) Metaheuristic	i) Neighborhood Search: GRASP
Jungwattanaki et al. (2009)	UR	C_{max}; $\sum U_j$	ST_{sd}-NS Skp_Stage	Bicriteria	- Approximate: i) Heuristic; ii) Metaheuristic	i) Constructive ii) Neighborhood Search: TS; and Evolutionary: GA and SA.

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Naderi; Zandieh; Roshanaei (2009)	ID	C_{max}; T_{max}	ST_{sd}-NS	Bicriteria	- Approximate: i) Metaheuristic	i) Hybrid: SA/LS
Naderi et al. (2009)	ID	C_{max}; $\sum T_j$	ST_{sd}-NS Transport	Bicriteria	- Approximate: i) Metaheuristic	i) Hybrid: SA/LS
Weng; Fujimura (2009a)	UR	$\sum E_j$; $\sum T_j$	-	Bicriteria	- Approximate: i) Heuristic	i) Improvement
Weng; Fujimura (2009b)	ID	$\sum w_jE_j$; $\sum w_jT_j$	-	Bicriteria	- Approximate: i) Heuristic	i) Constructive
Dugardin; Yalaoui; Amodeo (2010)	ID	BTK; C_{max}	Dom_Estage Reentrant	Bicriteria	- Approximate: i) Metaheuristic	i) Evolutionary: GA
Karimi; Zandieh; Karamooz (2010)	ID	C_{max}; $\sum T_j$	Batch ST_{sd}-NS Skp_Stage	Bicriteria	- Approximate: i) Metaheuristic	i) Evolutionary: GA
Khalouli; Ghedjati; Hamzaoui (2010)	ID	$\sum w_jE_j$; $\sum w_jT_j$	-	Bicriteria	- Approximate: i) Metaheuristic	i) Swarm Intelligence: ACO
Li; Wang; Huo (2010)	ID	$\sum W_j$; MIT	ST_{sd}-NS	Bicriteria	- Approximate: i) Metaheuristic	i) Evolutionary: GA
Rashidi; Jahandar; Zandieh (2010)	UR	C_{max}; T_{max}	ST_{sd}-NS Block	Bicriteria	- Approximate: i) Metaheuristic	i) Evolutionary: GA
Behnamian; Zandieh (2011)	ID	$\sum E_j$; $\sum T_j^2$	ST_{sd}-NS L_WT	Bicriteria	- Optimum - Approximate: i) Metaheuristic	MIP i) Evolutionary: CCA
Cho et al. (2011)	ID	C_{max};$\sum T_j$	Reentrant	Bicriteria	- Approximate: i) Metaheuristic	i) Evolutionary: GA
Li et al. (2011)	ID	C_{max};$\sum T_j$	ST_{sd}-NS	Bicriteria	- Approximate: i) Metaheuristic	i) Evolutionary: GA
Mousavi; Zandieh; Amiri (2011)	ID	C_{max};$\sum T_j$	ST_{sd}-NS	Bicriteria	- Approximate: i) Metaheuristic	i) Neighborhood Search: VNS
Pereira (2011)	ID	$\sum w_jE_j$; $\sum w_jT_j$	ST_{sd}-NS Diff_r_j	Bicriteria	- Optimum - Approximate: i) Metaheuristic	MIP i) Neighborhood Search: ILS; Evolutionary: GA ; and Hybrid: GA/LS
Zandieh; Karimi (2011)	ID	$\sum w_jT_j$; C_{max}	Batch ST_{sd}-NS	Bicriteria	- Optimum - Approximate: i) Metaheuristic	MIP i) Evolutionary: GA
Han et al. (2012)	ID	$\sum w_jE_j$;$\sum w_jT_j$	-	Bicriteria	- Approximate: i) Metaheuristic	i) Hybrid: PSO/DE
Weng; Wei; Fujimura (2012)	UR	$\sum E_j$; $\sum T_j$	Dyn_Arr	Bicriteria	- Approximate: i) Heuristic	i) Constructive
Bozorgirad; Logendran (2013)	UR	WIP; $\sum T_j$	Batch ST_{sd}-NS	Bicriteria	- Optimum - Approximate: i) Metaheuristic	MIP i) Neighborhood Search: TS

