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A hierarchical model for multiple range production systems

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Abstract: Production system types evolved lately to multiple range production systems (MPRS) in the context of more complex and more interconnected economical functions and more restrictive time-efficiency constraints. In MRPSs, interactions between components are various and numerous. Concurrency, resource sharing and synchronization occur. Uncertainty, multiple state and control variables and various nonlinear relations characterize MRPSs. To properly handle these aspects, the modern production systems tend to be automated and consequently two tasks are required: (1) to describe as exact as possible the system, both structurally and behaviorally (by a proper model) and (2) to develop an adequate control strategy for the system. In the paper a hierarchical model for MRPSs and a genetic_algorithm-based control strategy are proposed.

1. INTRODUCTION

Any manufacturing process combines specific production factors in order to obtain certain material goods: industrial products or commodities. The production systems significantly evolved in the last fifty years by adapting to the new practical technical and organizational conditions. As demand and bid for goods became more and more diverse and more and more customizable, a vast transition from unique range production systems to multiple range production systems emerged. The type of production system in a manufacturing enterprise is a great influence on the decision making process, on the space organization for the industrial plant, on the scheduling methods, on the technical preparation for the new products, on the record control methodology.

In the *multiple range production systems* (MRPSs), frequent changes of sorts on the functional resources occur. Nowadays, MRPS is basic for the most manufacturing branches, such as: food industry, chemicals, pharmaceuticals, furniture, electronic devices and so on.

This kind of production system requires *automated process-oriented decision strategies*. The processes in the enterprise must ensure a rational accomplishment of both management and executive activities. The global enterprise performance depends on the combined effects of all internal activities and it increases by adopting efficient organizational methods for all the processes involved. Among the main activities in a manufacturing enterprise, whatever production system uses (unique or multiple range), the *scheduling* process is a critical one, from the efficiency perspective. This is the reason for the numerous research studies and the various approaches, in the last decades, to find optimal solutions and to design an unifying theory for the vast scheduling contexts in the real world (see Kaufmann, 1964; Conway *et al*., 1967; Filip *et al*., 1983; Brucker and Schlie, 1990; Jain and Meeran, 1999; Filip, 2005; Brucker, 2006; Blazewicz *et al*., 2007; Pinedo, 2008; Guschinskaya and Dolgui, 2009; Hurkens, 2009; Kurtoglu *et al*., 2010).

Production scheduling, named also *shop scheduling*, has an applicative importance first of all for the production management area, grace to the inherent infusion of efficiency to attain the set of global objectives of the production system (profitability, a high market share, product excellence etc.). On the other hand, the scheduling constitutes an active research subject also for the operational research area, for combinatorial optimization, for cybernetics and even for the optimal control in discrete event systems domain.

Production scheduling in MRPSs is a decision process for optimal time-allocation of (limited) resources to jobs, ordinarily fragmented in elementary operations. The resources must be available and the optimization criterion is singular (minimizing the makespan) or multiple. The *complexity* of this stage in the manufacturing process has many causes: the variability of operations sequences on the resources, the variability of manufacturing recipes for every sort of product and the interactions between in-process products during the manufacturing. All these aspects require a more delicate handling of scheduling in MRPSs comparing to the unique range production systems.

The scheduling function in a production system must efficiently interact with many other functions. These interactions are system-dependent, may substantially vary and often are put on work by ERPs (Enterprise Resource Planning) - integrated multi-modular information systems, designed to maximize the efficiency of the decision flow in the enterprise, from the lower levels to the highest level.

Many process models were proposed and tested for MRPSs. Though the discrete-event system model (DES) seemed theoretically very appropriate, for the real instances the mathematical model comprises hundreds or thousands of variables. Therefore, other models, both conventional and unconventional, were developed. In the first class we can mention (timed) coloured Petri nets (Jensen, 1991), waiting line systems (Hall, 1991), Markov chains, Monte Carlo simulation, logical formulations and general decision models.

The so-called unconventional models are procedural models, most of them based on artificial intelligence. Here, knowledge-based systems, agent-based models, genetic algorithms, expert systems, fuzzy techniques, neural networks (Rabelo, 1990) and hybrids of them worth to be mentioned. High attention was put on the agent-based models, such as: negotiation techniques (Pinedo, 2008), Ant Colony Optimization (Cicirello and Smith, 2001), Particle Swarm Optimization (Zhang *et al*., 2009) and Wasp Behavior Model (Theraulaz *et al*., 1991).

