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Multi-Objective Flexible Job Shop Scheduling Optimization Models (I)

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Abstract

In manufacturing area, the most difficult problems related to the time-efficiency frequently occur if the jobs to be scheduled are heterogeneous, if there are alternative routes on the machines for the jobs and multiple objectives are imposed. This framework, named Multi-Objective Flexible Job Shop Scheduling Problems (MOFJSSP), has been formalized, modeled and studied in the last decades from many perspectives in order to capture all the influential factors and to optimally solve the multi-objective problem while satisfying the multiple specific constraints. The author focused the research on the various optimization models adequate for the (MOF)JSSP, both conventional and non-conventional: Petri nets, waiting systems, general decision models, logical formulations as STRIPS language, Markov processes, Monte Carlo simulation and procedural models (agent-based models, evolutionary algorithms, expert systems, fuzzy techniques, neural networks). The structure, classification and analysis of the optimization models is extensively new, as the MOFJSSP models were less reported in the literature than the JSSP models. All the models are analyzed in the research (which is divided into two parts), in general case and for a specific real JSS process in drugs industry based on over 600 tasks to be optimally scheduled. The conclusions in this first part of the study reveal the complexity of MOFJSSP and the analysis outcome of two optimization models for MOFJSSP: waiting systems and STRIPS language. The results of the research (part I and II) point out the limits or critical aspects of all the mentioned optimization models and the process characteristics that claim certain model as the most adequate.

Key words: *flexible job shop scheduling, optimization model, time-efficiency, multi-objective*

JEL Classification: *C61, L65*

Introduction

Nowadays, many manufacturing companies, regardless of dimension, take an intensive use of Enterprise Resource Planning (ERP) systems, the reason being the beneficial role of information technology in management at all the levels. These information systems, trying to satisfy the general performance objectives - quality, efficiency and security - on a limited resources background, have a global perspective over the enterprise. However, in every department, specialized tools operate to contribute to the general objectives and also to ensure an adequate relationship with the decision tools in other departments. The present study focuses on the scheduling department, where the specific performance refers to time. Setting the manufacturing schedules such that a minimum time is necessary to complete all the jobs in a certain time horizon is one of the main components in almost every ERP system.

One of the not-easy-to-handle production systems is based on manufacturing a range of product types, not a single type, on a set of machines, following certain formulas. For every industry specific time horizon, a number of batches named jobs (of all types), must be efficient scheduled in the job shop. The jobs are heterogeneous and consequently frequent changes on the manufacture equipment and frequent changes for the operational sequences occur. This kind of production system is specific to many industries, such as: pharmaceuticals, chemicals, food industry, furniture, electronic devices and so on.

The vast theoretical and practical background (Brucker and Schlie, 1990; Applegate and Cook, 1991; Jain and Meeran, 1999) of this manufacture condition is grouped around the concept of *Job Shop Scheduling Problems* (JSSP). In short, a JSSP states that a finite set of heterogeneous jobs formed by many operations have to be optimally scheduled on a set of finite machines such that the precedence constraint, the non-preemption constraint and the resource capacity constraint are satisfied. The main objective is to obtain a minimum makespan for the set of jobs, characterized by some attributes as: ready time, processing time on resource, due date, priority etc. The resources, on the other hand, can be energetic, human labor type, machine and so on and certain attributes also for them are set. Note that in the theoretical formulation, all the resources are considered machines. An optimal schedule is the output of the JSSP; it is a time-optimal allocation of the limited resources to the operations.

The scheduling process becomes more difficult when the routings of the jobs on the resources are flexible and multiple objectives must be simultaneously satisfied, for example: minimize lateness, maximize workload, minimize jobs flow time, minimize work-in-process, minimize cost to set the machines, maximize total workload on the machines. All these manufacturing circumstances frame the problem in the multi-objective flexible JSSP (MOFJSSP) category. The mathematical formulation for MOFJSSP is presented in the next section, together with a case study in drugs industry.

