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A Lean-based ORR system for non-repetitive manufacturing

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Abstract

Lean implementations are no longer limited to high volume production and are becoming increasingly common in low volume, high variety non-repetitive companies. Such companies, usually with make-to-order or engineer-to-order production, have normally been modeled with a job shop production system, but many of them actually have a dominant flow in production. Moreover, one of the main characteristics of Lean implementation is that it streamlines production flow, makes it unidirectional, and reduces setup and lot size. Consequently, a significant number of production systems are better modelled as flow shops, rather than as job shops.

This has an impact on production management approaches, and in particular on Order Review and Release systems. In fact, ORR systems have been designed with job shops in mind, because they are the most complex systems to manage, and because they are considered the optimal system for non-repetitive production. We believe that job shop designed ORR systems are not the best ones for flow shop systems. We consequently propose a new ORR system designed for non-repetitive production in flow shops, and based on Lean Principles.

The simulation campaign run to test the new model shows that it yields lower lead time and increases output.

Keywords: ORR, lean, non repetitive production, workload control, flow shop, simulation

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This has an impact on production management approaches, and in particular on Order Review and Release systems. In fact, ORR systems have been designed with job shops in mind, because they are the most complex systems to manage, and because they are considered the optimal system for non-repetitive production. We believe that job shop designed ORR systems are not the best ones for flow shop systems. We consequently propose a new ORR system designed for non-repetitive production in flow shops, and based on Lean Principles. The simulation campaign run to test the new model, shows that it yields lower lead time and increases output.

Keywords: ORR, balance releases, upper bound workload control, flow shop, simulation

1. Introduction

The Lean approach is becoming increasingly popular in manufacturing and service companies. This approach started in the automotive industry and was then adopted by other high volume manufacturers, with good examples in consumer electronics, white goods, air conditioners, etc.

In more recent years Lean implementations have also targeted low-volume high-variety companies (Portioli-Staudacher and Tantardini, 2008a) - frequently with make-to-order or engineer-to-order production - although Lean transformations are more difficult in these companies, and not all Lean techniques and methodologies are implemented (Portioli-Staudacher and Tantardini, 2008a; 2008b). For example, pacing production at the takt time is much more difficult to achieve, and kanbans are of little use when pieces are designed to customer requirements. Nonetheless, other aspects, such as streamlining processes, setup time reduction and flexibility increase so as to reduce lot size, 5 S and operators' involvement, are actively pursued and in many cases implemented.

This shift to the Lean approach, and in particular to focusing on product families value streams - dedicating resources – and to streamlining the process, has in many cases changed the structure of the production system of these companies, even though it may not yet be evident. In fact, there is now a dominating flow in production.

Make-to-order and engineer-to-order companies are generally modeled as job shops. This is because job shops are the most flexible production systems and can therefore easily adapt to producing the very high variety offered by these companies. Moreover, job shops are the most complex systems to manage. This is the reason why researchers have mostly focused on developing production planning and control approaches for such systems (Oosterman et al. 2000). In particular, Order Review and Release (ORR) systems are appropriate means with which to plan MTO and ETO production, and job shops (see for example Land and Gaalman,

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3 1996, 1998; Moreira and Alves, 2009; Baykasoğlu and Gökçen, 2010). In fact, ORR systems
4
5 have been developed essentially for job shops.
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8 But, because of the changes engendered by Lean in the approach to production systems (look
9
10 at the flow, not at the single resources), and the changes that MTO and ETO companies are
11
12 undertaking by adopting the Lean approach, there is an increasing number of companies that
13
14 can be better modeled as flow shops rather than as job shops, because the flow of products is
15
16 no longer tangled, is streamlined, and has no recycles. We believe that ORR systems
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18 developed for job shops are not those best suited for use in these new systems. In fact, as also
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20 noted by Weng et al. (2008), we believe that the applicability and the effectiveness of
21
22 production planning and control approaches depend on shop floor configuration. The aim of
23
24 this paper is therefore to present an ORR system specifically designed for MTO and ETO
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26 companies (i.e. companies that produce a very high variety of products, with wide differences
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28 among them in terms of processing time so that the workload for each product is very
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30 different from that of the others (see for example Kingsman and Mercer, 1997; White and
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32 Prybutok, 2001) with a streamlined production flow and small setup times (because of a Lean
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34 transformation, or for any other reason). Henceforth we shall call these companies ‘non-
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36 repetitive companies’, as in White and Prybutok (2001).
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46 **2. Literature review**

47 *2.1. Order Review and Release Systems*

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49 An Order Review and Release (ORR) system consists of an Order Entry (OE) phase, a pre-
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51 shop pool management phase (in which customers’ orders are stored before being released to
52
53 the shop) and an order release phase (Bechte, 1988; Bergamaschi et al. 1997).
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55

56
57 Figure 1 shows the reference framework for ORR systems (adapted from Bergamaschi et al.,
58
59 1997). In this framework, also the main nomenclature adopted in this paper is highlighted.
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[FIGURE 1 HERE]

The creation and use of the pre-shop pool protects the shop against external dynamics such as demand variability by exploiting a backlog of non-released orders (Land and Gaalman, 1996; Bertrand and Van Ooijen, 2002). Tatsiopoulos (1997) highlights that the availability of a good mechanism for the selection of orders to be released is the key factor in the successful use of a pre-shop pool. Order release is a decision fundamental for the system's performance (Land and Gaalman, 1996; Land, 2006; Baykasoğlu and Gökçen, 2010; Lu et al., 2010). Henrich et al. (2002) point out that the order release phase is crucial for simplifying the remaining process of production system management. In fact, an ORR system makes it possible to control WIP levels in the shop, reduce shop congestion, and increase the workload balance among workcenters (Melnik and Ragatz, 1989), thus reducing and stabilizing shop floor throughput times (Bechte, 1988; Hendry and Wong, 1994; Bergamaschi et al, 1997; Sabuncuoglu and Karapinar, 1999).

Finally, the possibility of stabilizing shop floor throughput time and workcentres' workloads enables companies to quote more reliable due dates (Breithaupt et al. 2002; Stevenson et al., 2005; Stevenson and Hendry, 2006; Baykasoğlu and Gökçen, 2010).

In fact, with a good order release rule, performances are less dependent on the dispatching rule (because the queues are shorter), so that a simple First-Come-First-Served (FCFS) rule can be adopted (Becthe, 1988; Wein, 1988; Land and Gaalman, 1996; Kingsman, 2000).

Using a FCFS rule minimizes the standard deviation of shop floor throughput times, making their estimation more reliable.

Reducing the WIP through holding jobs in the pre-shop pool allows the management to delay final decisions on production. This reduces the impact of changes in production orders

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3 quantities, the need to expedite, and the amount of space occupied on the shop floor. It also
4
5 increases the flexibility of specs modifications after order confirmation (Land and Gaalman,
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7 1996; Stevenson and Hendry, 2006). Bertrand and Van Ooijen (2002) also highlight how
8
9 workload control decreases the decision-making pressure on the operator through the lower
10
11 congestion and the higher transparency of the production system. Bechte (1988) reports that
12
13 workload control implementation can reduce the number of people involved in production
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15 planning and control by up to 40%. Workload control with an ORR system is also in line with
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17 Lean approach principles. In fact, ORR can be used to focus on, speed up, and stabilize the
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19 flow.
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24 Finally, ORR systems seem to have the potential to enable such companies to increase
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26 efficiency in supply chain integration (Hendry, 2006) and to significantly improve operational
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28 performances (Hendry et al., 2008).
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34 *2.2. Workload limiting and workload balancing*

