European Journal of Operational Research 239 (2014) 854–864

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Innovative Applications of O.R.

# The design of simple subcontracting rules for make-to-order shops: An assessment by simulation

Matthias Thürer [a,*], Mark Stevenson [b,1], Ting Qu [c], Moacir Godinho Filho [d]

[a] Jinan University, Huangpu Road, No 601, 510632 Guangzhou, China
[b] Department of Management Science, Lancaster University Management School, Lancaster University, Lancaster LA1 4YX, UK
[c] Guangdong CIMS Provincial Key Lab, School of Electromechanical Engineering, Guangdong University of Technology, Guangzhou, China
[d] Department of Industrial Engineering, Rodovia Washington Luís, km 235, Caixa Postal 676, Monjolinho, 13565-905 São Carlos, SP, Brazil

ARTICLE INFO

*Article history:*
Received 4 May 2013
Accepted 16 June 2014
Available online 25 June 2014

*Keywords:*
Production
Subcontracting
Make-to-order
Workload Control
Job shop

ABSTRACT

Subcontracting can be an important means of overcoming capacity shortages and of workload balancing, especially in make-to-order companies characterized by high variety, high demand variation and a job shop configuration. But there is a lack of simple, yet powerful subcontracting rules suitable for such contexts. The few existing rules were developed for single work center shops and neglect the actual subcontracting lead time, meaning some subcontracted jobs are destined to become tardy. This study uses Workload Control theory on matching required and available capacity over time to propose four new rules that address these shortcomings. The new rules are compared against four existing rules using an assembly job shop simulation model where the final, assembled product consists of several sub-assemblies that either flow through an internal job shop or are subcontracted. The best new rules stabilize the direct load queuing in front of a work center and significantly improve performance compared to the existing rules. For example, when the workload exceeds capacity by 10%, a 50% reduction in percentage tardy can be achieved. By examining how the workload behaves over time, we reveal that improvements come from selectively subcontracting the sub-assemblies that would otherwise cause overloads, thereby cutting off peaks in the workload.



## 1. Introduction

Workload balancing is a key concept for managing the performance of make-to-order companies, which often suffer from large workload fluctuations (Thürer et al., 2014). Two established approaches for maintaining a balanced workload are: (i) holding inventory, meaning capacity usage is fairly constant and demand peaks are satisfied from stock and (ii) dynamic pricing and promotions, thus manipulating demand to fit capacity. But there is also a third option – subcontracting during overload periods (Kamien & Li, 1990). Given the high degree of customization common in make-to-order companies, this may even be a more suitable approach than (i) and (ii) above. This study outlines four new subcontracting rules for a high-variety make-to-order environment to cope with periods where requirements exceed available capacity. The focus is on simple rules applicable to managers of small and medium-sized shops – which often produce on a make-to-order basis (e.g. Stevenson, Hendry, & Kingsman, 2005) – to determine which jobs to subcontract and which to process internally.

While much recent research has focused on subcontracting (e.g. Chen & Li, 2008; Chung & Choi, 2013; Lee & Choi, 2011; Lee & Sung, 2008a, 2008b; Qi, 2011), most of this has assumed a static scheduling problem and/or deterministic demand. This limits the applicability of the work to dynamic production environments with stochastic demand – like high-variety make-to-order companies. To the best of our knowledge, the only study on simple subcontracting rules for make-to-order companies was presented by Bertrand and Sridharan (2001). The authors introduced four rules to guide the subcontracting decision and used discrete event simulation to evaluate their impact in a single work center shop. Bertrand and Sridharan's (2001) results showed that subcontracting rules can lead to significant performance improvements, especially when the current shop floor workload is considered. The paper represents an important starting point for further work, but – as is often the case when exploring a new field – the authors focused on the mathematical tractability of their work at the

* Corresponding author.
*E-mail addresses:* matthiasthurer@workloadcontrol.com (M. Thürer), m.stevenson@lancaster.ac.uk (M. Stevenson), quting@gdut.edu.cn (T. Qu), moacir@dep.ufscar.br (M. Godinho Filho).
[1] Tel.: +44 1524 593847.

http://dx.doi.org/10.1016/j.ejor.2014.06.018
0377-2217/

expense of practicality. Hence, their rules have two key shortcomings: (i) they were developed for a single work center shop – in practice, multiple work centers usually exist and (ii) they do not consider the actual subcontracting lead time – i.e. whether a job actually can meet its due date – resulting in jobs being subcontracted that will inevitably become tardy. It follows that there is a need to extend Bertrand and Sridharan's (2001) study by developing and testing subcontracting rules that: (i) are suitable for shops with multiple work centers and both high routing and high processing time variability and (ii) ensure only jobs that can realistically meet their due date if subcontracted are selected.