For this kind of economic process, various optimization models are available: Petri nets, waiting systems, general decision models, logical formulations such as STRIPS language, Markov processes, Monte Carlo simulation, agent-based models, evolutionary algorithms, expert systems, fuzzy techniques and neural networks. As a precise division of the models in strictly descriptive ones and strictly normative ones could not be done, all of them have descriptive and normative attributes. In the third section of the paper an analysis of these models is started, in order to settle the models limits and advantages and to observe the particular characteristics of the manufacture processes that require certain model as the most adequate. In this first part of the research two models are analyzed, waiting systems and STRIPS language, and in part II the other models are to be dissected.

Multi-Objective Flexible Job Shop Scheduling Problem

Less formally, a job shop scheduling process consists in computing an optimal sequence that the jobs in a production plan must be put on work on the machines. The jobs are formed by many operations, for every job we know the routing on the machines and the corresponding processing times and the explicit order for the operations of the jobs. We seek a minimum makespan schedule for the jobs, while satisfying three cumulative constraints.

The mathematical formulation for this kind of hard scheduling problem was extended (Nicoară et al., 2011) from the deterministic predictive JSSP (Brucker and Schlie, 1990) to include the type II flexibility, where alternative routings for the jobs are allowed. In the mathematical model of Flexible Job Shop Scheduling Problem (FJSSP) described below (Nicoară et al., 2011) the natural assumptions are used: a) the jobs ready times are set to 0, b) all the machines are available at time 0, c) the number of machines and jobs are finite and constant in time, d) the processing times of the operations are finite and constant, and e) the probability for machine breakdowns and the setup times are statistically included in the processing times.

The *input data* of FJSSP are:

- a finite set M of m ($m \in Z$) machines, where Z is the set of integers;
- a finite set J of jobs, each job $i \in J$ consisting in an ordered sequence of n_i operations, $o_{i,j}, j = \overline{1, n_i}$;
- for each operation $o_{i,j}$ $(i \in J,\ j = \overline{1, n_i})$, the set of machines which can perform it, $MA_{i,j} \subseteq M$, with $card(MA_{i,j}) \geq 1$, where $card(MA_{i,j})$ is the cardinality of the set $MA_{i,j}$, and the processing times $\tau_{i,j}^{k} \in Z$, $k \in MA_{i,j}$ are given.

Therefore, to each operation, $o_{i,j}$, one can associate a set $D_{i,j}$ of processing times:

$$D_{i,j} = \{\tau_{i,j}^{k} \in Z \mid i \in J,\ j = \overline{1, n_i},\ k \in MA_{i,j}\}. \tag{1}$$

A solution is a valid schedule for J, defined as a collection of machine schedules as in:

$$s_k : \{o_{i,j} \mid k \in MA_{i,j}, i \in J,\ j = \overline{1, n_i}\} \rightarrow Z,\ k = \overline{1, m}, \tag{2}$$

which satisfies the constraints associated to the process (Jain and Meeran, 1999):

- the precedence constraint: for two consecutive operations of a job, the successor operation must be processed only after the first one ended;
- the non-preemption constraint: an operation, once started, can not be interrupted to be continued later;
- the resource capacity constraint: a machine processes one and only one operation at a time and an operation is processed by at most a machine at a time.

An overall schedule is $S = \{s_k \mid k = \overline{1, m}\}$, where all the operations performed on all the machines $k = \overline{1, m}$ are scheduled.

The uni-objective *(F)JSSP solution* is the overall schedule, S, which consists in all the operations of all the jobs on the machines, ordered by the positive integer values of the functions $s_k, k = \overline{1, m}$. To this schedule a *performance measure*, $C_{\max}(S)$, is assigned to be minimised:

$$C_{\max}(S) = \max_{i \in J, j = \overline{1, n_i}, k = \overline{1, m}} (s_k(o_{i,ni}) + \tau_{i,ni}). \tag{3}$$

The relation (3) computes the *makespan* as the maximum end time, considering all the operations in the schedule.