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36 ORR systems are articulated and quite complex. Several authors have classified and
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38 determined the characteristics of the ORR systems (for example Philipoom et al., 1993;
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40 Bergamaschi et al., 1997; Sabuncuoglu and Karapinar, 1999). Bergamaschi et al. (1997)
41
42 classify ORR systems on 8 different axes. Different ORR systems have very different
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44 performances, depending on their structure and on the setting of their parameters (see for
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46 example Perona and Portioli, 1998; van Ooijen, 1998; Land, 2006).
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50 The vast majority of ORR systems release jobs to the shop with the main aim of limiting
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52 workloads in the shop rather than balancing workloads among different workcentres.
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55 The workload limiting mechanism is simple and produces an implicit workload balance
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57 among workcentres, because while no additional jobs are released to over-loaded
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59 workcentres, it is still possible to release jobs to under-loaded ones (Bechte, 1988; Perona and
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3 Portioli, 1998). Germs and Riezebos (2010) point out that the advantages from limiting
4 workload on the shop are only obtained when the release mechanism also improves the
5 balance of workload on the shop floor. In fact, they measure the effectiveness of a workload
6 control system as the ability of the system to balance workload on the shop.
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12 Nonetheless, only a relatively small number of papers consider workload balancing as a main
13 goal. To be mentioned in particular are those by Irastorza and Deane (1974), Shimoyashiro et
14 al. (1984), Onur and Fabrycky (1987), Van Ooijen (1998), and Cigolini and Portioli-
15 Staudacher (2002).
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22 Irastorza and Deane (1974) propose a mathematical formulation with which to solve the
23 workload balance problem and also respect due dates. This formulation is rather complex
24 from both a conceptual and solution point of view, even if it yields good improvements in
25 comparison with the performance of an uncontrolled system (immediate release).
26 Shimoyashiro et al. (1984) use a heuristic approach in an attempt to balance workloads not
27 only between different workcentres, but also between different time periods. Their results
28 show a substantial advantage in the case of systems which use a balance model versus
29 systems which release jobs on their planned release date, without any input control.
30 Unfortunately, these authors do not make comparisons between balancing and limiting
31 systems.
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45 Van Ooijen (1998) compares a balance-oriented release system, a limiting system and
46 immediate release, highlighting the improvements in throughput times and timeliness
47 achieved by the workload balancing system. Van Ooijen (1998) shows that the workload
48 balancing system entails a strong risk of performance detriment on the due date-related
49 indicators. In fact, if a proper corrective is not in place, jobs that do not balance well may be
50 continuously delayed in the release phase, because less urgent jobs that balance the workload
51 better are always preferred. This effect, implicit in ORR systems (Melnik and Ragatz, 1989),
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3 seems very marked in the case of workload balancing systems. This also seems to be the
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5 finding of the paper by Cigolini and Portioli-Staudacher (2002), which compares a workload
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7 balancing system with several workload limiting systems.
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10 Although Cigolini and Portioli-Staudacher (2002) note that the workload balancing system is
11
12 more robust against the environmental factor variation than limiting systems, they find that it
13
14 is not possible to conclude that one model is superior to another. However, the two authors
15
16 find that when mix imbalance (i.e. processing times variability) increases, the advantages of
17
18 the workload balancing system over the upper-bound-only system increase for the throughput
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20 time, while there is no clear evidence for a trend relative to the percentage of late jobs.
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22 Cigolini and Portioli-Staudacher (2002) suggest that different parameter settings could result
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24 in different results, but there are no further developments in this direction in the literature.
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32 *2.3. Production system configuration*

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34 ORR can be used with any type of system. However, the literature has focused almost
35
36 exclusively on the job shop system (Oosterman et al., 2000), probably because it is a very
37
38 common configuration, especially within SMEs, and because it is considered to be the most
39
40 difficult to manage. Notable exceptions are the papers by Enns (1995), Oosterman et al.
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42 (2000), Portioli-Staudacher (2002) and Thürer et al. (2010), which also analyze flow shop
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44 configurations.
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48 On the other hand, the relevance of unidirectional configurations is quite well documented in
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50 the literature (see for example Oosterman et al, 2000; Portioli-Staudacher, 2002). A number
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52 of authors (see for example Enns, 1995; Raman, 1995) suggest that the flow shop
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54 configurations can be used to effectively represent many real systems that exhibit very closely
55
56 interlaced and variable production flows because it is often possible to highlight a general
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58 flow pattern in those systems.
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3 Moreover, in recent years an increasing number of non-repetitive companies have started to
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5 implement the Lean Approach. This approach suggests dedicating production resources to
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7 production families, streamlining production flows, and avoiding production re-circles. It
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9 therefore suggests creating more unidirectional production flows, with lower variability in
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11 routing length and sequence. As a consequence, many production systems can be better
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13 modeled as flow shop systems.
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17 The aim of this paper is to present an ORR system specifically designed for companies with a
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19 unidirectional, dominant production flow, yet producing very different products with wide
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21 differences in processing times. In fact, we believe that an ORR system specifically designed
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23 for flow shop systems will enhance the advantages, already mentioned by Oosterman et al.
24
25 (2000), of using ORR systems in these contexts.
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32 **3. The modeled system**

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34 In this paper we consider companies whose production follows a dominant flow/sequence.
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36 Such companies can be found, for example, in the ceramics industry and in furniture
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38 manufacturing. In many non-repetitive companies, products often follow the same sequence
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40 of operations. This fact induces certain companies to set up virtual cells (see for example
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42 Drolet et al. 1996; Kannan and Ghosh, 1996; Nomden et al. 2006). In other cases, different
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44 routings are followed either for strong technical reasons or by deliberate choice. In these
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46 instances, the production process can be changed so that a group of products requiring the
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48 same resources follows the same sequence. In the case of furniture, for example, several
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50 kitchen manufacturers employ a functional layout in order to share competences among
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52 operators more easily (e.g. wood cutting is very different from painting). However, the
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54 production flow is sequential. Figure 2 shows the simplified layout of a company producing
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56 customized kitchens. The layout is a functional layout, but from the production management
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3 point of view the system is better modeled as a flow shop. Cutting always precedes transverse
4 cutting and swaging. Drilling (in joinery shops) always precedes the final assembly stages,
5 but it is carried out after all the painting and drying and finishing operations have been
6 performed. In this kitchen company, products are very different in size and processing time.
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15 [FIGURE 2 HERE]
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20 Other examples of the type of company addressed in this paper are Motawi Tileworks
21 (described in Lander and Liker, 2007), a manufacturer of high-end, handmade decorative
22 tiles, or ABC Inc. (described in Cutright et al., 2008), a manufacturer of plastic containers in
23 several custom-designed shapes.
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29 In these companies, high variability levels (in processing times, in priorities, etc.) generate
30 significant amounts of work-in-process between stages to maximize workcentres' utilization -
31 and thus throughput levels. The high work-in-process level also protects the system against
32 the impact of dynamic bottlenecks, i.e. the variability in workload that causes the bottleneck
33 to change from one stage to another over time, depending on the mix of customer demand.
34 This effect is stronger when processing time variability is high. However, high work-in-
35 process level is costly, increases indirect costs, and reduces flexibility.
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48 **4. Proposed ORR model**

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50 The aim of the model proposed is to release jobs from the pre-shop pool by leveling the
51 workload along the flow, i.e. we aim to release homogeneous workloads on each workcentre
52 in order to improve the production flow, to decrease the workload in the shop, and to reduce
53 the throughput time in the shop (shop floor throughput time) and in the system (gross
54 throughput time).
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3 Unlike many other ORR systems presented in the literature (see for example Cigolini and
4 Portioli-Staudacher, 2002), the focus of the one proposed here is not on balancing workload
5 and capacity on each workcentre (i.e. releasing more load on workcentres with little load
6 already released to the shop). Rather, the focus is on a balanced release, i.e. leveling only the
7 workload of the jobs being released.
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11 In other words, we disregard the imbalance existing in the shop, and we focus on releasing
12 balanced loads in order to obtain a smooth workload pattern released every time.
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16 In the following part, we will use the reference framework proposed by Bergamaschi et al.
17 (1997) to describe the ORR system developed. In the next section, we also describe the
18 decisions that we took when setting the parameters for the ORR system.
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20