Lately, many software tools to support production from the product design to the manufacturing shop floor are also available. Cachapa *et al*. (2011) use smart devices into a virtual production platform plus Web Services interfaces as an engineering SoA-based tool. Other instruments are cluster tools to schedule special facilities (Wu *et al*., 2008; Chan *et al*., 2011; Wu and Zhou, 2010), robotic cells, material handling systems (Agrawal and Heragu, 2006).

In the next section, a hierarchical approach for MRPS organizations is proposed, focused on scheduling in the last hierarchical level. A control system theory perspective is used, where the system is objective-oriented. This approach aims an adequate placement of the scheduling subsystem in the ensemble, from two perspectives:

- the causal relations for the specific objectives and
- the interconnections with the other subsystems.

The last section concludes the proposed hierarchical model.

2. HMRPS: A HIERARCHICAL APPROACH FOR MRPSs

Most of the production systems, including MRPSs, are complex systems, marked by uncertainty, with numerous state and control variables and many nonlinear relations. To efficiently control such systems, the hierarchical approach proves to be the most adequate methodology (Filip, 2005), and decision support systems best match as a solution in the complex production enterprises.

Hereinafter, decomposition in smaller, hierarchically organized, subsystems for MRPSs is proposed, where three main levels are involved. It was called HMRPS (*Hierarchical MRPS*). This structural perspective is oriented to the scheduling function, which constitutes the central interest point in this research. The analyzed levels, as Fig. 1 illustrates, are the following:

(1) the first level: general management;
(2) the second level: production planning;
(3) the third level: production scheduling.

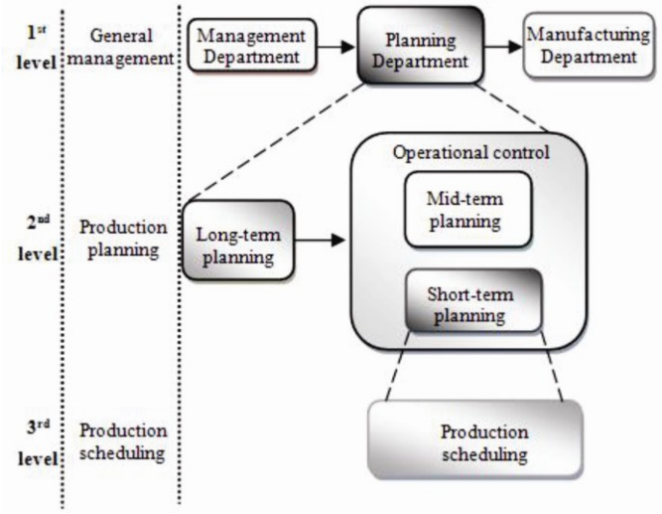

Fig. 1. Three levels hierarchy in HMRPS

2.1 *The first level of HMRPS*

Fig. 2 depicts the interacting subsystems on the first level of HMRPS:

- the management subsystem (Management Department), which elaborates commands to the subordinate services in order to maintain a *reference economical state* (RES), determined by the general performance requirements (quality, efficiency, and security) in a limited available resources context. MR/ER/FR/IR/HR in Fig. 2 are the material, energetic, financial, informational, and human resources;
- the production planning subsystem (Planning Department), which executes the command imposed by the Management Department and determines a production schedule to be asserted to the Manufacturing Department. By "schedule" we mean a resource time-allocation to the jobs in the production plan;
- the manufacturing subsystem (Manufacturing Department) which implements the schedule;
- the capitalizing subsystem (Commercial Department);
- the subsystems to evaluate system-environment state (Marketing Department and Functional Department for income evaluation).

The system on the first level of HMRPS is a combined automated control system. The Management Dept. acts as a controller, the Planning Dept. acts as executive element, the Manufacturing + Commercial Depts. as controlled process, and the Marketing + Functional Depts. as transducers for the preventive, respectively corrective components. The closed-loop control is achieved by a preventive component (the upper loop in Fig. 2) and a corrective component (the lower loop in Fig. 2).

