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► **To cite this version:**

Matthias Thürer, Cristovao Silva, M Stevenson. Workload Control Release Mechanisms: From Practice Back to Theory Building. *International Journal of Production Research*, 2010, 48 (12), pp.3593-3617. 10.1080/00207540902922810 . hal-00583569

HAL Id: hal-00583569

<https://hal.science/hal-00583569>

Submitted on 6 Apr 2011

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Journal:	<i>International Journal of Production Research</i>
Manuscript ID:	TPRS-2008-IJPR-0520.R1
Manuscript Type:	Original Manuscript
Date Submitted by the Author:	08-Dec-2008
Complete List of Authors:	Thürer, Matthias; Technical University Berlin Silva, Cristovao; University of Coimbra, Mechanical Engineering Department Stevenson, M; Lancaster University, Dept of Management Science
Keywords:	ORDER RELEASE, JOB SHOP, MANUFACTURING CONTROL SYSTEMS, PRODUCTION PLANNING
Keywords (user):	Rush orders, Workload Control



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Matthias Thürer, Cristovao Silva, and Mark Stevenson *

Name: Matthias Thürer
Institution: Technical University Berlin
Address: Institut für Werkzeugmaschinen und Fabrikbetrieb
Pascalstr. 8-9
10587 Berlin
Germany

Name: Dr Cristovao Silva
Institution: University of Coimbra
Address: Mechanical Engineering Department
Pólo II Pinhal de Marrocos
3030 Coimbra
Portugal
E-mail: cristovao@gestao.dem.uc.pt
Tel: 00 351 239 790 757
Fax: 00 351 239 790 710

Name: Dr Mark Stevenson
Institution: Lancaster University
Address: Department of Management Science
Lancaster University Management School
Lancaster University
LA1 4YX
U.K.
E-mail: m.stevenson@lancaster.ac.uk
Tel: 00 44 1524 594015
Fax: 00 44 1524 844885

Keywords: *Workload Control, Order Release Mechanism, Production Planning and Control, Job Size, Rush Orders.*

* Corresponding Author: m.stevenson@lancaster.ac.uk

Workload Control Release Mechanisms: From Practice Back to Theory Building

Abstract

Much Workload Control research has focussed on the order release stage but failed to address practical considerations that impact practical application. Order release mechanisms have been developed through simulations that neglect job size variation effects while empirical evidence suggests groups of small/large jobs are often found in practice. When job sizes vary, it is difficult to release all jobs effectively – small jobs favour a short period between releases and a tight workload bounding while large jobs require a longer period between releases and a slacker workload bounding. This paper represents a return from a case study setting to theory building. Through simulation, the impact of job sizes on overall performance is explored using all three aggregate load approaches. Options tested include: using distinct load capacities for small/large jobs and prioritizing based on job size or routing length. Results suggest the best solution is assigning priority based on routing length; this improved performance, especially for large jobs, and allowed a short release period to be applied, as favoured by small jobs. These ideas have also been applied to a second practical problem: how to handle rush orders. Again, prioritization, given to rush orders, leads to the best overall shop performance.

Keywords: *Workload Control, Order Release Mechanism, Production Planning and Control, Job Size, Rush Orders*

Workload Control Release Mechanisms: From Practice Back to Theory Building

1. Introduction

Workload Control (WLC) is a method of planning and controlling production which has received much attention in recent years. While the customer enquiry and order acceptance stages are important, a large proportion of the literature focuses on the order release stage through which the level of Work-In-Process (WIP) on the shop floor is regulated (e.g., Hendry & Wong, 1994; Missbauer, 1997; Land & Gaalman, 1998; Bertrand & Van Ooijen, 2002; Breithaupt *et al.*, 2002; Cigolini & Portioli-Staudacher, 2002). The unifying theme in this research is the use of a pre-shop pool in which all jobs ‘compete’ against each other for release. Land & Gaalman (1998) explain that a pool can absorb fluctuations in the flow of incoming orders, reduce WIP costs, increase shop floor transparency, reduce waste caused by order cancellations, allow later ordering of raw materials and reduce the need to expedite jobs on the shop floor.