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Ebrahiny; Fatemi Ghomi; Karimi (2013)	ID	C_{max};$\sum T_j$	ST_{sd}-NS Stoc_d_j	Bicriteria	- Approximate: i) Metaheuristic	i) Evolutionary: GA
Fadaei; Zandieh (2013)	ID	C_{max}; $\sum T_j$	Batch ST_{sd}-NS	Bicriteria	- Approximate: i) Metaheuristic	i) Evolutionary: GA
Jolai et al (2013)	ID	C_{max};T_{max}	No-wait	Bicriteria	- Optimum - Approximate: i) Metaheuristic	MIPi) Evolutionary: SA

5. MULTICRITERIA HYBRID FLOW SHOP SCHEDULING PROBLEM: LITERATURE ANALYSES

Methods for the multicriteria Hybrid Flow Shop (HFS) were found in 46 papers.

Figure 3 shows the number of papers published per year, and Figure 4 shows the evolution of research in multicriteria HFS scheduling problem.

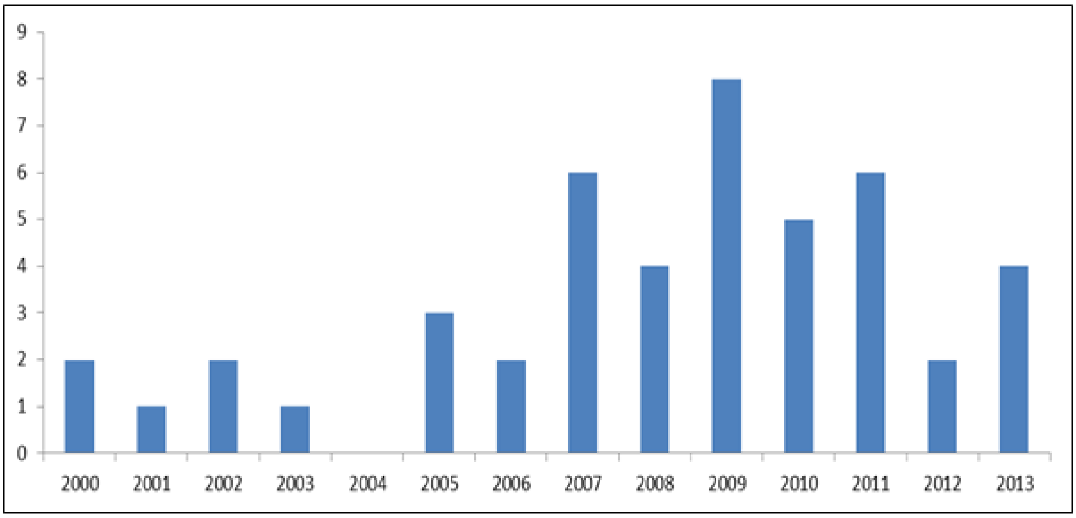

Figure 3: Number of publicarions per year in multicriteria HFS scheduling problem