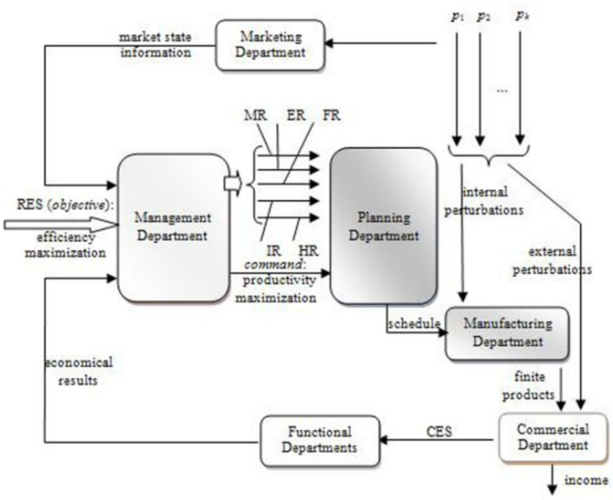

Fig. 2. The 1st level of HMRPS (adaptation from (Paraschiv and Radulescu, 2007))

The internal perturbations refer to plant damages, to personnel non-availability or other special events, to internal cause supply misadjust, to internal normative changes, to changes in machines stand etc. Reduction of effects of these perturbations is regularly achieved in a feedback manner. The external perturbations, offset in a feed forward manner, can be: fluctuations on the financial market or working material market, changes in clients' orders (quantitatively, qualitatively or deadlines), changes in standing rules etc. Most of these perturbations regularly act, at least indirectly, both at the Manufacturing Department level and the Commercial Department level.

The system on this level is a discrete, nonlinear optimization tracking system, with multivariable input and multivariable output. An ideal model for such complex systems would embody in a mathematical framework all the relationships in the system. But in real life, they are too complex to allow comprising in exact mathematical relations all these phenomena; this is practically a difficult or even impossible task (Filip, 2005). Automation for such systems supposes to achieve two tasks: (1) accurately describing the structure and the behaviour of the system and (2) developing an adequate strategy to control it.

2.2 The second level of HMRPS

The control strategy in the first hierarchical level is the attribute of Management Department, which determines, by means of some specific commands, the efficiency of all subordinate departments. Among them, the Planning Department lies in a priority position: the productivity of Manufacturing Department and consequently the efficiency of the global production system depend on the planning decision. By this reason, on the second level in the control system, the planning subsystem is considered. It models long-term, mid-term and short-term planning for the manufacturing (see Fig. 3). The goal of planning consists in time-echeloning of jobs (which are functionally interconnected) such that they are not mutually excluded and they lead to fulfil the production objectives.

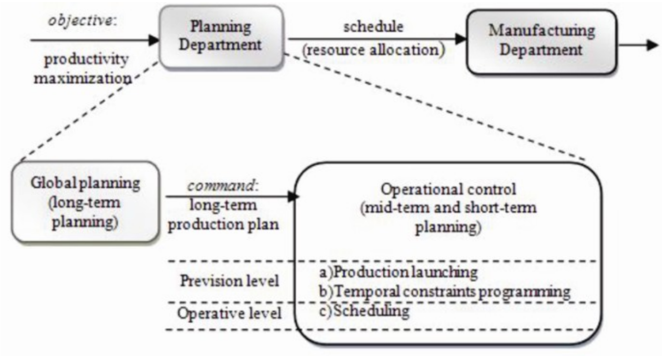

Fig. 3. The 2nd level of HMRPS

The long-term planning is made for relative long time intervals (1-3 years) and refers to organizational production system definition (unique products / multiple range products, flow shop / open shop / job sop, series / parallel etc.), to investments, to life cycles of products, and to global policy. The elaborated command is the long-term production plan and it is imposed to the Operational control Department. Here, this plan is rhythmically performed as volume, sorts, quality and prescribed terms.

The pair "operational control - controlled process (manufacturing)" can be viewed on two levels: [1] a prevision level (mid-term planning) and [2] an operative level (scheduling or short-term planning: machine control), by a two-loop control model (as Fig. 4 shows).

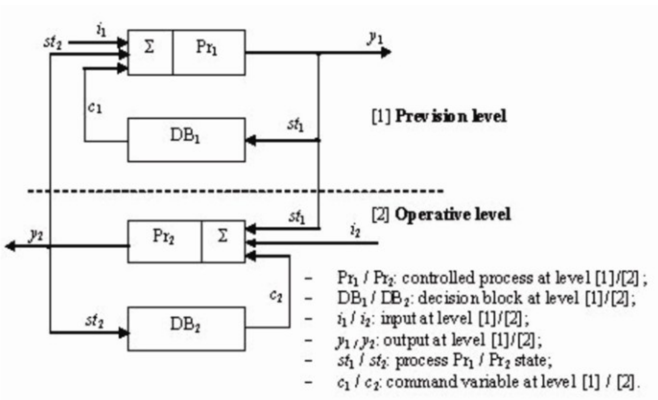

Fig. 4. Two-loop control model for the Operational control

On level [1] the aggregation of information is greater than on level [2], on level [2] the frequency of decisions is greater than on level [1].