A pre-shop pool can be particularly important where there is instability, such as in the manufacture of bespoke or highly customised products where job sizes (e.g., unit processing times or quantities) vary. However, when job sizes do vary, it can be difficult to plan and control the release of all jobs effectively – jobs with a small workload favour a short period between releases and a tight bounding of the released workload while jobs with a large workload require more time between releases and a slacker bounding of the released workload. This is supported by Land (2006) who explains that a long release period delays certain jobs and can increase gross throughput times while a short release period can hinder the progress of large jobs. Despite the above, simulation studies have tended to ignore this problem at the release stage. Meanwhile, recent case study research identified accommodating job size variations within WLC theory as an important problem for researchers to address in order to improve the effective implementation of WLC in practice (see: Stevenson & Silva, 2008).

In response, this paper explores means of balancing the needs of small and large jobs by attempting to improve the performance of large jobs whilst maintaining a short period between releases (also known as the check or release period), as favoured by small jobs. Oosterman *et al.* (2000) suggest that a 2-Erlang distribution may be a better approach (than

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3 the exponential distribution) to modelling the processing times found in real-life job shops
4 and most studies since Oosterman *et al.* (2000) have adopted this distribution. The simulations
5 described herein use both exponentially distributed and 2-Erlang distributed processing times
6 in order to analyze the implications of the choice of distribution.
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10 In an extension, this paper also seeks to build on recent research by Hendry *et al.*
11 (2008) who investigated issues arising from implementing WLC through comparative case
12 study analysis. The authors examined two implementation projects, one at a capital goods
13 manufacturer in The Netherlands and one at a subcontract engineering firm in the UK. The
14 authors investigated how implementation issues that arise in the context of WLC should be
15 addressed to enable improved implementation in practice. The study identified seventeen
16 implementation issues and raised a series of research questions. These include: “how can
17 future, replacement part, rush orders be considered most effectively within the WLC
18 concept?” One solution the authors suggest is reserving a percentage of capacity for rush
19 orders; however, while suggestions are made, the performance of means of handling rush
20 orders within a WLC system are not tested. After investigating the issue of job size variation
21 in this paper, the findings are used to explore this second important practical problem. This
22 paper represents a return from recent field research to a theory building and testing
23 environment and continues the recent trend in WLC research to more accurately reflect
24 practical considerations in job shop simulations and in the development of theory in order to
25 improve the practical applicability of the methodology (e.g., Perona & Miragliotta, 2000;
26 Bertrand & Van Ooijen, 2002; Henrich *et al.*, 2004).
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41 The remainder of this paper is organised as follows. Section 2 reviews literature on
42 order release mechanisms before the research method is outlined in Section 3. Section 4
43 describes the simulation model and the different approaches we investigate to address job size
44 variation. Simulation results are summarised and discussed in Section 5 before Section 6
45 extends the results to the problem of how best to handle rush orders within the WLC concept.
46 Final conclusions are presented in Section 7.
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55 2. Literature Review

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57 This review considers two core elements of this paper: (1) the influence of the size of a job on
58 performance; and, (2) order release mechanisms. Section 2.1 provides a short review of how
59 job size has been modelled in the literature before Section 2.2 explores order release
60 mechanisms. It is not our intention here to provide a comprehensive review of the literature

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3 on order release mechanisms - many exhaustive reviews of the literature have previously been
4 presented (e.g., Philipoom *et al.*, 1993; Wisner, 1995; Bergamaschi *et al.*, 1997; Sabuncuoglu
5 & Karapinar, 1999). However, two of the most important methodological aspects at the order
6 release stage, included in the classification of order review/release mechanisms by
7 Bergamaschi *et al.* (1997), are: the way in which the methodology accounts for the workload
8 of a job over time; and, the way in which the workloads of shop floor resources are bounded.
9 The impact of processing times, a major contributing factor to overall job size variation, on
10 these two elements is considered before the literature is assessed in Section 2.3.
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14 For a broader review of production planning and control, see: Zäpfel & Missbauer
15 (1993) and Stevenson *et al.*, (2005). For a review of WLC, see Land & Gaalman (1996).
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18 19 20 21 22 23 *2.1 Modelling Job Size Variation*