The *objective* is to minimize the performance measure, which indicates, from the temporal constraints point of view, how well the scheduling is handled. More precisely, the primary objective consists in minimization of the makespan:

$$C_{\max}^{*}(S) = \min_{S \in \{feasible\_schedules\}} (C_{\max}(S)). \tag{4}$$

A schedule with minimum makespan is named *optimal solution of the (F)JSSP*.

For the multi-objective FJSSP (MOFJSSP), additional objectives to the makespan are considered, as we mentioned above.

A MOFJSSP Case Study in Drugs Industry

In drugs industry, most of the scheduling systems are MOFJSSP-type. The case study covers such a manufacturing process, where 16 different types of pellets drugs are produced (see table 1), using some flexible routes, on 20 machines (see figure 1 and table 2) (Nicoară, 2011).

In figure 1 the technological sequences of operations on the machines is provided.

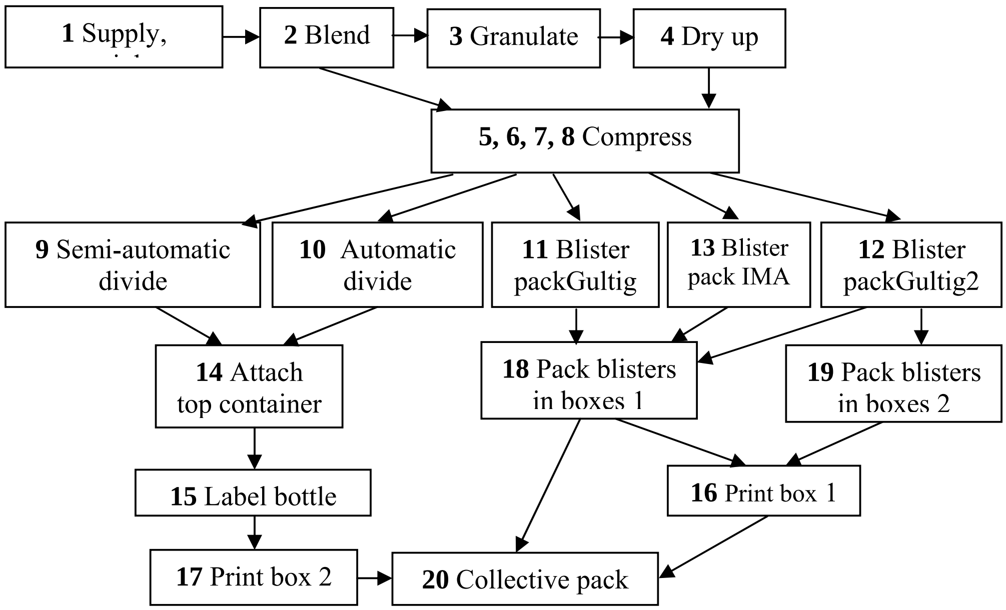

Fig. 1. The primal technological sequences of operations on the machines (Nicoară, 2011)

In the MOFJSSP formulation, every batch in every type of drug corresponds to a job, and the production phases to complete a batch correspond to operations of that job.

The considered process instance is an average dimension instance: 79 jobs for a scheduling horizon of one month, according to table 1. The input data in table 2 indicate a total number of 606 operations to be scheduled.

Table 1. Product types distribution on batches

Poduct type	*No. batches*	*Batches index*
1 (Analgin)	8	1..8
2 (Antacid)	1	9
3 (Ascovit 100)	13	10..22
4 (Ascovit 200)	4	23..26
5 (Ascovit 60)	3	27..29
6 (Biseptrim cl.)	1	30
7 (Biseptrim)	19	31..49
8 (Ephimigrin)	1	0

Poduct type	*No. batches*	*Batches index*
9 (Europirin T)	3	51..53
10 (Europirin)	3	54..56
11 (Eurosept)	4	57..60
12 (Paracetamol Pus)	2	61..62
13 (Paracetamol Sinus)	11	63..73
14 (Paracetamol)	3	74..76
15 (Tussin Forte)	2	77..78
16 (Tussin)	1	79

An example of feasible schedule for the 606 operations may be the sequence of pairs (i,j):

$$(6,1)(76,1)(53,1) \dots (69,3) \dots (54,8)(60,8)$$

ordered by the start times associated to the operations, where i is a job in J and j is an operation in the job i. The detailed description of the schedule is in table 3.