The objective in the 1st level of HMRPS - efficiency maximization - becomes in the 2nd level the *productivity maximization* objective.

2.2 The third level of HMRPS

The operative level corresponds to the short-term planning (often monthly or weekly), named *scheduling*, which constitutes the third hierarchical level of HMRPS. This stage details the plan elaborated at the previous level, which is relatively broad (as sorts and times of delivery). In the scheduling stage, the jobs in the plan are distributed in time and space, while using work-centers based on the available information about the sorts structure and the technological process.

As we move down in the hierarchy from the Management Department towards the Manufacturing Department, the elaborated commands get a more technical aspect, against the economical aspect. The step where this phenomenon is directly observable is the passage from planning to scheduling. Planning is preponderantly economic oriented, scheduling is preponderantly technically oriented. Planning refers to a global level of production, which has to be allocated on every resource by scheduling. Scheduling stage gets the planning result (the production plan) as a constraint. Additional inputs are the temporal and other nature constraints provided by the prevision level of Operation control function. The objective to maximize the productivity (at the previous level) is converted at the current hierarchic level into the objective to *minimize the makespan*.

The scheduling subsystem, illustrated in Fig. 5, is an optimal control system where the control agent (controller + executive element) elaborates the command for resources allocation to operations in the production plan (the schedule) based on a scheduling strategy and on its input. In this framework, the shop is the controlled object.

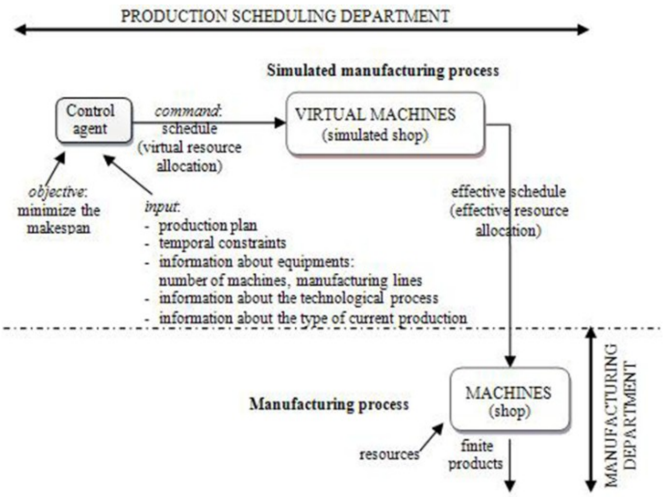

Fig. 5. The 3rd level of HMRPS

A segregation of manufacturing process in two sections – a virtual process (the controlled process) and the proper process – is made. The reason for this is keeping a general character for the proposed control structure. The virtual manufacturing process is required when the scheduling strategy elaborates the command to effectively allocate the resources as a result of processing a set of different allocation scenarios. In this case, the different scenarios may be simultaneously applied (at each iteration of the strategy) to the same controlled process, with no mutual interaction. It is obvious that without such a virtual process, all the scenarios could not be simultaneously imposed as commands to the real resources. Examples for such scheduling strategies are population-based optimization techniques as genetic algorithms (GA), Ant Colony Optimization, Particle Swarm Optimization.

Here a GA-based scheduling strategy is proposed. The controller takes decisions to adaptively run genetic operators, based on monitoring the population state in every generation. The mechanisms for the adaptive strategy are two: a dynamical application of the crossover and mutation and a partial reinitialization of the population every time when the average progress of the genetic operators is below a given threshold. Both mechanisms have the goal to avoid the premature convergence of the genetic algorithm towards suboptimal regions. The executive element assumes and executes this command by applying selection, crossover, mutation and reinitialization of the population.

The state of the system at moment t is P_t - the population of the genetic algorithm at generation t. It is a set of scheduling sequences. The transition function is:

$$P_{t+1} = \delta\,(P_t\,, input, random\_factor, t).$$

It specifies transition of the system from generation t to generation $t + 1$, by means of the genetic operators and it has no analytical form; in fact, the genetic algorithm simulates the natural evolutionary process, unknown in its essence.