21
22 Regarding the *Order Release Mechanism* (Bergamaschi et al. 1997), we chose the load
23 limited approach. In this case, at every discrete time interval (*timing convention*), the model
24 releases jobs in order to reach a predetermined load level in the system. This is a practical and
25 simple approach often adopted in the literature and in practice (see for example Bechte, 1988;
26 Land and Gaalman, 1998).
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28

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30 Because we focused on a situation in which job processing times are highly variable, we
31 chose to use the total amount of workload in the shop as the *Workload measure* (Bergamaschi
32 et al. 1997), rather than the total number of jobs in the shop.
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35
36 We adopted the total shop load logic for the *Aggregation of workload measure* (Bergamaschi
37 et al. 1997), which does not produce any feedback on how the workload is distributed among
38 workcenters in the shop. This is a simple approach that does not require much information.
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42 We then adopted the atemporal shop load method (Oosterman et al. 2000) for *Workload*
43 *accounting over time* (Bergamaschi et al. 1997).
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3 Regarding the *Workload control* axis, the model proposed aims to balance workloads
4 released, i.e. it seeks to release a similar amount of workload to each workcentre so as to
5
6 create an even pattern in the workload released at every release period, rather than limiting the
7
8 workload. The model allows a limit in a workcentre to be exceeded if by doing so the released
9
10 limit profile is more balanced (more evenly distributed among workcentres).
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14 This is a new way of balancing that enlarges the framework of Bergamaschi et al., 1997. The
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16 model proposed then adopts a passive *Capacity planning* approach. In fact, it acts only on
17
18 input to maintain desired performances and does not act on the capacity of different
19
20 workcentres.
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24 We adopted an extended *schedule visibility* approach, considering both the release for the next
25
26 period and the release for future periods. Several authors suggest that this is a better choice
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28 (Fredendall and Melnyk, 1995; Bergamaschi et al., 1997) and may be the answer to the
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30 problem of due date performances of balancing systems highlighted by van Ooijen (1998).
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32 The use in this paper of the extended visibility approach is also a significant difference
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34 between our model and the balancing model proposed by Cigolini and Portioli-Staudacher
35
36 (2002).
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40 The overall amount of work released depends on the workload in the shop and the target
41
42 workload level. The overall workload released is the amount necessary to take the load in the
43
44 shop from the initial load (load before release) to the target one. For subsequent release
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46 periods, the workload to be released is taken as identical to the capacity during the release
47
48 period for every workcentre.
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52
53 The mathematical formulation of the model proposed is presented below. Since the model
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55 aims at balancing releases, we will refer to it as BLR (i.e. BaLanced Releases).
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4.1. Parameters of the model

K is the total number of stages in the flow shop.

N is the total number of jobs in the pre-shop pool.

$t(i,k)$ is the processing time of job i on workcentre k .

$DD(i)$ is the due date of job i .

TWL is the target workload for the shop after a release. The target workload is a lever in the hands of management. In the BLR the target workload is defined at total shop level. Because all workcentres have the same capacity, the target workload for every workcentre is $TWL(k) = TWL / K$ and it is identical for every workcentre.

Cap is the capacity for the single workcentre in the release period, which is the same for every workcentre and constant in the short-medium term. Cap is the work capacity in minutes.

$W(p)$ represents the penalty associated with the workload unbalancing in release period p . Because future periods impact less, we set $W(p) > W(p+1)$.

r represents the penalty associated with the over-load for every workcentre, compared with under-load: we set here $r = 1$ as in Cigolini and Portioli (2002).

$ERD(i)$ is the earliest release date of job i , i.e. the first planning period in which the specific job can be considered for release in the shop. At the earliest release date, we assume that all the material and components needed to produce the specific job are available.

$LRD(i)$ is the latest release date of job i , i.e. the latest planning period for releasing the job and completing it on time. The $LRD(i)$ is calculated as the difference between the due date $DD(i)$ of job i and the shop floor throughput time associated with the workload level set. Shop floor throughput time is evaluated from the target workload in the shop, properly converted into release periods.

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TIME LIMIT (TL) represents the number of release periods that are considered in the pre-shop pool planning (i.e. in the schedule visibility). Jobs from an ERD(i) beyond the time limit are not considered for release.

4.2. Variables of the model

$x(i,p)$ is a binary variable: $x(i,p)=1$ if job i is planned to be released in period p ; 0 otherwise.

$RL(p,k)$ is the workload on workcentre k due to jobs that are to be released in period p .

IL is the initial load (Bechte, 1988) already in the shop before the start of the release procedure. This load is due to all jobs still present in the shop, and is accounted with the atemporal shop load approach (Bergamaschi et al. 1997; Oosterman et al. 2000).

$UL(p,k)$ is the under-load, on workcentre k and in period p .

$OL(p,k)$ is the over-load, on workcentre k and in period p .

4.3. Objective Function

$$\min \sum_{k=1}^K \sum_{p=1}^{TL} w(p)(UL(p,k) + r \cdot OL(p,k)) \quad (1)$$

The objective function expresses the goal of minimizing the unbalancing of workload among workcentres, and unbalancing over time, with closer periods being weighted more because they are more critical.

4.4. Constraints

$$UL(p,k) = \begin{cases} \max \left(\left(\frac{TWL - IL}{K} \right) - RL(p,k); 0 \right) & p = 1, k = 1, \dots, K \\ \max(cap - RL(p,k); 0) & \forall p > 1, k = 1, \dots, K \end{cases} \quad (2)$$

Constraints (2) define the under-load for the different periods to be scheduled for every workcenter.

$$OL(p, k) = \begin{cases} \max\left(RL(p, k) - \left(\frac{TWL - IL}{K}\right); 0 \right) & p = 1, k = 1, \dots, K \\ \max(RL(p, k) - cap; 0) & \forall p > 1, k = 1, \dots, K \end{cases} \quad (3)$$

Constraints (3) define the over-load for the first and the subsequent periods to be scheduled for every workcentre.

$$RL(p, k) = \sum_{i=1}^N t(i, k) \cdot x(i, p) \quad \forall p, \forall k \quad (4)$$

$$\sum_{p=1}^{TL} x(i, p) = 1 \quad \forall i \mid LRD(i) \leq TL \quad (5)$$

$$\sum_{p=1}^{TL} x(i, p) \leq 1 \quad \forall i \mid LRD(i) > TL \quad (6)$$

Constraints (4) calculate the workload that is to be released for every release period on each workcentre. With constraints (5), every job that is to be released within the TL is assigned to one and only one period. Constraints (6) ensure that jobs that can be released in a period beyond the TL are either not released or assigned for release to one period only.

$$x(i, 1) = 1 \quad \forall i \mid LRD(i) \leq TimeNow \quad (7)$$

$$x(i, p) = 0 \quad \forall i, \forall p \mid ERD(i) > p \quad (8)$$

Constraints (7) force the release in the current period of all jobs in the pre-shop pool with a LRD(i) in the current period, or earlier. This ensures that balancing does not postpone job releases beyond their latest release date for any job. The purpose is to deal with the trade-off between lateness of jobs and workloads balance also highlighted by Van Ooijen (1998) and Cigolini and Portioli-Staudacher (2002). Also Van Ooijen (1998) uses the latest release date to limit the time that a job can wait in the pre-shop pool. Constraints (8) force the jobs to be considered for release just in case the release period is subsequent or equal to their earliest release date.