24 A selection of previous WLC simulation studies is summarised in Table 1 based on the
25 summary of order review/release mechanisms by Wisner (1995). The table includes various
26 approaches to modelling processing times. Job size variation is evident in many of the models
27 but the problem which results from this variation is not addressed. It is also evident from
28 Table 1 that recent studies favour a 2-Erlang distribution, as previously described.
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34 [Take in Table 1]
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37 To the best of our knowledge, the contribution and influence of different job sizes on
38 overall shop performance, and ways of accommodating job size variation, has not been
39 explicitly considered. Papers typically seek to avoid the impact of job size variation,
40 especially the presence of large jobs, rather than to address the issue within the WLC
41 methodology. Therefore, the processing times generated are typically much smaller than the
42 release intervals used in the studies, avoiding problems in the relationship between the check
43 period and the size of jobs, as noted by Land (2006).
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49 Other contributions disregard processing time variation even further. For example,
50 alternative approaches to WLC, including card based methods like CONWIP, often do not
51 consider the size of jobs at all in the release decision. Instead, they control the number of
52 cards (or jobs) in circulation and treat each job in the same way. It is acknowledged that these
53 simplifications may reflect the characteristics of the environment for which the methodologies
54 are designed. For example, Fowler *et al.* (2002) explain that in the semi-conductor industry,
55 where CONWIP has been implemented, it is not unreasonable to assume that processing times
56 are constant. This is not a reasonable assumption in many other contexts.
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2.2 The Impact of Processing Times on Two Aspects of Order Release Mechanisms

There are three notable approaches to accounting for the workload of a job over time when it is being considered for release:

- (1) Aggregate load approaches attribute the workload of a job to relevant work centres at the moment of release irrespective of the routing of a job prior to arrival at a work centre (e.g., Bertrand & Wortmann, 1981; Hendry & Kingsman, 1991; Kingsman, 2000; Kingsman & Hendry, 2002; Stevenson, 2006a; Stevenson & Hendry, 2006). The workload hence includes direct and indirect load without distinguishing between the two. The traditional aggregate load method pays particular attention to the set-up and processing times of jobs in the determination of the workload but has been criticised for having difficulty in providing sufficient control in job shop simulations (e.g., Perona & Portioli, 1998; Oosterman *et al.*, 2000). Adaptations of the traditional aggregate load approach include the corrected and extended aggregate load approaches.
- (2) Probabilistic approaches (e.g., Bechte, 1988 and 1994; Wiendahl, 1995) assign a percentage of the workload of a job to relevant work centres at release, based on the probability of the job reaching the work centre in the planning period. Breithaupt *et al.* (2002) criticise probabilistic approaches for neglecting the influence of processing times on order progress.
- (3) Time bucketing approaches (e.g., Bobrowski, 1989) divide the planning horizon into load periods/time buckets; forward or backward scheduling is then used to assign a job to a load period and it is only included in the period for which it will be the direct load. In recent years, the time bucketing approach has received little attention in the literature.

Of the above approaches, job size variation has a particularly detrimental effect on the aggregate load release method. For example, in relation to the traditional aggregate load approach to WLC:

- When a large job is released, it will have a big impact on the current workloads of all work centres in its routing, even when it is queuing or being processed elsewhere. This can distort the 'true state' of the shop floor and affect the release of other jobs from the pool. It could result in some work centres being left idle and others overloaded.
- Grouping machines can improve the timeliness of feedback information from the shop floor. This can be particularly important for the aggregate load method; however, when