In response, this study outlines four new rules that draw on Workload Control theory (e.g. Fredendall, Ojha, & Patterson, 2010; Thürer, Stevenson, Silva, Land, & Fredendall, 2012; Thürer et al., 2014) and compares them against Bertrand and Sridharan's (2001) rules using an assembly job shop simulation model. Workload Control is a production planning and control concept for small and medium-sized make-to-order shops (Hendry & Kingsman, 1989; Zäpfel & Missbauer, 1993; Stevenson et al., 2005) that matches required and available capacity over time, molding the workload into a shape that can be produced profitably and on time (Kingsman, Tatsiopoulos, & Hendry, 1989; Kingsman, 2000). This balances the workload across work centers and over time, and means Workload Control is especially suitable as a theoretical backdrop to new subcontracting rules. The study also contributes to Workload Control theory: although the Workload Control literature recognizes subcontracting as an important output control mechanism, along with overtime and reallocating operators from under-loaded to overloaded work centers (e.g. Kingsman & Hendry, 2002), it lacks explicit theory on the subcontracting decision, as recently noted by Hendry, Huang, and Stevenson (2013) when implementing the Workload Control concept in practice.

## 2. Literature review: simple rules for subcontracting

The literature on subcontracting (and outsourcing) is vast. This section reviews work from a stream of this literature that has some relevance to our study.

### 2.1. Relevant subcontracting literature

Back in the 1990s, Webster, Alder, and Muhlemann (1997) highlighted the lack of research on subcontracting and related issues in manufacturing. Since then, there has been growing interest, especially in the scheduling literature. For example, Lee, Jeong, and Moon (2002) developed an advanced planning and scheduling model with subcontracting options for an assembly job shop that aimed to minimize the make-span subject to a due date constraint for the sub-assembly job shop. Chung, Lee, Shin, and Park (2005) developed an algorithm for the job shop scheduling problem that decreased tardiness by either rescheduling or subcontracting operations at bottleneck resources, while Merzifonluoglu, Geunes, and Romeijn (2007) provided profit-maximizing production planning models for determining the optimal demand and internal production capacity levels when subcontracting and overtime options are available. Meanwhile, Chen and Li (2008) studied a model with parallel machines in which a manufacturer receives a set of customer orders and has to decide which to process and which to subcontract. The model also provided a production schedule for internally produced jobs that minimizes the sum of the production and subcontracting costs.

In addition, Lee and Sung (2008a, 2008b) considered a single-machine scheduling problem where a set of orders must either be allocated to a single machine or be undertaken externally, while Bichescu, Fry, and Polak (2009) used harmonic analysis to create a portfolio of recurrent in-sourcing and outsourcing contracts to balance the workload. Qi (2011) later studied the production scheduling problem for a two-stage flow shop with subcontracting options, while Lee and Choi (2011) and Chung and Choi (2013) looked to minimize the sum of the make-span and total outsourcing (or subcontracting) costs: Lee and Choi (2011) for a two-stage production system with half-finished goods; and Chung and Choi (2013) for a two-machine ordered flow shop problem.

While such papers make a valuable contribution – and some, e.g. Lee et al. (2002), are actually in the context of a complex assembly job shop – they assume the scheduling problem is static (not dynamic) and that demand is deterministic. This limits the applicability of the work to the complex production environments typically found in make-to-order shops in practice. To the best of our knowledge, the only study to date on simple subcontracting rules to guide decisions regarding which jobs to subcontract and which to process internally that is relevant to high-variety environments with stochastic demand was presented by Bertrand and Sridharan (2001). It is therefore this particular study that will be used as a starting point for the (re)design of simple subcontracting rules for make-to order shops. The study will be discussed next.

### 2.2. Existing simple subcontracting rules for make-to-order shops

Four rules were introduced by Bertrand and Sridharan (2001) as follows:

- *Subcontracting Rule 1:* The subcontracting decision is taken immediately upon the arrival of a job. If the total remaining slack time of job $j$ (i.e. job $j$'s due date ($d_j$) minus the current time $t$) is shorter than a predetermined critical lead time ($L^C$), it is processed internally and released to the internal shop. Otherwise, i.e. if $d_j - t \geqslant L^C$, the job is subcontracted.
- *Subcontracting Rule 2:* The subcontracting decision is taken at periodic time intervals of length $T$. Jobs await the subcontracting decision in a pre-shop pool. First, a maximum number of jobs ($m$) is determined for the internal shop. At the beginning of each period, all jobs in the pool are sequenced according to the Earliest Due Date (EDD) rule. Then, starting with the first job in the sequence, jobs are selected for internal processing and released into the internal shop as long as the number of selected jobs $\leqslant m$. Any remaining jobs are then subcontracted.
- *Subcontracting Rule 3:* This rule is similar to Rule 2 but incorporates feedback on the current work-in-process on the shop floor. First, a workload norm ($N$) or specific upper workload limit is determined for the internal shop. At the beginning of each period, all jobs in the pre-shop pool are sequenced according to the EDD rule. Then, starting with the first job in the sequence, jobs are selected for internal processing and released to the internal shop as long as the aggregate of the selected workload and the current remaining workload on the shop floor $\leqslant N$. As with Rule 2, any remaining jobs are then subcontracted.
- *Subcontracting Rule 4:* This rule is similar to Rule 3 except that only those jobs that did not fit the norm for which the total remaining slack time is less than or equal to the expected subcontracting lead time $\left(L_j^S\right)$ plus the period until the next subcontracting decision, i.e. $d_j - t \leqslant L_j^S + T$, are subcontracted. The remaining jobs wait in the pre-shop pool for the next subcontracting decision.

Bertrand and Sridharan (2001) examined the performance of their four rules using simulation. They found Rule 3 and Rule 4 to be the best-performing options, underlining the importance of feedback information on the current workload for making subcontracting decisions. But, despite the important contribution of their