4.5. *System of weights adopted in BLR model*

Forcing the release of jobs with a LRD in current period avoids the continuous delay of jobs that do not balance well. But it is an On-Off approach. Due date has no impact: it is not considered in the release objective function. This myopic approach may result in periods with forced releases that considerably unbalance the workload, and periods with significant overloads (forced release also overloads the workload limit).

The model proposed overcomes this by adopting an extended visibility (Bergamaschi et al. 1997). By considering future periods as well, it is possible to take account of the fact that in, say, the 4th period a number of jobs will be forced for release.

The unbalance caused in period 4 is considered and weighted against the balance in previous periods. Thus a different solution is found, with a lower balancing of previous periods, but also a much better balance in the critical period.

Because the situation in future periods is more uncertain (e.g. new customer orders arrive), the unbalance of distant periods is weighted less than balancing in closer periods.

We have defined a negative exponential expression for weights definition, where the period is used as the exponent: $w(p) = 1/2^p$.

5. **Benchmark model: the Upper Bound Only Release (UBR) Model**

In order to test the BLR model proposed, we chose a benchmark model that many studies have shown to be a good performer. The benchmark model that we used was the Upper Bound Only one (see for example Bechte, 1988; Land and Gaalman, 1998; Cigolini and Portioli-Staudacher, 2002 and Land, 2006) in the best performing version (see Oosterman et al., 2000), i.e. with a workload accounting done at each workcentre, considering only the tasks remaining to be performed.

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3 In this model, jobs in the pre-shop pool are sequenced with an earliest release date priority
4 (see for example Bechte, 1988; Land and Gaalman, 1998; Land, 2006). Starting from jobs
5 with the highest priority, a job is released if its workload, added to the workload already
6 present in the shop, does not exceed the target workload set on each workstation that it is
7 going to visit.
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10 If a job is found to exceed the target workload, the job is not released, and a subsequent job is
11 considered. This is reiterated until all the jobs within the TL in the pre-shop pool have been
12 considered.
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14
15 Table 1 set out the characteristics of both the ORR system proposed and the benchmark ORR
16 system.
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18 [TABLE 1 HERE]
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22 **6. ORR parameters**

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24 In the ORR systems described in this paper, we identified the following parameters (Land,
25 2006): (1) Workload norms; (2) Time limit; (3) Planned station throughput time; (4) Release
26 period length.
27

28
29 Parameter setting is a quite critical activity (Perona and Portioli, 1998). Thus, we will briefly
30 discuss the decisions we made in this regard. In particular, the same decisions about
31 parameters will be considered for the two ORR systems compared, because our aim was to
32 compare their performances under the same operating conditions.
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34

35 *6.1. Workload norms*

36
37 For a description of Workload norms see Land and Gaalman (1996), Oosterman et al. (2000)
38 and Land (2006). The system had no bottlenecks that could be determined *a priori*. This
39 means that, on average, the workload was balanced on the different workcentres.
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3 As reference values for the different norms we chose ones ranging from situations of very
4 short queues in the shop to situations in which the shop is very loaded.
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10 6.2. *Time limit*

11
12 ‘Time limit’ defines the set of jobs in the pre-shop pool that can be selected for the release. In
13 particular, only jobs with earliest release dates within the time limit can be considered in the
14 release procedure.
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19
20 When a long time limit is set, a lower Gross Throughput Time (GTT) is obtained, because it
21 is possible to choose among a higher portion of jobs in the pre shop pool. When a long time
22 limit is set, a better workload balancing may result (Land and Gaalman, 1998; Land, 2006). In
23 this case, the percentage of tardy jobs is reduced, even if the standard deviation of tardy jobs
24 increases (Land, 2006). Conversely, when the time limit decreases, the gross throughput time
25 increases (Land, 2006). We used a long time limit as in Land (2006) in order to exploit the possibility of
26 reducing the Gross Throughput times. The increase in late jobs standard deviation that Land
27 (2006) describes was controlled in the model proposed through the extended schedule
28 visibility (Bergamaschi et al.1997).
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43 6.3 *Planned station throughput time*

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45 Planned station throughput time is not controlled at single workcentre level, but rather at total
46 shop level by the *Aggregation of workload measure*. The shop floor throughput time is used
47 to determine the latest release date, and it is calculated as the total workload in the shop (in
48 minutes), appropriately converted into work days.
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57 6.4 *Release period length*

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3 It is difficult to define optimal values, especially in dynamic situations (Perona and Portioli,
4 1998; Land, 2006). We consequently gave priority to a practical value in defining the *release*
5 *period length*. In our case we fixed the release period length to one day, as in many real
6 companies. This yields a release of about 16 jobs / day, which is in line with the rate that we
7 have found in many companies.
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10 11 12 13 14 15 16 17 **7. Description of the simulation model**

18 A simulation study was conducted to test the model proposed.

19
20 The model used in the simulation study was kept simple, in order to have no disturbances that
21 might prevent the full characterization of the effects.
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23

24 Shop floor configuration was a pure flow shop composed of 5 workcentres with the same
25 capacity. When a customer order arrives, job processing times are taken from a lognormal
26 distribution with identical parameters for every workcentre.
27
28

29 We opted for a lognormal distribution because such a distribution is quite realistic in
30 describing processing times on workcentres and allows the simulation of high variability in
31 processing times. For the sake of simplicity, operation processing times on workcentres were
32 set as deterministic. This means that there was no difference between the planned processing
33 time and the actual processing time.
34
35

36 Set-up times were sequence independent. It was thus possible to consider them as comprised
37 in job processing times (Cigolini and Portioli-Staudacher, 2002). For job dispatching, the
38 FCFS rule was used. Table 2 summarizes the characteristics of the simulation model. In
39 setting due dates, we gave a fixed allowance to the job entering the pre-shop pool, as done, for
40 example, by Oosterman et al. (2000) and Land (2006). Thus, due dates were set by giving a
41 constant slack of 20 days to the order reception date. The choice was justified by the use of a
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3 pure flow shop system in which the routing for all products was identical. Moreover, this due
4 date assignment method is simple and has scant influence on the system's other variables.
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8 When comparing the systems, we referred to the typical requirement of the companies with
9 which we have been working: minimize the resources needed to satisfy customer demand,
10 with a limit on maximum delivery time. This is the same as saying 'maximize the output
11 achievable with the given resources, with a cap on delivery time'.
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16 We therefore decided to compare the two ORR systems controlling the workload in the
17 system (i.e. what we called System Workload), which is given by the sum of the workload in
18 the shop and the workload in the pre-shop pool.
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23 This approach makes it possible to focus on the main feature of the ORR: the effectiveness of
24 the release rule to smooth variability in the shop. In fact, the workload in the pre-shop pool
25 has two main purposes: (1) to have a set of jobs from which to choose in order to achieve a
26 better balance of the workload in the shop, thereby reduce workload variability in the shop;
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35 (2) to absorb workload variation in the input to the system.

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37 In this study we have managed to keep the System Workload constant by increasing /
38 decreasing the overall input rate every day – according to the output of the system – thus
39 avoiding the impact of volume variations in customer demand.
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44 This is also done by companies (albeit not on a daily base but on a longer horizon), which
45 increase selling activities when demand is low and decrease them (or increase capacity) when
46 demand is high.
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51 The right level of System Workload was set by running the system with a high System
52 Workload and then decreasing it until the point when a further decrease caused a significant
53 reduction in the system output.
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60 [TABLE 2 HERE]

7.1. *Experimental design*

Experimental variables and simulated levels are presented in Table 3.