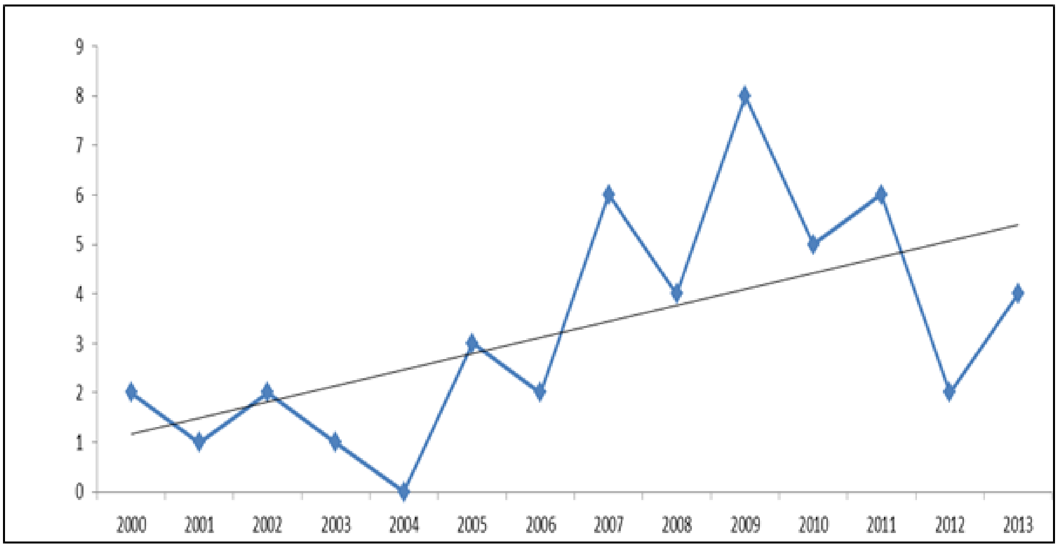

Figure 4: Evolution of research in multicriteria HFS scheduling problem

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When analyzing Figure 4, it can be seen that, although in some years the number of publications decreased, there is a growth trend in the researches in multicriteria HFS.

Regarding to the machine set environments in HFS considered, as shown in Figure 5, in most papers (85%), the identical parallel machines environment is adopted; in 10 (13%), the unrelated parallel machines environment is adopted, and; in only 1 paper (2%), the dedicated parallel machines environment is adopted. Figure 5 shows the percentage of use of the different types of parallel machines in developing solution methods for the multicriteria Hybrid Flow Shop.

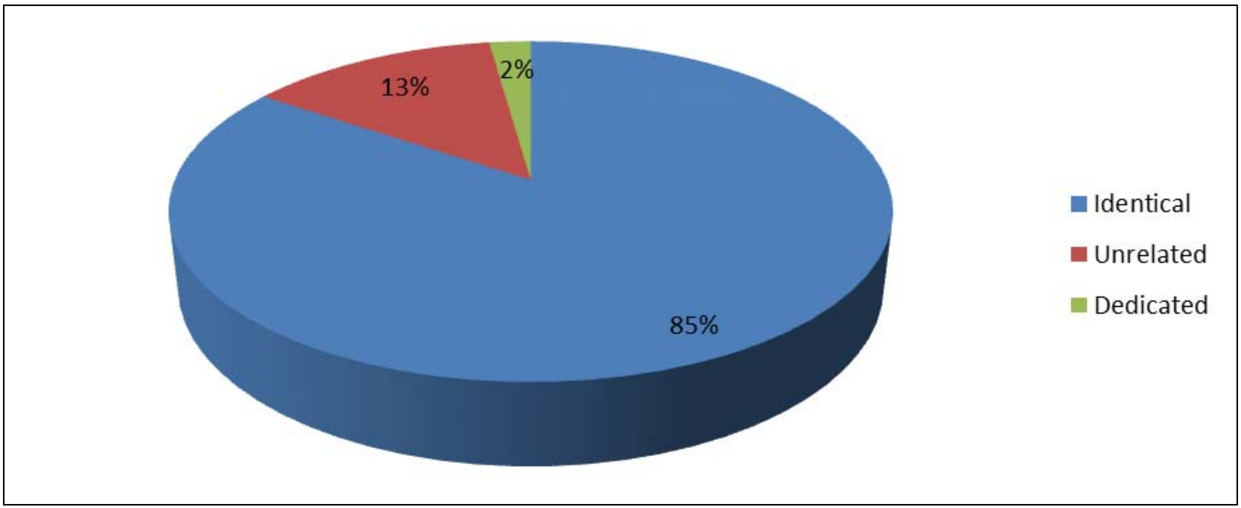

Figure 5: Machines types in parallel used for developing solution methods for multicriteria HFS

Restrictions are present in 38 papers (82.60%):