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3 processing times are large, the workload requirements of a job can be misrepresented if
4 machine capacities are grouped (see: Stevenson & Silva, 2008).
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8 Workload bounding refers to the use of parameters to restrict the workload (e.g., on
9 the shop floor). The bounding of the workload is related to the period between releases.
10 Perona & Portioli (1998) demonstrate the need to adjust the interval between releases when
11 considering small and large orders. Large workload limits and long periods between releases
12 would allow large jobs to be released but would undermine overall control of workloads.
13 Hence, a large release period may solve one problem but deteriorate the speed of release for
14 small jobs. If customers expect a short delivery lead time for small orders, the increase in pool
15 waiting time for these orders may affect due date adherence.
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19 Traditionally, the workload is controlled using maximum and/or minimum bounds (or
20 norms). A key research challenge is determining the level at which to set workload norms.
21 This is a subject of much debate. Enns & Prongue Costa (2002) advise that a control level set
22 too high is ineffective but that too low a level provides inadequate throughput. Land (2004)
23 shows that although tightening workload norms hinders the timing of job release, queues on
24 the shop floor fluctuate less and suggests that the difficulties experienced by jobs with long
25 routings and/or large processing times when norms are tight can be compensated for by
26 increasing job priority. It is rare that research in this area considers the impact of large jobs on
27 the bounding of workloads; exceptions include: Bechte (1988), Hendry (1989) and Cigolini &
28 Portioli-Staudacher (2002). When the load limit is reached in Bechte's (1988) probabilistic
29 approach, release is continued for one additional job that would visit the fully loaded work
30 centre. Similarly, Hendry (1989) describes a 'Force Release' mechanism which allows the
31 user to release a job which would exceed the upper bound of one or more shop floor
32 resources. Cigolini & Portioli-Staudacher (2002) describe a workload balancing procedure
33 based upon striking a balance between improving utilisation at an under-loaded work centre at
34 risk of starvation at the expense of overload elsewhere. Individual work centres can be
35 overloaded as long as the overall workload balance across all work centres is improved. These
36 solutions provide flexibility which goes some way to allowing large jobs to be released.
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54 55 *2.3 Assessment of the Literature*

56 Job size variation is an important problem impacting the performance of existing WLC theory
57 at the order release stage but one which has received insufficient attention to date. Existing
58 theory has a tendency to treat all jobs equally. In contrast, it is argued here that where there
59 are distinct differences in job size, disregarding the impact of this variation is inappropriate
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3 and such models are unlikely to result in an effective solution for all jobs. In what follows, we
4 acknowledge that small jobs have different requirements to large jobs and experiment with
5 adapting the release mechanism to reflect this. This includes allowing the workload norm to
6 be exceeded (from Bechte, 1988) and increasing job priority for large jobs (from Land, 2004).
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10 Job size variation has a particularly detrimental effect on the aggregate load method
11 and hence it is the method in most need of development. Moreover, this is the simplest
12 method and, given that it is argued that managers prefer simplicity, is considered the one most
13 likely to be successfully implemented in practice. Therefore, the study will use aggregate load
14 methods as the basis for workload accounting over time (the traditional, corrected and
15 extended aggregate load methods). With regards to workload bounding: difficulties in setting
16 effective workload norms may be caused by attempting to find a single bound that will meet
17 the needs of all jobs. Therefore, we try to accommodate differences between groups of jobs
18 more explicitly within the bounding of the WLC concept.
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29 **3. Methodology**