To derive the single replication length, we adopted the procedure described in Mosca et al. (Mosca et al., 1982), and we calculated the Mean Square Pure Error (MSPE) on the performances shop floor throughput time, daily throughput level, and gross throughput time. The initial warm-up period was calculated via the Welch procedure (Welch, 1983).

[TABLE 3 HERE]

7.2. *Performance recorded*

A large number of performance measures were recorded. The job-average gross throughput time (Land, 2006) was used as the main performance to assess the results for the two release methods. We also considered the performances related to load unbalancing among workstations and to loading stability. The number of jobs produced daily was also recorded.

8. **Simulation results**

Figure 3 reports the gross throughput time (GTT) values as the shop floor throughput time (SFTT) was varied. SFTT is related to the shop Total Workload which is controlled by increasing / decreasing the norms for the Shop floor. The higher the norms, the higher the shop Total Workload and the higher the SFTT.

[FIGURE 3 HERE]

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3 As the shop Total Workload is decreased, SFTT decreases but generally not so for GTT. The
4
5 Upper Bound Release model (UBR) shows a small increase in GTT as SFTT changes from
6
7 32.3 to 25.9, and a sharper increase for smaller SFTT.
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9

10 By contrast, the Balanced Release model (BLR) shows a decrease in GTT as the SFTT is
11
12 reduced from 36.6 to 16.9, and then increases for further decrease in the SFTT.
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15 BLR yields shorter GTT than UBR for every SFTT level tested. Moreover, BLR presents a
16
17 minimum in GTT at very low values of SFTT.
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20 Although UBR is considered a good ORR system, BLR outperforms it for all SFTT levels,
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22 and allows the company to have both a very small SFTT (i.e. low WIP levels) and a short
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24 GTT.
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27 Because BLR achieves the best GTT (and output) at a much smaller SFTT (norms' level), its
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29 workload in the pre-shop pool is higher and can be reduced without significantly affecting the
30
31 output performances. In Figure 4 we compare UBR at its original System Workload level
32
33 with BLR at a lower System Workload level.
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35

36 With BLR it is possible to maintain an edge in the output of about +0.4% while reducing the
37
38 GTT by about 15% (from 37.75 hours to 32.20 hours)
39
40

41 Therefore, a company adopting UBR must keep a high WIP level, and long GTT in order to
42
43 have a high output. By contrast, a company adopting BLR can run at a much lower WIP level,
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45 decrease the System Workload (thus having a shorter delivery time) and still maintain a
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47 higher output.
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53 [FIGURE 4 HERE]
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57 We then wanted to assess the impact of the job processing times variability, since this is a
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59 fundamental variable in non-repetitive companies. We consequently tested how the relative
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3 performances of the two models changed as the job processing times variability was
4 decreased or increased. Figure 5 and Figure 6 show the comparison for job processing times
5 variability levels of 20% and 80%.
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12 [FIGURE 5 HERE]
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17 In the case of 20% variability, the performances of UBR and BLR are very similar. However,
18 it is interesting to note that a certain advantage in using the BLR model for medium-low
19 workload levels still remains.
20
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23
24 In particular, even though there is not a statistically significant increase in output level, BLR
25 shows a 7.44% better GTT and a 32.26% better SFTT. This means a faster delivery time, a
26 lower WIP (and less space needed), and a more flexible system. In fact, with a smaller WIP
27 the frozen horizon (when it is no longer possible to accept changes to the customer orders as
28 regards specifications/quantity) is shorter.
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39 [FIGURE 6 HERE]
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44 When higher job processing time variability levels are considered, see Figure 6, the two
45 models exhibit greater differences, with an increasing advantage of BLR. This is an
46 interesting finding, because job processing times variability is usually high in non-repetitive
47 companies.
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53 Table 4 gives an overview of the comparison between a system adopting BLR and a system
54 adopting UBR, considering different levels of processing time variability.
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60 [TABLE 4 HERE]

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6 The section on BLR and on UBR presents the value of GTT achievable, the SFTT which
7 yields that GTT, and the output in number of pieces produced over the period simulated.

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10 The percentage difference section presents the percentage difference in performances between
11 the proposed BLR model and the benchmark UBR. In analyzing the differences, we used the
12 paired t-test in order to assess the statistical significance of the differences found, as in Land
13 and Gaalman (1998) and in Germs and Riezebos (2010).

14
15 BLR yields lower GTT, lower SFTT and higher output, and its advantage in GTT increases as
16 the processing time variability increases.

17
18 This advantage on all the considered performances enables the company to optimize the
19 trade-offs according to its market's needs. If, for example, the market values delivery times
20 more than cost, the company can reduce the system workload further. This will reduce the
21 output (and thus increase the unit cost), but will shorten GTT.

22
23 Table 5 presents the decrease in GTT, SFTT, and output when job processing time variability
24 is at 80% and System Workload for BLR is reduced down to 12.000 and then 10.000.

25
26 By contrast, if cost is more important, System Workload can be increased, thus increasing the
27 output but also GTT and SFTT.

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46 [TABLE 5 HERE]
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50 9. Discussion of the results

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52 The improvements achieved by BLR can be explained by the following three elements:

- 53 • flow balancing rather than workload-capacity balancing;
- 54 • explicit load balancing rather than implicit load balancing (achieved through load
55 limiting);
- 56
- 57
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- 60

- extended visibility rather than limited visibility.

9.1. Flow balancing

BLR takes into account the fact that there is a unidirectional dominant flow in the production system, and it is thus difficult to rebalance the workload of an under-loaded downstream workcentre with a new release. In fact, the new jobs released will take time to reach – say – workcentre 4, because they have to be processed on workcentres 1-3 first. By contrast, in job shops, different jobs have different gateway workcentres; therefore a job with its first operation on an under-loaded workcentre can be used to immediately rebalance workload.

Moreover, the spread of Lean principles, the endeavor to shorten queues, and adopting FIFO as a dispatching rule make the system considered even more different from job shops, and the BLR leverages this aspect as well and disregards the workload already in the shop (which will all be processed before the new released one, thus having little interaction between the two) and focuses only on the new release, aiming at an even flow through releasing the same amount of work at each workcentre.

9.2. Explicit balancing

Because BLR focuses on the new release, which is a small amount of work compared to the overall workload, it is crucial to achieve a perfect balance. Therefore BLR has balancing as an explicit objective.

In the BLR model we made it possible, as in Cigolini and Portioli-Staudacher (2002), to penalize under-loads and over-loads differently; but like Cigolini and Portioli-Staudacher (2002) we ran the experimental campaign giving the same penalty to both under-loading and over-loading. We leave determination of the best penalty setting to be applied for under-loads and over-loads to future research.

We collected information on the workload released in each period for each workcenter, and we computed an unbalance index to measure how good BLR was in releasing the same amount of work on each workcenter.

The unbalance index was defined for each period as the ratio between the variation in workload released at each workcenter and the average workload released at each workcenter, then averaged over all simulated periods, as presented in expression (9).

$$WLUI = \frac{1}{P} \sum_{p=1}^P \left(\sqrt{\frac{\sum_{k=1}^K (RL(p,k) - \overline{RL}(p))^2}{K}} / \overline{RL}(p) \right) \quad (9)$$

where p is the simulation period, P is the number of periods of the simulation run, $RL(p,k)$ is the workload released in period p on workcentre k and $\overline{RL}(p)$ is the average workload released to the workcenters in period p .

In Figure 7, the graph for the workload unbalance index is presented for 80% processing time variability at different SFTT levels.

The lower the value of the index, the better the balance, because the same amount of load is released to each workcenter.

[FIGURE 7 HERE]

In order to understand better the values for BLR we compared them to the ones of UBR.