- Setup times restrictions are the ones that appears more, being considered in 81.57% (31 papers) of these papers; dependent and non-anticipatory setup are present in 23 works (74.19% of papers with setup times restrictions); while independent and non-anticipatory setup are present in 7 works (22.59% of papers with setup times restrictions); of papers with setup times restrictions, only Quadt; Kuhn (2007) investigate the development of solution methods with anticipatory setup;
- Batch sizes and scheduling restrictions are present in 36.84%;
- Finite horizon scheduling restrictions, in 13.15%;
- Jobs that can skip stages restrictions are considered in 10.52%;

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- Limited buffers and different release dates restrictions appear in 7.89%;
- Lost operations, precedence, transport time, and reentrant flow restrictions are present in 5.26% of papers each;
- Blocking, removal times, no-wait, stochastic due dates, window due dates, remaining level of resources, resource bottleneck, dominant stage, dynamic arrival of jobs, and limited waiting time restrictions were seen in 2.63% of the papers each.

From the 46 papers, 37 papers (80.43%) address the development of methods with bicriteria function; 3 papers (6.52%) work with the development of methods with a tricriteria function, and; 6 papers (13.04%) address the development of methods with multicriteria function.

Concerning the bicriteria functions, performance criteria related to delayed jobs (ΣT_j, $\Sigma w_j T_j$, T_{max}, ΣU_j, and ΣW_j), combined with other criteria, appear in 19 papers (51.35%); Makespan (C_{max}) is present in 16 papers (43,24%); the criteria oriented just-in-time scheduling ($\sum w_j E_j$ and $\sum w_j T_j$, $\sum T_j$ and $\sum E_j$, $\sum c_j E_j$, and $\sum c_j T_j$) appear in 12 papers (35.29%); Total Setup Cost (TSC) criteria are present in 3 papers (8.10%); Total Setup Time (TST) and Mean Flow Time ($\sum F_j/n$) are adopted in 2 papers each (5.40%); others criteria, as Bottleneck Utilization Rate (BTK), Capacity Utilization Rate (CPT), Inventory Cost (IC), Overtime (OT), Total Idle Time (MIT), and Work-In-Process (WIP) appear in 1 paper each (2.70%).

Regarding the tricriteria functions, earliness, tardiness, and waiting time ($\sum w_j E_j$, $\sum w_j T_j$ and $\sum w_j W_j$) criteria appear in 2 papers simultaneously (66.66%); Lateness, makespan, and Tardiness (C_{max}, $\sum L_j$ and $\sum T_j$) are present in 2 papers simultaneously (33.33%).

In the papers that adopt a multicriteria function, the following performance criteria are considered: Internal Buffer Size (IBS); Inventory Cost (IC); Lateness Maximum (L_{max}); Makespan (C_{max}); Maximum Tardiness (T_{max}); Mean Flow Time ($\sum F_j/n$); Number of Families (NF); Number of Late Jobs (ΣU_j); Tardy Work Ratio (TWR); Total Completion Time (ΣC_j); Total Earliness ($\sum E_j$); Total Lateness (ΣLj); Total Setup Cost (TSC); Total Setup Time (TCT); Total Tardiness (ΣT_j); Total Waiting ($\sum W_j$); Transport Cost (TC); Weighted Due Date of Jobs ($\Sigma c_j d_j$); Weighted Number of

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Late Jobs (Σc_jU_j); Weighted Total Tardiness (Σw_jT_j), and; Work-In-Process (WIP). The performance criteria related to delayed or advances of jobs (ΣT_j, Σw_jT_j, T_{max}, L_{max}, ΣE_j, ΣU_j and ΣW_j), combined with others criteria, stand out as the performance criteria most frequently adopted (83.33%).

Regarding the solution methods developed, in terms of methods categories, it was found that 30 papers (65.21%) presents approximate methods; 3 papers (6.52%) presents optimum methods, and; 13 (28.26%) presents methods in both categories.

It stands out that, several papers that present methods in both categories, do not address the development of optimum methods. These papers present only mixed integer programming formulations, that are solved by specific solvers (i.e., CPLEX), and their results provide parameters to evaluate the approximate methods developed.