Table 2. Input data for the drug industry instance

Product type	*No. jobs*	*No. op.*	**Routings of the jobs on the machines**									
			Machine / machines									
			Processing times (minutes)									
1	8	6	**1**	**2**	**7**	**11,13**	**18**	**20**				
			5	10	476	200,167	800	113				
2	1	10	**1**	**2**	**3**	**4**	**8**	**9,10**	**14**	**15**	**17**	**20**
			5	15	20	30	320	685,342	394	137	253	120
3	13	8	**1**	**2**	**5,6**	**9,10**	**14**	**15**	**17**	**20**		
			5	20	150,206	325,313	684	214	341	188		
4	4	7	**1**	**2**	**5,7**	**12**	**18**	**16**	**20**			
			5	20	120,222	133	500	300	75			
5	3	8	**1**	**2**	**7**	**9,10**	**14**	**15**	**17**	**20**		
			5	20	315	263,225	560	150	239	132		
6	1	7	**1**	**2**	**5,6**	**12**	**19**	**16**	**20**			
			5	10	83,105	67	250	84	38			
7	19	7	**1**	**2**	**5,6**	**12**	**18**	**16**	**20**			
			5	10	83,105	67	108	84	38			
8	1	9	**1**	**2**	**3**	**4**	**5,7**	**13**	**18**	**16**	**20**	
			5	10	10	20	120,159	200	400	150	38	
9	3	6	**1**	**2**	**7**	**11,13**	**18**	**20**				
			5	10	360	286,222	800	150				
10	3	8	**1**	**2**	**3**	**4**	**7**	**11,13**	**18**	**20**		
			5	10	355	120	65	357,278	700	188		
11	4	10	**1**	**2**	**3**	**4**	**8**	**9,10**	**14**	**15**	**17**	**20**
			5	20	45	30	554	605,510	567	172	316	150
12	2	8	**1**	**2**	**3**	**4**	**5**	**11**	**18**	**20**		
			5	10	43	38	180	230	600	113		
13	11	9	**1**	**2**	**3**	**4**	**5**	**11**	**18**	**16**	**20**	
			5	10	28	46	280	230	290	150	113	
14	3	6	**1**	**2**	**5,6**	**11**	**18**	**20**				
			5	10	424,457	366	970	375				
15	2	10	**1**	**2**	**3**	**4**	**5**	**9,10**	**14**	**15**	**17**	**20**
			5	15	32	31	60	375,188	450	136	173	113
16	1	8	**1**	**2**	**5**	**9,10**	**14**	**15**	**17**	**20**		
			8	15	120	425,363	305	272	346	225		

Table 3. A schedule description

No. operation	*Product type*	*Operation description*	*Start processing time (min.)*	*on the machine*
(6,1)	1	Supply, weigh Analgin	0	1
(76,1)	14	Supply, weigh Paracetamol	5	1
(53,1)	9	Supply, weigh Europirin T	10	1
…	...	...	…	…
(69,3)	13	Granulate Paracetamol Sinus	1923	3
(74,4)	14	Blister pack Gultig 1 Paracetamol	3434	11
(8,1)	1	Granulate Analgin	1951	3
(44,6)	7	Print box 1 Biseptrim	3389	16
…	...	...	…	…
(54,8)	10	Collective pack Europirin	22590	20
(60,8)	11	Collective pack Eurosept	22925	20

The measure unit for the schedule makespan is regularly the eight-hour shift. Examples of some other two objectives are: minimizing the number of late operations compared to 44 shifts value and minimizing the average ratio of idle times in the workshop.