Figure 7 clearly shows that the BLR model has a low WLUI for the most of values of SFTT.

BLR curve also shows that the workload balancing decreases for high shop workload levels.

By contrast, in the case of UBR, balancing is almost unaffected by the shop workload level.

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3 For high levels of workload in the shop, BLR performances are less good because the pre-
4 shop pool is not much populated. In such conditions, the balancing model has little possibility
5 of choosing the jobs that can balance the next release better. When the workload in the shop is
6 too low, even a good balance is not enough: the unavoidable variability in the queues of each
7 workcenter causes starvation, and the output decreases. In addition, in this case the model's
8 balancing possibilities are jeopardized by the fact that the reduced output causes an increase
9 in the GTT i.e. in the length of stay in the system. This increases the number of jobs in the
10 pre-shop pool that reach the Latest Release Date and are thus forced to the shop regardless of
11 their impact on the balancing of the released workload (WLUI increases).
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24 The fact that some other studies do not report such strong differences (see for example
25 Cigolini and Portioli-Staudacher, 2002) is mostly related to the different system
26 configurations – job shop systems rather than flow shop systems – and to the fact that existing
27 balance systems balance workload and capacity rather than released workload itself.
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36 *9.3. Extended visibility*

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38 When the workload balancing is the main goal, a number of jobs that do not well balance
39 workloads may be greatly delayed in the release and thus may contribute to significantly
40 worse timeliness performances (Van Ooijen, 1998; Cigolini and Portioli-Staudacher, 2002).
41 This problem is inherent in ORR systems (Melnik and Ragatz, 1989), and it has been
42 highlighted by a number of studies (see for example Van Ooijen, 1998). It also seems to play
43 a decisive role in the experimentations of Cigolini and Portioli-Staudacher (2002), who report
44 worse performances in job timeliness when a model aimed at balancing workloads is adopted.
45
46 In order to avoid this problem, Van Ooijen (1998) controlled the maximum time that every
47 job could wait in the pre-shop pool, although he found that this countermeasure did not
48 significantly improve the system's performance.
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3 The use of the latest release date as a tool to control the maximum time that a job can wait in
4 the pool may not result in good outcomes because in this situation a job that does not balance
5 well may be shifted to subsequent releases until its Latest Release Date. At the Latest Release
6 Date it is forced into the shop, thus probably spoiling the release balance of that period.
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12 In BLR, the risk is mitigated by the use of an extended schedule visibility approach. Extended
13 schedule visibility plans releases for the current period and all future periods within the time
14 limit. This makes it possible to consider workload balance in the present period together with
15 workload balance in future ones.
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22 Therefore, if a job is postponed until, say, period 3 because it is not well balancing, but no
23 later because its LRD is in period 3, this unbalancing in period 3 is considered together with
24 balancing in the current period and the other ones, and an overall good balancing is pursued.
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29 It is likely that BLR schedules the release for period 2 if the overall workload balance over
30 the future periods is better than if the job is released in period 3.
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34 In other words, simply setting a limit on the latest possible release is an on-off condition: it
35 has no impact before the LRD, and it is an unavoidable constraint at the LRD. With an
36 extended schedule visibility, the constraint on release date is transformed into a balancing
37 issue, compromising balancing in different periods to find an overall better situation.
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45 **10. Conclusions**

46 Workload control has proved to be a rather effective approach for production planning and
47 control, particularly in non-repetitive companies. Researchers and practitioners have focused
48 on ORR systems for job shops, but more and more companies are adopting Lean Principles
49 and streamlining their production processes, thereby making them more of flow-shop type.
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3 In this paper we have presented a new ORR system, named BLR, specifically designed for
4 flow shops and consistent with the Lean approach, intended to reduce WIP and Gross
5
6 Throughput Time, and to level workload release over time (balance flow, not capacity).
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10 We compared it to UBR, one of the best existing ORR models (see Oosterman et al., 2000).
11

12 BLR achieved higher output with much shorter GTT and SFTT. Requiring a smaller WIP,
13
14 BLR has smaller inventory costs, space cost, and shorter frozen horizon, thus making the
15
16 system more flexible.
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18
19 All these advantages have been shown to increase as job processing time variability increases,
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21 thus making BLR most suitable for non-repetitive production. Nonetheless, good advantages
22
23 are also achieved with low job processing time variability.
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26
27 Finally, BLR's workload accounting over time is much easier than UBR's because it is done
28
29 at the shop level in an aggregate form, while UBR requires keeping track of the advancement
30
31 of jobs at each workcentre. This makes BLR quite suitable for implementation in SMEs as
32
33 well.
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35
36 The only disadvantage of BLR is that it requires a more sophisticated release rule, which
37
38 takes longer computational time, but this does not seem to be a major problem because CPU
39
40 time is quite inexpensive today, and takes only 1 minute on a PC for a 5-stage flow shop with
41
42 about 145 jobs in the system.
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44

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46 Future research work will deepen knowledge on the impact of different parameter settings on
47
48 the performance of the proposed BLR model compared with existing ones, and the impact of
49
50 adopting more sophisticated methods to measure the workload in the shop.
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53 54 55 **Acknowledgements**

56
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Figure 1 – ORR framework

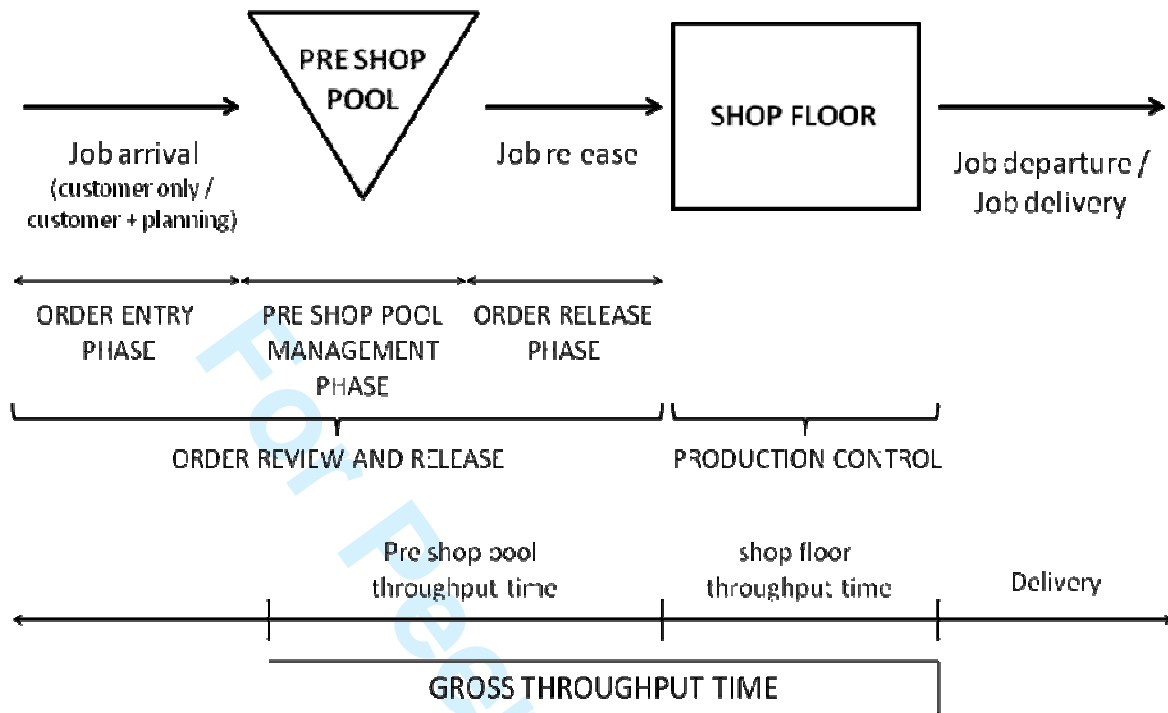
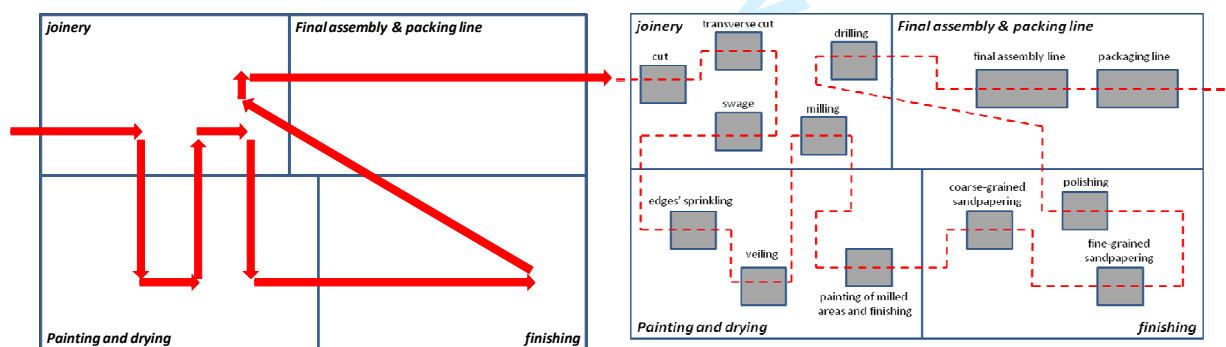


