

## Reactive scheduling in a make-to-order flexible job shop with re-entrant process and assembly: a mathematical programming approach

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A mixed-integer linear programming model is presented for the scheduling of flexible job shops, a production mode characteristic of make-to-order industries. Re-entrant process (multiple visits to the same machine group) and a final assembly stage are simultaneously considered in the model. The formulation uses a continuous time representation and optimises an objective function that is a weighted sum of order earliness, order tardiness and in-process inventory. An algorithm for predictive-reactive scheduling is derived from the proposed model to deal with the arrival of new orders. This is illustrated with a realistic example based on data from the mould making industry. Different reactive scheduling scenarios, ranging from unchanged schedule to full re-scheduling, are optimally generated for order insertion in a predictive schedule. Since choosing the most suitable scenario requires balancing criteria of scheduling efficiency and stability, measures of schedule changes were computed for each re-scheduling solution. The short computational times obtained are promising regarding future application of this approach in the manufacturing environment studied.

**Keywords:** reactive scheduling; flexible job shop; re-entrant process; assembly; mixed-integer linear programming

### 1. Introduction

Reactive scheduling has received far less attention in the scheduling literature than optimal or near-optimal production schedule generation, the development of which started in the 1950s with the seminal paper by Johnson (1954) on the two-machine flow shop problem (Pinedo 1995; Potts and Strusevich 2009). However, the ability to revise a schedule effectively in order to cope with unexpected events such as machine failures, processing time delays, arrival of new orders and unavailable material is as important as the scheduling problem itself in industrial environments, which are dynamic in nature. An analysis of the literature shows that interest in reactive scheduling techniques intensified in the 1990s and the first review papers specifically aimed at reactive scheduling research appeared about a decade ago (Raheja and Subramaniam 2002; Vieira, Herrmann, and Lin 2003).

Production scheduling research within the Operations Research community has traditionally been focused on discrete parts manufacturing systems, where products are fabricated as individual units. These are divided into two types: flow shops, where all jobs visit a set of machines in the same sequence, and job shops, where jobs visit the machines in different sequences (machines being grouped into work centres). Many methodologies have been applied to solve the problem of obtaining schedules for job shop systems, named the job shop scheduling problem (JSP) in the literature. These solutions methods that can be broadly classified as either exact or approximate are comprehensively reviewed in Jain and Meeran (1999) and more recently in Potts and Strusevich (2009). Among the first type is mathematical programming which, when applied to JSPs, usually results in models of the mixed-integer linear programming (MILP) type. Except for a few simple configurations of the system, the computational burden of solving an MILP model increases exponentially with problem size for most JSPs, as results from the Theory of Complexity have proved in the past decades. However, the capabilities of computational tools currently available justify that this approach should be further explored and enhanced with new formulations for scheduling job shop environments. In the research here presented the mould making industry was the motivating application.

A mould is a specially designed tool consisting of a 'base' and one or more 'cavities' contoured to the exact specifications of the desired product. A closer look at modern life daily environments shows the ubiquity of moulded pieces

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