Optimization Models for (MOF)JSSP

Scheduling in manufacturing has an applicative importance first of all for the production management department, because of its role in objectives accomplishment at production level (profitability, a high market share, product excellence etc.). The scheduling constitutes an active research subject also for the operational research area, for the combinatorial optimization, for cybernetics and even for the system control theory.

In the flexible job shop scheduling systems, the asynchronous events dynamics, the parallel evolutions in time of the events, the competition for the resources and the conditional dependences are not only present, but determinant (Panaitescu, 2006). The most adequate model to describe these systems is the discrete-event system model (DES).

A mathematical model which accepts all the tangible and intangible factors that determines the evolution in time of a DES is overly complex (hundreds or even thousands of variables) to allow analytical solutions. Therefore, for the representation, modeling and simulation of DES one must use tools of other type. These are conventional models and unconventional models.

Among the conventional models there are to be mentioned:

- waiting systems;
- Petri nets;
- general decision models;
- logical formulations such as STRIPS language;
- Markov processes;
- Monte Carlo simulation.

The unconventional models are procedural models and include, among others:

- agent-based models;
- genetic algorithms;
- expert systems and knowledge-based systems;
- fuzzy techniques;
- neural networks.

Waiting Systems

A job shop scheduling system can be modeled as a waiting system, where a number of *clients* (jobs) may be waiting some services from the manufacturing line (Panaitescu, 2006). *Performing a service* consists, in the JSSP context, in completing a sequence of operations on the machines in the job shop. After the sequential run over the entire set of required operations, a client is totally served and can leave the process, as figure 2 depicts (example for a waiting thread formed by only three jobs in the drugs industry instance). When flexible JSS is the case, different clients can require different successions of operations, and is allowed some operations to be executed on one of many available resources.

Serving control in a waiting system involves accuracy in operations sequences order for all clients, accuracy in resource allocation and unloading for every operation, performing some type of service as soon as a resource becomes available for that operation (this will lead to a maximum number of served clients, in different stages) and reproducibility of performing services without circular blockages by reason of shared usage on some resources (Păstrăvanu et al., 2002).

This approach, based on client-server relationships, is adequate when the main purpose is not to optimize a function, but to balance waiting costs with serving costs. Additionally, the model is mainly oriented on random client arrivals, on serving on few identical posts and it does not consider the flexibility aspect of scheduling.

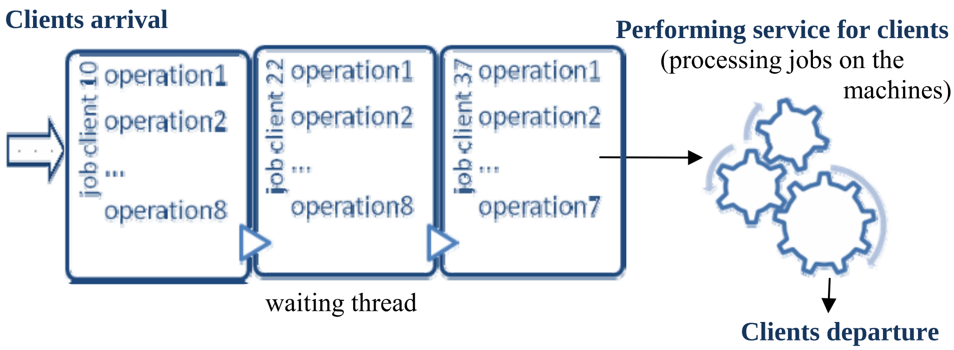

Fig. 2. A JSS process model as waiting system
(Nicoară, 2011, adaptation on (Paraschiv and Rădulescu, 2007))

STRIPS Language

STRIPS (Stanford Research Institute Problem Solver) is a descriptive language proposed by Fikes and Nilsson (1971) for knowledge representation domain. It is adequate for both job representation and job scheduling. STRIPS logical formalization is based on states (represented as sets of logical statements) and actions (with preconditions and effects).