30 *3.1 Empirical Grounding for the Study*

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33 Recent case study research (see: Stevenson, 2006a/b; Silva *et al.*, 2006; Hendry *et al.*, 2008;
34 Stevenson & Silva, 2008) identified practical considerations which affect how the WLC
35 concept is used in practice. Among these is the importance of accommodating processing time
36 variation within the WLC methodology, thus providing an empirical grounding for this study.
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42 Company M (see: Silva *et al.*, 2006 and Stevenson & Silva, 2008) produce one-off
43 aluminium moulds for pre-series production and steel mould components for large series
44 production (e.g., for the automotive and electronics industries). Each aluminium mould is
45 engineered-to-order and typically comprises of a large number of components, some are very
46 simple, others are more complex. Processing time variation across jobs is prominent, which
47 results in high job size variation. Under the WLC concept that Silva *et al.* (2006) attempted to
48 implement, all components had to 'compete' against each other for the same set of resources;
49 this led to implementation problems and resulted in large jobs performing worse than small
50 jobs. The poor performance of large jobs was particularly striking if one considered that the
51 *relative* gross throughput time of large jobs should be smaller than the relative gross
52 throughput of small jobs if delivery lead times are to be competitive. Even if small and large
53 jobs performed equally well, based on gross throughput time as a percentage of a job's work
54 content, the lateness of large jobs was not acceptable while, in contrast, a degree of
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deterioration in the performance of small jobs would be 'acceptable'. Thus, to differentiate according to job size, and to find an optimal balance between the requirements of job sizes, appeared to be vital in order to implement the system successfully in this context.

The authors have observed a similar phenomenon in a very different production setting - a plastic bag manufacturer. The majority of production orders are processed in less than 24 hours but, like in Company M, a significant proportion take more than one working day. Unlike in Company M, this is not due to differing product complexity but to differing order quantities. Again, job size variation caused significant problems for the application of existing WLC theory in this company.

3.2 Research Questions

To overcome the detrimental effect of job size variation on performance, as noted from the literature and observed in practice, the research began with the following questions:

- (1) How can the existence of groups of 'small' and 'large' job sizes be best incorporated within the order release mechanism of the Workload Control concept?
- (2) How can a balance between the requirements of 'small' and 'large' processing times be best achieved in order to improve the release mechanism and overall shop performance?

The best way to explore this problem is considered to be through simulation; hence, this study represents model-based research driven by empirical findings. Bertrand & Fransoo (2002) explain that: "*in this class of research, the primary concern of the researcher is to ensure that there is a model fit between observations and actions in reality and the model made of that reality*". The authors also explain that: "*quantitative model-based research is a rational, objective, scientific approach*". Simulation thus provides us with a good means of testing and evaluating new ideas in a controlled environment which can be replicated by other researchers.

3.3 Iterative Approach to Theory Building

This paper tests several release mechanisms which seek to avoid the problems outlined in the above sections and obtain a 'best-of-both-worlds' solution. The research follows an iterative approach to building, testing and refining theory, as illustrated in Figure 1. The concept of WLC is often cited as being developed to overcome the lead time syndrome (Mather & Plossl, 1978). Throughout the 1980s and 1990s, WLC theory has been developed, tested and refined through simulation. Refined theory has been incorporated within the design of decision

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3 support systems and applied during case study research. This study closes one iteration of the
4 loop. It starts with the identification of a problem encountered in recent case study work, for
5 which several possible solutions, representing practical extensions to WLC theory, are
6 proposed. To test these solutions, the study returns to the simulation environment previously
7 used by many authors to test the WLC theory. Replicating the traditional WLC simulation
8 environment, which is a simplification of a real-life shop floor, allows research to identify the
9 best solution to the problem encountered whilst maintaining consistency with the WLC
10 simulation research methodology used in the past. The outcomes of these tests can be
11 considered when implementing WLC systems in practice in the future, allowing the next
12 iteration of research to confirm the effectiveness of the solutions proposed by this study.
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14 Hence, the paper demonstrates the complementary roles which case and simulation modelling
15 research can play in the development of theory and improvement of practice.
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[Take in Figure 1]

4. Simulation Model

4.1 Shop Characteristics

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36 A pure job shop simulation model, according to the characteristics outlined by Melnyk &
37 Ragatz (1989), has been developed using SIMUL8 © software. This model is used in many
38 WLC simulation studies (e.g., Hendry & Wong, 1994; Oosterman *et al.*, 2000; Land, 2006).
39 The shop contains six work centres, where each is a single and unique source of capacity,
40 which remains constant. The routing length varies from one to six operations. Each operation
41 requires one specific work centre; routing and operation processing time characteristics are
42 known upon job entry. A particular work centre is required at most once in the routing of a
43 job; all stations have an equal probability of being visited. A First-Come-First-Served (FCFS)
44 dispatching rule is used on the shop floor.
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4.2 Release Mechanisms

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56 In this study, the assumption is that all orders are accepted, that materials are available, and
57 that the process plan (including information regarding routing sequence, processing times,
58 etc) is known. Orders flow directly into the pre-shop pool; hence, like in most previous
59 studies, a pool of confirmed orders is the starting point. At release time 't', jobs in the pool are
60 considered according to shortest slack.

