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Stochastic flexible flow shop scheduling problem under quantitative and qualitative decision criteria

Eliana María González-Neira [a,c,*], Rafael Guillermo García-Cáceres [b], Juan Pablo Caballero-Villalobos [a], Lina Paola Molina-Sánchez [a], Jairo R. Montoya-Torres [d]

[a] Departamento de Ingeniería Industrial, Facultad de Ingeniería, Pontificia Universidad Javeriana, Cra. 7 No. 40-62 – Edificio José Gabriel Maldonado, Bogotá, Colombia
[b] UNIAGUSTINIANA, Avenida Ciudad de Cali # 11B – 95, Bogotá, Colombia
[c] Escuela Internacional de Ciencias Económicas y Administrativas, Universidad de La Sabana, Km 7 autopista norte de Bogotá, D.C., Chía, Colombia
[d] School of Management, Universidad de los Andes, Calle 21 # 1-20, Bogotá, D.C., Colombia

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ABSTRACT

This paper addresses a bi-criteria stochastic flexible flow shop (SFFS) scheduling problem in which one criterion is quantitative and the other is qualitative. The quantitative criterion is the total weighted tardiness and the qualitative criterion is the importance of the customer for the company. To solve this problem, the integral analysis method (IAM), which consists of four stages (description of the problem, cardinal analysis, ordinal analysis and integration analysis), was used. The cardinal analysis implements both a mixed integral linear programming (MILP) model and a simulation-optimization approach for the total weighted tardiness solution. The ordinal analysis is performed by stochastic multicriteria acceptability analysis with ordinal data (SMAA-O) in which each alternative is qualified depending on customer importance. Finally, to address the integral analysis, deterministic SMAA is applied to select those alternatives that exhibited the best integral characteristics in terms of minimizing tardiness penalty costs and timely fulfillment of due dates according to customer strategic importance for the company. Results show that IAM enables selection of the alternatives that accomplish in the best way both types of criteria.
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1. Introduction

A flexible flow shop scheduling problem (FFS) consists of a series of production stages, in which at least one of them has two or more machines in parallel, but all jobs must follow the same procession route. They flow from one stage to another, being processed only by one machine in each stage (Pinedo, 2012). As demonstrated by Garey and Johnson (1977) and Gupta (1988), this is an NP-hard problem, which means that optimal solutions are likely to be found in a reasonable computational time only for small-sized instances. Moreover, FFS environments have been widely studied due to their versatility and applicability to different industries such as the chemical, petrochemical, textile, electronics (Azizoğlu, Çakmak, & Kondakci, 2001), stainless steel (Tseng, Liao, & Liao, 2008), car assembly chain (Jungwattanakit, Reodecha, Chaovalitwongse, & Werner, 2009; Wang, 2005), packaging (Chen & Chen, 2009b), food, metallurgical and pharmaceutical (Gholami, Zandieh, & Alem-Tabriz, 2009; Liu, Wang, & Jin, 2008) industries. However, solution approaches traditionally studied in the academic literature have been questioned due to many assumptions that limit their applicability to real-life environments (Linn & Zhang, 1999; Ruiz & Vázquez-Rodríguez, 2010).

On the one hand, in the literature, a common assumption about FFS studies is that all parameters are known in advance and do not change over time, i.e. all parameters are deterministic (Wang & Choi, 2014). Nevertheless, different sources of randomness are present in real production systems, such as stochastic processing, setup or release times; machine breakdowns; modifications of due dates; out of stock of raw materials, etc. (Elyasi & Salmasi, 2013b). Pinedo (2012) mentions that there are various ways for modeling randomness. One of them is by modeling the machines breakdowns as an integral part of the processing times (Pinedo,

* Corresponding author at: Departamento de Ingeniería Industrial, Facultad de Ingeniería, Pontificia Universidad Javeriana, Cra. 7 No. 40-62 – Edificio José Gabriel Maldonado, Bogotá, Colombia.

E-mail addresses: eliana.gonzalez@javeriana.edu.co, elianagone@unisabana.edu.co (E.M. González-Neira), rafael.garcia@uniagustiniana.edu.co (R.G. García-Cáceres), juan.caballero@javeriana.edu.co (J.P. Caballero-Villalobos), molina.lina@javeriana.edu.co (L.P. Molina-Sánchez), jr.montoya@uniandes.edu.co (J.R. Montoya-Torres).

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2012) or by doing the same with setup times (Jabbarizadeh, Zandieh, & Talebi, 2009).

On the other hand, regarding to the scheduling criteria for both the deterministic and stochastic cases, it is observed that makespan has been the most studied measure (Gourgand, Grangeon, & Norre, 2000; Ruiz & Vázquez-Rodríguez, 2010). However, functions that take into account the delivery of jobs on time, such as: tardy jobs, tardiness, maximum tardiness, among others, are important criteria in highly competitive markets (Armentano & de França Filho, 2007), because they work as indicators of customer service.