Considering both papers that describe only the approximate methods as those present methods in both categories, the vast majority develop metaheuristics, present in 33 papers (71.73%); heuristics appear in 16 (34.78%).

Concerning the heuristics subclassification, from the 16 papers, that investigates the development of heuristics, 12 papers (75%) deal with the development of constructive heuristics, and; 4 (25%) deal with the development of improvement heuristics.

Concerning the metaheuristic subclassification, from the 33 papers that present metaheuristics, 10 papers (30.30%) present metaheuristics of neighborhood search; 21 (63.63%) presents metaheuristics based on evolutionary methods; 3 (9,09%) presents metaheuristics based on swarm intelligence; and; 8 papers (24.24%) presents hybrids metaheuristics.

From the papers which present metaheuristics, it was observed that several papers develop more than one type of method; the Genetic Algorithm stands out as one of the methods that is most often adopted, being present in 19 papers (57.57%); Simulated Annealing appears in 10 papers (30.30%); Tabu Search appear in 5 (15.15%); Local Search in 5 (15.15%); Variable Neighborhood Search appears in 3 papers (9,09%); Ant Colony Optimization, and Particle Swarm Optimization appear in 2 papers each (5,88%), and; Colonial Competitive Algorithm, Differential Evolution,

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Greedy Randomized Adaptive Search Procedure, and Iterated Local Search appear in 1 each (6.06%).

In relation to papers that address the development of hybrids metaheuristics, solution methods that combine Tabu Search and Simulated Annealing are presented by Janiak et al (2007), and Fakhrzad; Heydari (2008); Local Search combined with Simulated Annealing is presented by Naderi; Zandieh; Roshanaei (2009), and Naderi et al. (2009); Local Search combined with Genetic Algorithm is presented by Pereira (2011); Genetic Algorithm with Simulated Annealing is presented by Jenabi; Fatemi Ghomi; Karimi (2007); Genetic Algorithm with Local Search, Simulated Annealing and Variable Neighborhood Search is presented by Behanamian; Fatemi Ghomi; Zandieh (2009); one solution method that combines Swarm Optimization with Differential Evolution is presented by Han et al. (2012).

Concerning the optimum method type, from the 15 papers, 12 papers (80%) present and discuss the development of methods based only on programming linear and non-linear mathematical formulations, according to the characteristics of the problems under study; only 3 papers (20%) present mathematical formulations and discuss the development of methods based on Lagrangian Relaxation and Dynamic Programming.

Figure 6 shows the percentage of papers by solution method(s) developed.