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3 A job is attributed to the load of the work centres corresponding to its routing at the
4 moment of release. If this aggregated load fits within the workload norm, the job is released to
5 the shop floor. If one or more norms would be exceeded, the job must wait until at least the
6 next release period. This procedure is repeated until all jobs in the pool at release time 't' have
7 been considered for release once. Three aggregate load approaches are applied:
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11 • The traditional (or classical) aggregate load approach (B), as described by Tatsiopoulou
12 (1983), Hendry (1989) and Section 2.2 of this paper.
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14 • The extended aggregate load approach (C), developed in response to problems caused by
15 a lack of feedback information from the shop floor, as experienced by Tatsiopoulou
16 (1983) while implementing the traditional aggregate load approach. Under the extended
17 approach, a job contributes to the workloads of all stations in its routing until it leaves the
18 shop floor. Hence, only feedback when the job leaves the shop floor is needed.
- 19
20 • The corrected aggregate load approach (B'), developed to account for the routing (and
21 routing length) of jobs in the aggregation procedure (ignored by the traditional approach).
22 Under the corrected approach (see: Land & Gaalman, 1996), the load contribution at the
23 moment of release is depreciated according to the position of a work centre in the routing
24 of a job. The further downstream a work centre is, the higher the depreciation factor.
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35 In this study, the check period is set to 5 time units, i.e., jobs in the pool are considered
36 for release every 5 time units. To avoid unnecessary complexity and enable a clear insight
37 into the performance of the system, the planning horizon equals the check period.
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42 4.3 Job Characteristics and Due Date Setting Procedure

43 Due dates are set by adding a random allowance to the job entry time: see equation (1) below,
44 as described in Oosterman *et al.* (2000) and Land (2006). Land (2006) states that the
45 minimum value should cover a station throughput time of 5 time units (the maximum
46 processing time plus one time unit) for a maximum of 6 operations plus a waiting time before
47 release of 5 time units.
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$$53 \text{ Due date} = \text{Job entry time} + a, \text{ with } a \text{ uniformly distributed } [35, 60] \quad (1)$$

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57 Recent studies have modelled processing times using a 2-Erlang distribution. In this
58 study, 2-Erlang and exponential distributions (both with a mean of 1 time unit) will be used in
59 order to analyze the influence that the modelling approach has on performance. All relevant
60 performance measures are arithmetically derivable from the two performance measures we

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3 collect. The chosen inter-arrival time of jobs (see Table 3) guarantees a machine utilization
4 rate of 90% for all the workload norms tested. Thus, for the workload norms tested, the output
5 is not affected by the load limitation.
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9 The characteristics of our job shop and jobs are summarised in Table 2 and Table 3,
10 respectively.
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12 [Take in Table 2 & Table 3]
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15 16 17 *4.4 Job Size*

18 The main research objective is to analyze the influence of different job size on overall
19 performance. Therefore, jobs are subdivided into ten groups according to job size: nine groups
20 are defined for jobs smaller than 9 time units (using an interval of one time unit); and, one
21 group is defined for jobs larger than 9 time units. To ease comparison, results for the different
22 job sizes are summarized in two groups. Jobs larger than 3 time units are considered ‘large
23 jobs’; jobs less than or equal to 3 time units are considered ‘small jobs’. All large jobs showed
24 a similar performance pattern; the same is true of small jobs.
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27 Figure 2 shows the distribution of job sizes using the exponential and 2-Erlang
28 distributions. There is a notable difference between exponentially distributed processing times
29 and 2-Erlang distributed processing times, particularly with regard to the number of large
30 jobs. The exponential distribution shows a much higher number of very large jobs and a
31 higher number of very small jobs. Job size for the 2-Erlang distribution is more settled around
32 a mean of 3.5, showing less variance. 50% of jobs on the shop floor are smaller than 3.5 time
33 units (the expected value for job size given a mean: routing length of 3.5 and processing time
34 of 1 time unit) but represent only 30% of the total shop floor workload; 70% of the shop floor
35 load is represented by the 50% of jobs larger than 3.5 time units.
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38 [Take in Figure 2]
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50 51 52 *4.5 Experimental Design*