Figure 2 - shop configuration

Product moves back and forth in different departments

Looking more in detail the flow is unidirectional



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Figure 3 – variability index (sigma/mu) 35%

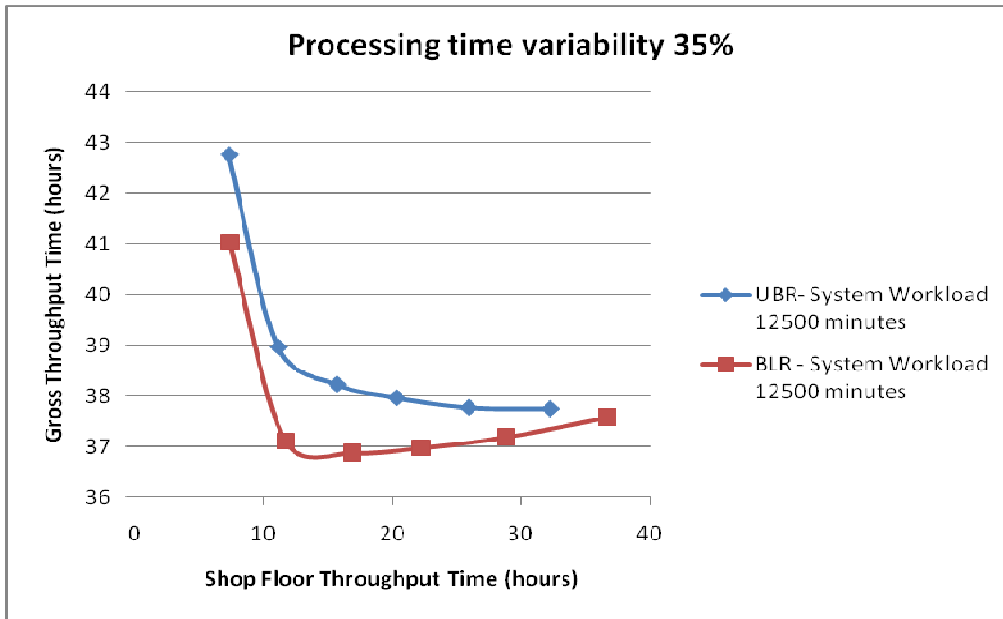


Figure 4 – variability index 35% varying the System Workload for BLR

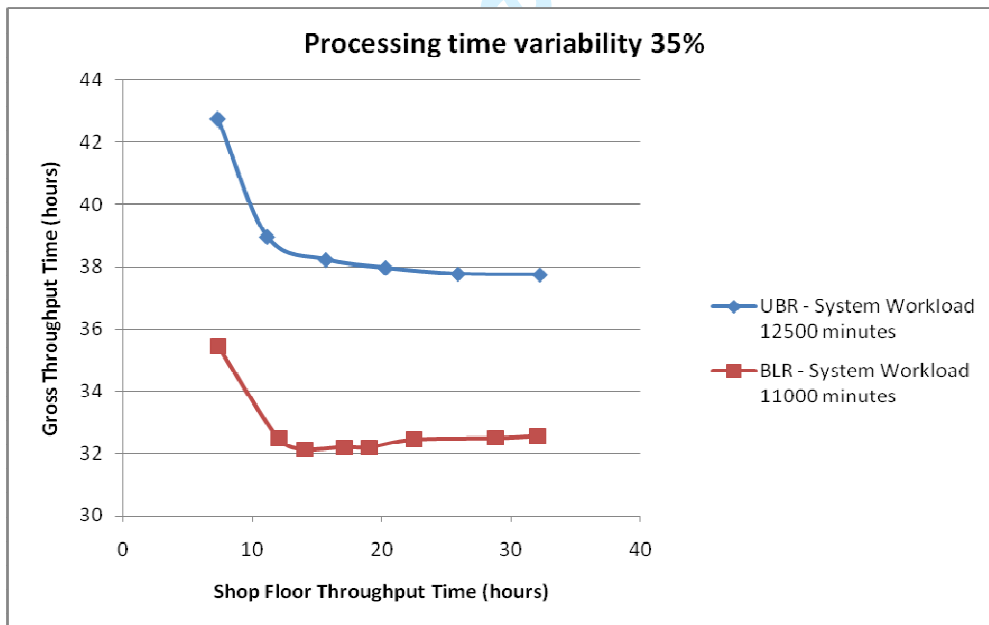


Figure 5 - variability index (sigma/mu) 20%

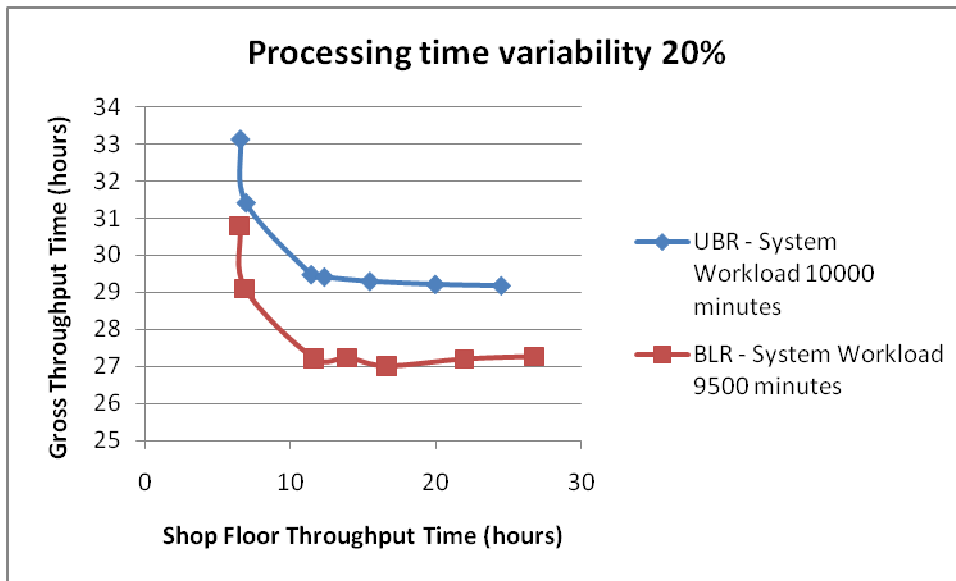
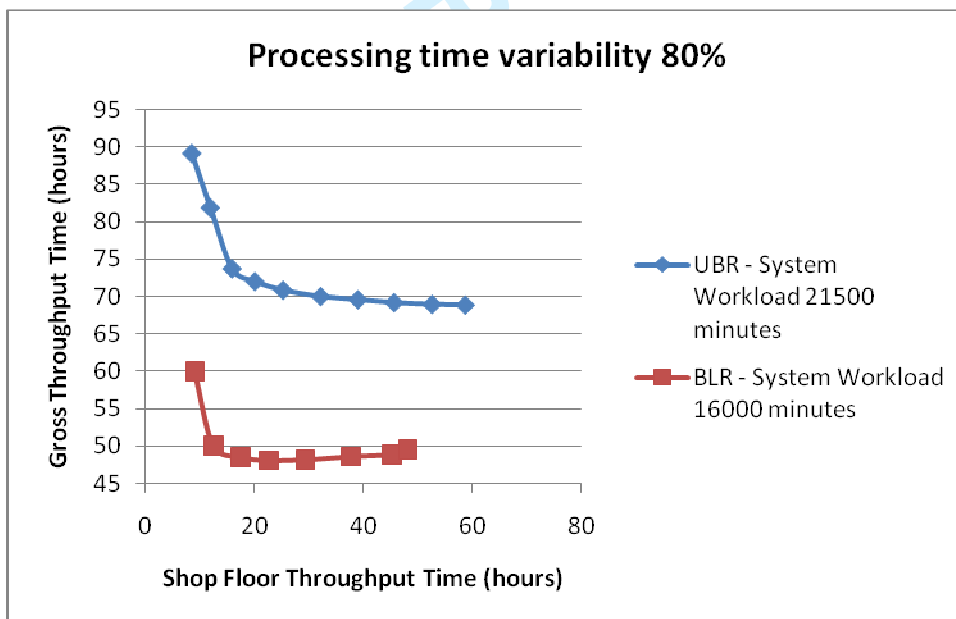
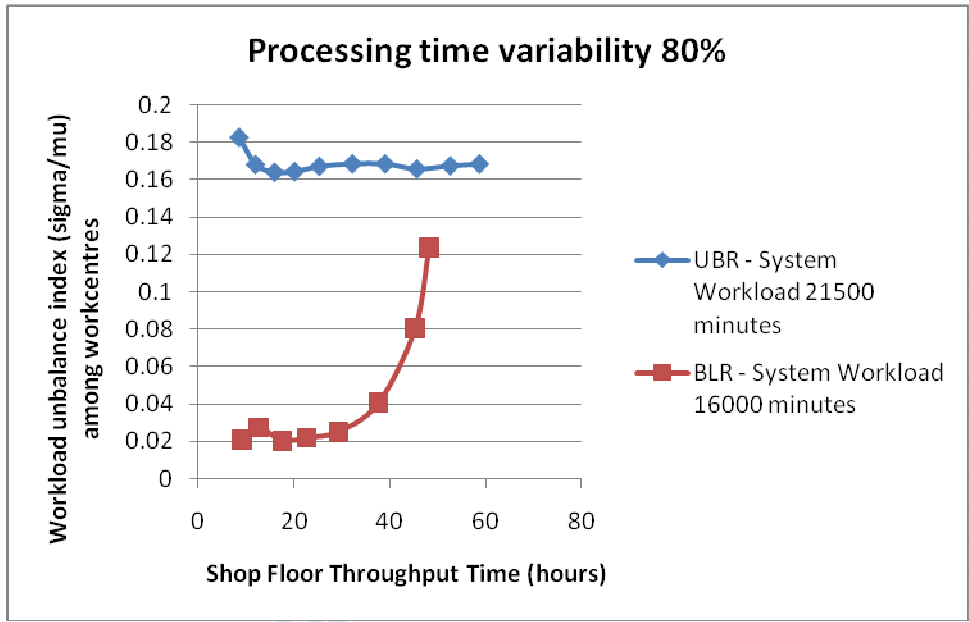


Figure 6 - variability index (sigma/mu) 80%



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Figure 7 – workload balance in daily release



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Table 1 – characteristics of the two ORR systems considered

ORR system characteristic (Bergamaschi et al., 1997)	BLR	UBR
Order Release Mechanism	Load limited	Load limited
Timing convention	Discrete	Discrete
Workload measure	Workload in the shop	Workload in the shop
Aggregation of workload measure	Total shop load (see Bergamaschi et al., 1997)	Load by each workcentre (see Bergamaschi et al., 1997)
Workload accounting over time	Atemporal – shop load (see Bergamaschi et al., 1997 and Oosterman et al., 2000)	Atemporal – aggregate load (see Bergamaschi et al., 1997 and Oosterman et al., 2000)
Workload control	Workload Balance	Upper bound only
Capacity planning	Passive	Passive
Schedule visibility	Extended	Limited

Table 2 – characteristics of the simulation model

Shop configuration	Pure flow shop with 5 workcentres
Workcentres production capacity	480 minutes every day, each workcentre
Routing length	5 stages; deterministic routing for every job
Operation processing times	Operation processing times deterministic
Distribution of jobs' processing times (identical for every workcentre)	Lognormal: mean 29.7 minutes, standard deviation: variable among the different experimentations
Set-up times	Sequence independent