For the FJSSP, STRIPS representations involve relations such as *antecede*(i, j_1, j_2) to formalize that in job i, operation j_1 is antecedent to operation j_2 and actions such as *schedule*(i_1, j_1, i_2, j_2) to schedule operation $o_{i2,j2}$ after operation $o_{i1,j1}$.

The extensions of the base language contain also negation, conditional effects, state variables, quantifiers and concurrent actions.

STRIPS model allows divide et impera strategies (which prove to be efficient to job scheduling) and this is the major advantage of the model. Various studies on jobs representations and scheduling algorithms, such as (Gelfond and Lifschitz, 1993), show instead that other representation languages are more suitable than STRIPS to simulate and solve the real scheduling problems. Such languages are the genetic-based representation languages.

In part II of the research the other optimization models for (MOF)JSSP will be described and analyzed.

Conclusion

The complexity of scheduling in manufacturing when the context is not simple - namely when the jobs to be scheduled are structurally different (regarding number of operations and processing order on the machines), when there are flexible routings on the machines for the jobs and multiple objectives are required - led to different approaches in optimization modeling for this kind of processes. All these approaches follow the general discrete-event system model; in fact, they are particular timed DES. As the evolution in time of flexible scheduling is also complex, analytical formulations for (MO)FJSS models are not available. Among the various descriptive and prescriptive optimization models, the waiting systems is especially suitable to stochastic scheduling and is quite limited regarding the flexibility characteristic. The STRIPS model allows a rigorous formalization for states and events in the system, but the proper strategies based on this language to optimally schedule becomes too complex for the big real scheduling problems. In part II of the research other optimization models, more adequate to MOFJSSP, are to be analyzed.

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Modele de optimizare pentru ordonanțarea flexibilă multiobiectiv a producției multisortimentale (I)

Rezumat

În domeniul producției, cele mai dificile probleme în legătură cu obiectivul de eficiență temporală apar frecvent când sarcinile de planificat sunt eterogene, când există posibilitatea rutelor alternative pe maşini ale sarcinilor şi când se impun obiective multiple. Acest cadru, numit Probleme de Ordonanțare Flexibilă Multiobiectiv a Producției Multisortimentale (POFMOPM), a fost formalizat, modelat şi studiat în ultimele decenii din multiple perspective pentru a surprinde toți factorii de influență principali şi pentru a rezolva optim problema multiobiectiv astfel încât toate restricțiile specifice să fie satisfăcute. Autoarea a orientat cercetarea asupra diverselor modele de optimizare adecvate proceselor PO(FMO)PM, atât convenționale cât şi neconvenționale: rețelele Petri, sistemele cu aşteptare, modelele decizionale generale, formulările logice de tipul limbajului STRIPS, procesele Markov, simularea Monte Carlo şi modelele procedurale (modelele bazate pe agenți, algoritmii evoluționişti, sistemele expert, tehnicile fuzzy, rețelele neuronale). Structura, clasificarea şi analiza modelelor de optimizare este în mare parte nouă, deoarece în literatura de specialitate modele pentru procesele POFMOPM sunt mult mai puțin raportate decât în cazul proceselor de ordonanțare a producției multisortimentale (POPM). Toate modelele sunt analizate în studiul realizat (care este divizat în două părți) în cazul general şi pentru un proces POPM particular din industria de medicamente bazat pe peste 600 de operații de planificat. Concluziile primei părți se referă la complexitatea POFMOPM în producție şi la rezultatele analizei a două modele de optimizare: sistemele cu aşteptare şi limbajul STRIPS. Rezultatele întregii analize (partea I şi II) indică limitele şi aspectele critice ale tuturor modelelor menționate anterior şi caracteristicile proceselor care reclamă drept cele mai adecvate anumite modele de optimizare.