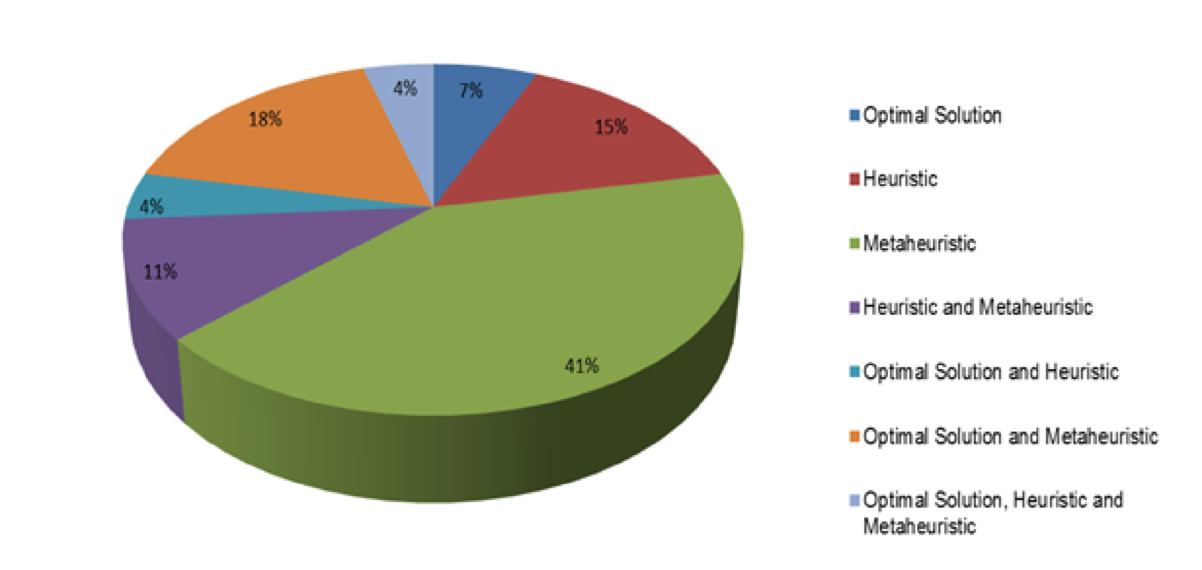

Figure 6: Multicriteria Hybrid Flow Shop scheduling problem – Percentage of papers by solution method(s) developed

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6. CONCLUSIONS

This article reviews the literature for multicriteria Hybrid Flow Shop (HFS) scheduling problem. 46 articles, published between 2000 and 2013, were found.

The papers were reviewed in terms of the following: the machine set environments in HFS considered; performance criteria adopted; constraint(s) considered; objective function used, and; solution method(s) developed, in terms of methods categories, approximate methods classification, heuristics subclassification, metaheuristic subclassification, optimum method type developed, and metaheuristic type developed.

The analysis on the number of publications over the years shows that there is a trend of growth in the researches in multicriteria HFS scheduling problem. It was not possible to compare the percentage growth in the number of papers published for decades, because the first paper addressing this problem was published in 2000.

Regarding to the machine set environments in HFS considered, identical parallel machine is present in ~~the~~ most papers; only 1 paper treats the HFS scheduling problem with dedicated parallel machines, and; uniform parallel machines are not treated in any article. In practice, with the exception of newly installed plants, the presence of identical parallel machines is not observed with frequency; since the acquisition of machinery in different periods of time, the technological innovations have caused improvements in the capabilities of the same.

The results also showed that, most of the papers are devoted to development of metaheuristics solution methods. Among the metaheuristics, the development of Genetic Algorithms and their variations stands out.

Regarding papers that present heuristics, it was found that constructive heuristics are the focus of a considerable percentage of them.

Among all the papers that present optimum methods, none of them dealt with the development of lower and upper bounds, dominance relationships and search strategies.

In respect of performance criteria the presence of multiple goals in real production environments were considered. Despite the fact that studies, considering more than two performance criteria in the development of solution methods for the

HFS scheduling problem were found. Only 9 papers (19.56% of works) adopted three or more performance criteria in the objective function.

The performance criteria related to delayed jobs (ΣT_j, $\Sigma w_j T_j$, T_{max}, ΣU_j and ΣW_j) stands out as one of the performance criteria that are most often adopted. The criteria oriented just-in-time scheduling ($\sum w_j E_j$ and $\sum w_j T_j$, $\sum T_j$ and $\sum E_j$, $\sum c_j E_j$ and $\sum c_j T_j$) and were also present in a large number of papers.

Notably, the vast majority of papers include constraints; however, many constraints were not investigated. A new research that considers several constraints is needed, to diminish the gap between the real-world industrial scheduling problems and their treatment in the literature. The most common restrictions are setup times. However, only one paper deals with anticipatory setups.

The analyzes show that, future research may follow different approaches: i) focus on the multicriteria HFS scheduling problems with uniformed and/or dedicated machines in parallel; ii) develop optimum methods to solve multicriteria HFS scheduling problems; iii) develop metaheuristics to solve multicriteria HFS scheduling problems and still not very addressed in literature, such as metaheuristics based on computation evolutionary and swarm intelligence; iv) develop lower bounds and uppers bounds, relations of dominance and different search strategies to obtain solutions for large multicriteria HFS scheduling problems, with reduced computational time; v) investigate the multicriteria HFS scheduling problems with several constraints, present in industries real-world and ignored in the literature, such as anticipatory setups.

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