Inter-arrival times	The number of new orders entering the pre shop pool every day varies as to maintain the total System WIP stable.
Due dates	Constant slack added (entry date + 20 days) (for a review of the main due date setting approaches in the literature see e.g. Weng et al., 2008)
Priority dispatching rule	FCFS
Release period length	1 time/day (at the beginning of the production day)
Time limit	Infinite
Production day length	480 minutes

Table 3- experimental variables and simulated levels

Experimental variable	Simulated levels			
variability coefficient for operation processing times (sigma/mu)	20%	35%	50%	80%
ORR system	BaLancing Release (BLR)		Upper Bound only Release (UBR)	
Initial load (minutes)	Between 580 and 4500 minutes depending on the variability levels of jobs' processing times			

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Table 4 – comparison of results (all the percentage differences are statistically significant - at 95% level of significance – except when * appears next to the percentage difference)

	BLR			UBR			Percentage differences		
Processing times variability (σ/μ)	Best GTT (hours)	SFTT at best GTT (hours)	Output at best GTT (pcs./day)	Best GTT (hours)	SFTT at best GTT (hours)	Output at best GTT (pcs./day)	GTT BLR vs UBR	SFTT BLR vs UBR	Output BLR vs UBR
20%	27.01	16.61	16.11	29.18	24.52	16.10	-7.44%	-32.26%	+0.06%*
35%	32.20	17.107	16.08	37.75	32.28	16.02	-14.75%	-34.05%	+0.4%
50%	35.47	17.31	16.01	46.37	37.85	15.93	-23.50%	-54.27%	+0.5%
80%	48.05	22.66	15.98	68.82	58.7	15.83	-30.18%	-61.40%	+1%

Table 5 – comparison of the performances of BLR and UBR at their optimal situation of output and GTT varying the System Workload level of BLR (all the percentage differences are statistically significant at 95% level of significance)

BLR's System Workload	BLR vs. UBR (at System Workload 21500 minutes)		
	GTT	SFTT	OUTPUT
10000 minutes	-58.40%	-62.21%	-0.8%
12000 minutes	-49.26%	-61.89%	+0.9%
16000 minutes	-30.18%	-61.40%	+1%
21500 minutes	-3.37%	-61.58%	+1.4%