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A multi-objective approach for design of reconfigurable transfer lines

Xavier Delorme* Sergey Malyutin* Alexandre Dolgui**

* Mines Saint-Étienne, LIMOS UMR CNRS 6158, France (e-mail: {delorme,sergey.malyutin}@emse.fr).
** Automation, Production & Computer Science Department, École des Mines de Nantes, France, (e-mail: alexandre.dolgui@mines-nantes.fr)

Abstract: This paper studies a multi-objective line balancing problem for reconfigurable transfer lines. In nowaday industry, machining lines need to be highly reconfigurable in order to cope with market's demand. However, the design of these reconfigurable lines implies more difficult optimisation problems to solve and new methods are required. Moreover, with the high level of uncertainty on demand, decision-makers now look to other criteria than the sole investment cost.
A new heuristic, based on the GRASP (greedy randomized adaptive search procedure) framework and using mixed integer programming for solving sub-problems, is proposed to deal with the search of trade-offs between cost and productivity for such reconfigurable transfer lines. A case study is also described and tested in order to illustrate the interest of the proposed approach.

Keywords: Assembly lines, reconfigurable lines, line balancing problem, multi-objective, production system design

1. INTRODUCTION

Our study concerns machining transfer lines used in industry for mass production. Historically, this type of production line was widely used for part production where high (but constant) production rate and low investment cost were required. However industry has now to deal with faster and faster evolutions of their clients' demands and must be able to adapt their production systems. In next years, the growing importance of Industry 4.0 will certainly increase this need to have production systems capable to cope with the quick evolutions of market as well as with customised production. As a consequence, transfer lines have to evolve in order to become more reconfigurable.

In order to design a production line several main steps are needed:

- Products analysis (basic operations to obtain the final product);
- Process planning (functional specification and conditions);
- Line configuration (serial flow, parallel line or U-line);
- Line layout (placement of machines) and transport system design;
- Detailed design and line implementation;
- Optimal scheduling for a mix of products;
- Line reconfiguration to reflect changes in products demand.

Usually, these steps are considered sequentially in order to deal with the complexity of the whole problem. In this paper we are focusing on the step of providing detailed design and implementation of reconfigurable lines which satisfy enterprise needs and has high production rate and low investment cost at the same time. Section 2 formally defines the problem considered in this paper and a literature review is presented in Section 3. The optimisation approach we propose is then described in Section 4. Finally, the results obtained in computational experiment are reported and discussed in Section 5.

2. RECONFIGURABLE TRANSFER LINES

In this section, we will study the multi-objective problem associated with the design of a reconfigurable machining line (RML). As introduced by Koren et al. (1999), reconfigurable manufacturing systems are designed to allow easy changes in their physical configuration to answer market fluctuations in both volume and type of product. To achieve this goal, the main required characteristics are: modularity, integrability, customisation, convertibility and diagnosability. The use of a RML is motivated by the increasingly shorter product runs and the need for more customisation (see Figure 1).

We consider paced and serial production line. The goal for machining lines is to assign set of operations to workstations equipped with a set of machines tools satisfying usual assembly lines constraints: processing time of operations and their precedence graph. However machining lines have several additional constraints:

- Inclusion constraints (some operations must be executed on the same stations);
- Exclusion constraints (some operations cannot be executed on the same workstations);

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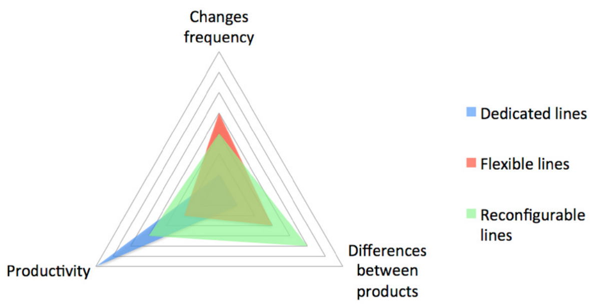

Fig. 1. Main differences of assembly lines

- Part fixing constraints (Part can be rotated, but after that some sides of the part can became not accessible and therefore the operation which must be executed cannot be executed).

In such a line, all the operations assigned to a station are performed sequentially by the same spindle, and thus sequence-dependent set-up times must be considered. Set-up times are related to the rotation of the part but also change and displacement of the tool. Finally, the sequential execution of operations, as well as the setup times, usually implies large workload times and, as a consequence, parallel machines can be required at some stations in order to increase the production rate. The interest of these lines as well as the main steps of their design has been described in Delorme et al. (2009).

Solution (which refers to line configuration) for the studied problem contains information about the following 3 decisions:

- Assignment of the set of operations to workstations and number of those workstations (balancing problem);
- Sequencing of the operations for each station (scheduling problem);
- Choice of the number of machines (equipment problem).

Also each solution has qualitative and quantitative characteristics of the obtained configuration for production line, those can be linked to the goals of enterprises as shown in Table 1. In this paper, we consider the goals of minimising investment cost and maximising throughput which gives us a multi-objective problem. This problem is NP-Hard since the sole balancing or scheduling problems are already NP-Hard even with only one objective.

3. LITERATURE REVIEW

A reconfigurable manufacturing system (RMS) is one designed at the outset for rapid change in its structure, as well as its hardware and software components, in order to quickly adjust its production capacity and functionality within a part family in response to sudden market changes or intrinsic system change (Koren et al., 1999). Reconfigurable Manufacturing Systems constitute a new class of systems characterised by adjustable structure that provides scalability and customised flexibility (Koren and Ulsoy [2]). The RMS goal is summarized by the statement "Exactly the capacity and functionality needed, exactly when needed". Ideal Reconfigurable Manufacturing Systems possess six core RMS characteristics: Modularity, Integrability, Customized flexibility, Scalability, Convertibility, and Diagnosability (Koren and Ulsoy, 2002; Landers et al., 2001). The ideal reconfigurable system provides exactly the functionality and production capacity needed, and can be economically adjusted exactly when needed (Mehrabi et al., 2000). The components of RMS are Computer Numerical Control (CNC) machines, which are operated by computer executing precisely programmed commands sets (Koren, 1983). More detailed explanations of the characteristics and definitions of reconfigurable manufacturing systems are given in Koren and Ulsoy (1998); Koren and Shpitalni (2011); Bi et al. (2008); Bruccoleri et al. (2005a,b); Azab and ElMaraghy (2007); Malhotra et al. (2009); Molina et al. (2005); Reuven (2007).

Table 1. Relation between production and management

Production line characteristics	**Key performance indicators for businesses**
• Number of workstations; • Number of machines.	Investment cost
Cycle time	Throughput
Reconfigurability	Changes frequency

A mixed integer programming (MIP) formulation has been proposed in Essafi et al. (2010) for a single objective version of this problem corresponding to the minimisation of the investment cost with an upper bound on the cycle time of the line, but only small size instances could be solved (less than 20 operations). Borisovsky et al. (2014) have proposed a new model, based on a set partitioning formulation, which has provided better performances but medium to large sized instances are still unsolvable. As a consequence, several heuristics have been proposed to deal with this problem (Essafi et al., 2012; Borisovsky et al., 2013).

4. PROPOSED APPROACH

In this section we will present 3 sub approaches and their combination in a metaheuristic used to solve the described problem.

4.1 Construction of a solution for a given sequence

Let's consider a fixed sequence of the operations of set N satisfying precedence constraints. The remaining decisions to be made are:

- Number of workstations and assignment of operations to workstations, which is equivalent to finding the places in the sequence of operations where there is a change of workstation;