In such a resource allocation system, (1) the input variables are the input data of the problem, the parameters of the algorithm and the objective(s), (2) the state variables are the candidate-solution population and its evaluation index, and (3) the output variable is the optimal schedule at the end of evolution. The random factor in the command mechanism is associated to the input, being specific to the genetic algorithm. This randomness, inherent to a genetic algorithm, causes a stochastic non-deterministic character to the control strategy, meaning that for the same input P_0 (initial population), the control law probably produce different output.

The command to genetically operate over the current population, addressed to the executive element, is a component of the command addressable to the virtual allocation process.

The Manufacturing Department has the role of implementing the schedule resulted from the Scheduling Department, taking into account the current value of the variables which describe the state of the controlled manufacturing system.

To note that the global objective (in the first hierarchical level of HMRPS), namely to maximize efficiency, is sequentially accomplished, in a cyclic manner, on short time intervals, by the Scheduling Department, as Fig. 6 shows.

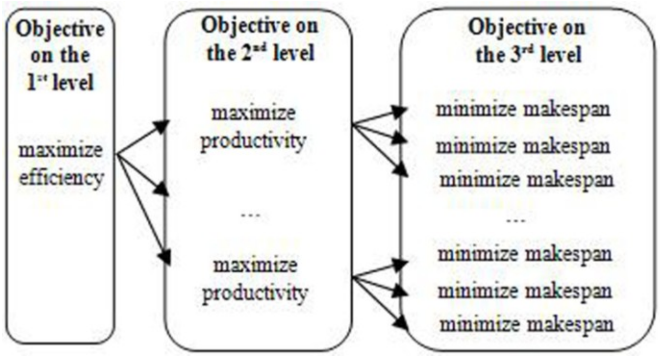

Fig. 6. Sequential accomplishment of the objective in the 1st level of HMRPS by objectives in the 2nd and the 3rd levels of HMRPS

The qualitative objective, meant to follow up the reference (RES) and to reject the effects of perturbations, is therefore detailed in quantitative objectives: maximize the productivity and minimize the makespan.

3. CONCLUSIONS

MRPSs are hierarchically approached in the proposed model, named HMRPS, on three levels: the first one corresponds to the global enterprise, the second one to the production planning sector and the third level corresponds to the scheduling sector. An automation theoretical perspective was used to build the model. Therefore, on every level, the controller, the executive element, the controlled process and the transducers are identified.

The first level of HMRPS is viewed as a combined closed-loop control system, where both preventive and corrective components properly handle the perturbations in order to meet the global efficiency maximization criteria. It is also a discrete, nonlinear optimization tracking system, with multivariable input and multivariable output.

The second level of the model gives focus to the long-term, mid-term and short-term planning. The subsystem is an open-loop system, where the objective is productivity maximization. By zooming forward the short-term planning (the operative sublevel) in this second level of HMRPS, *the third level* is obtained. Here, where scheduling function is analyzed, the commands are not anymore economically-oriented, but technically-oriented. The objective is minimizing the makespan (the total time spent by the machines to execute the jobs in the detailed production plan). This subsystem is an optimal control system where the adaptive command to optimally allocate the resources to the jobs is addressed to a (simulated) manufacturing process. When the optimization strategy used for allocation is a population-based metaheuristic, a virtual simulated process is needed, such that multiple allocation scenarios may be simultaneously tested on the manufacturing shop; when no such method is used, the command is addressed to the effective manufacturing process.

The proposed systemic model is consequently a general model, from the perspective of the various applicable control strategies. The same is also valid from the perspective of interactions between the various functions in the largely used ERPs.

Once defined the proper model for the system, developing an adequate control strategy is the next step. Both practitioners and theorists in automation control agree that many such strategies are applicable, especially the intelligent techniques and hybrids with classical control strategies. To mention a few: genetic algorithms, Ant Colony Optimization, Artificial Bee Colony Algorithm, gravitational search algorithms, Frog Leaping Algorithm (Stankovic *et al.*, 2001; Dumitrache, 2005; Xing *et al.*, 2010; Nicoara, 2011; Teekeng and Thammano, 2011; Bacanin and Tuba 2012; David *et al*., 2013). In the paper a genetic algorithm approach is proposed to model the scheduling strategy.

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