Additionally, a traditional scheduling objective function may include a priority factor or relative importance of jobs in comparison to others, called job weight. This job weight may include quantitative and/or qualitative aspects. When a due date related objective function is analyzed, we can find among quantitative elements the contractual penalties for late deliveries, rush shipping costs, lead time related costs, etc. (Elyasi & Salmasi, 2013a; Seidmann & Smith, 1981; van Ooijen & Bertrand, 2001; Vepsalainen & Morton, 1987). Qualitative elements may include customer importance, loss of customer confidence, loss of good will, loss of future sales, etc. (Alfieri, 2009; Elyasi & Salmasi, 2013a; Khoshjahan, Najafi, & Afshar-Nadjafi, 2013). However, despite this clear difference between the quantitative and qualitative meanings, job weights have been usually represented as a single number, i.e. from 1 to 10 for each job; that is, literature on scheduling often integrates quantitative and qualitative aspects into a single concept without differentiation between them. About this, García-Cáceres, Aráoz-Durand, and Gómez (2009) affirm that the process of quantification of a qualitative variable, leads to a loss of information and validity problems due to the categorization process. Consequently, we highlight the importance of using a multicriteria methodology that takes into account both quantitative and qualitative aspects simultaneously and separately in the optimization problem.

In order to provide solutions for some of these issues, the current work proposes a multicriteria optimization approach that takes into account both quantitative and qualitative criteria to solve a stochastic FFS (SFFS) scheduling problem, with stochastic processing times. The problem considers two different decision criteria related to job importance: (i) monetary cost of job tardiness as a quantitative aspect of decision, which is the total weighted tardiness (TWT) where the weights are in monetary units and (ii) the importance of the client as a qualitative criterion.

The decision-making problem is supported by the integral analysis method (IAM) (García-Cáceres, 2007). This is a methodology that incorporates quantitative and qualitative decision criteria under uncertainties. IAM has been applied to the solution of other combinatorial problems such as plant location (García-Cáceres et al., 2009) and the container loading problem (García-Cáceres, Vega-Mejía, & Caballero-Villalobos, 2011). Broadly speaking, IAM comprises four stages. The first one is the description of the problem. The second one is the cardinal analysis stage in which a mathematical programming model is developed and the problem must be solved from the quantitative perspective as is done in optimization literature; that is, with exact approaches, heuristics or metaheuristics combined with Monte Carlo simulation. Due to the NP-hardness of the problem (Gupta, 1988), meta-heuristic approaches are employed to obtain good solutions in a reasonable computational time. Thus, we selected the GRASP metaheuristic because it is a multi-start procedure that constructs its own initial solution (Feo & Resende, 1995), and it has shown good results in other scheduling problems. Also, we combined GRASP with a bottleneck heuristic that allows the problem to be solved as a parallel machine with release times. So, in this context, this paper proposes a hybrid GRASP-bottleneck simulation-optimization approach to minimize the total weighted tardiness, understood as the total monetary tardiness cost. Ordinal analysis is the third phase of IAM. In this stage the alternatives resulting from the cardinal analysis are processed by the customer importance criterion and resorted to an adapted and restricted version of stochastic multicriteria acceptability analysis with ordinal data (SMAA-O) and probability elements. Finally, the alternatives are analyzed in terms of both quantitative and qualitative aspects, using deterministic SMAA and probability elements. This is the integration analysis, the fourth and final step of this methodology.

The paper is organized as follows: Section 2 reviews works on FFS whose programming criterion has taken into account job weights, or in which one or more parameters have been stochastically established; Section 3 presents the four stages of IAM as applied to the problem under study; finally, Section 4 presents conclusions and research perspectives.

2. Literature review

This section presents an analysis of academic literature about the topics related to the problem under study and its characteristics. In the first instance, an overview of works about FFS problems is presented, followed by the analysis of related works about its stochastic version. Then, the review focuses on the analysis of works including qualitative criteria when solving scheduling problems in general terms. Next, a review of applications of GRASP and bottleneck-based heuristics for scheduling problems is presented. Lastly, the state of the art on IAM applications is outlined.

2.1. Flexible flow shop scheduling problem (FFS)

Several studies have been conducted corresponding to FFS reviews, in which a total of more than 200 papers have been analyzed (Kis & Pesch, 2005; Linn & Zhang, 1999; Quadt & Kuhn, 2007; Ribas, Leisten, & Framiñan, 2010; Ruiz & Vázquez-Rodríguez, 2010). Each state of the art classified the publications according to the solving method (exact algorithms, heuristics, metaheuristics and hybrid methods) and problem characterization (parallel machine type, objective function type, constraints). The main conclusion for the solving methods is about performance, which recommends concentrating efforts on the application of sophisticated techniques such as decomposition methods, metaheuristics and hybrid procedures to solve complex FFS problems (Ruiz & Vázquez-Rodríguez, 2010). On the other hand, the literature shows that it is necessary to consider other relevant aspects of the problem, such as: (i) unrelated parallel machines (Choi, Kim, & Lee, 2005; Jungwattanakit et al., 2009); (ii) objective functions contemplating tardiness, since most studies have focused on makespan reduction (Ruiz & Vázquez-Rodríguez, 2010); (iii) stochastic environments (Kianfar, Fatemi Ghomi, & Karimi, 2009); (iv) sequence-dependent setup times; (v) stage-skipping jobs (Tseng et al., 2008); and (vi) multiple objectives (Dugardin, Amodeo, & Yalaoui, 2009). Table 1 summarizes those researches that have dealt with due-date-related objectives and/or those that consider job importance (job weights).

2.2. Stochastic flexible flow shop (SFFS) scheduling

In the SFFS scheduling field considerably fewer papers have been published than those from deterministic cases. However, in recent years stochastic counterparts have received attention due to their applicability in real-life scenarios.

Table 2 presents the studies on SFFS problems. Among those studies, only four references considered tardiness as objective function, while the others considered the makespan, and none of

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