53 In the first stage of experiments (the ‘standard scenario’), the simulation model is run without
54 any special conditions and the performance of the different job sizes is analyzed. Then, the
55 following four approaches are implemented and will be compared with the standard scenario:
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- 58 • Distinct load capacities for small and large jobs: The capacity of each work centre is
59 divided into two parts and allocated proportionately to small and large jobs separately,
60 according to the size of the jobs.

- Prioritization: Jobs are prioritized in the pool according to job size or routing length. Either the largest job or longest routing is considered for release first.
- Exceeding the workload norm: The first job that exceeds the norm can be released. This should improve the performance of large jobs (more likely than small jobs to be the first to exceed the norm level).
- Load correction: Feedback from the shop floor, used in the traditional aggregate load approach, is corrected by the hypothetical downstream load. This represents the proportionate load of a job in-process at a work centre at job release but which is already complete. Under release method B, this proportion would continue to contribute until the whole job is complete at the work centre.

Each of the four approaches proposed above, plus the standard scenario, has been tested considering: two approaches for the generation of processing times, three aggregate load approaches and 13 load norm levels. This results in a full factorial design of experiments. The key results we focus upon are the gross (or total) throughput time and the (shop floor) throughput time. The (shop floor) throughput time describes the performance of the job after release and allows us to evaluate the performance of the shop floor. The gross throughput time, which incorporates the pool delay, provides an overview of the performance of the job across the whole system and indicates the percentage of late jobs to which it is directly related. Some preliminary tests were conducted in which mean job lateness was also analysed. These tests showed that the behaviour of the model was very similar in terms of mean job lateness and gross throughput time, i.e., good results in terms of gross throughput time meant good results in terms of mean lateness. Thus, the decision was made to focus on gross throughput time and to ignore mean job lateness during further testing.

Results are obtained by tightening the norm level stepwise down from infinity, represented by the right-hand starting point of the curves which follow in Section 5 and Section 6 (see Figures 3-11). A norm level of 100% is equivalent to the critical workload norm. The critical workload norm represents the point where the throughput time ceases to decrease, while the gross throughput time continues to rise; this will be determined empirically. Each experiment consists of 100 runs; results are collected over 10000 time units; the warm-up period is set to 3000 time units to avoid start-up effects.

5. Results

5.1 Results for the Standard Scenario

Figures 3 and 4 show the results for release method B, the traditional aggregate load approach, under the standard scenario. As the norm is tightened, the shop floor throughput time is reduced, caused by a reduction in the average waiting time in front of work centres. This, however, does not necessarily imply a reduction in the gross throughput time when the time in the pre-shop pool is also considered.

[Take in Figure 3 & Figure 4]

From the figures, it can also be concluded that in the standard scenario, large jobs generally perform worse than small jobs (particularly noticeable if processing times are exponentially distributed due to the greater job size variance). For both distributions, the gross throughput time for large jobs is high relative to that for small jobs. To minimise the percentage of late jobs, the delivery lead time has to be large but this reduces the competitiveness of due date quotations a company can realistically make at the customer enquiry stage. Similar results, consistent with those obtained by Oosterman *et al.* (2000), have been obtained for the corrected and extended aggregate load approaches. The corrected approach performs the best out of the three and the extended approach performs the worst.

5.2 Results Based on Different Load Capacities for Small and Large Jobs

One of the simplest potential solutions to our problem is to use different norm levels for small and large jobs and to distribute the load capacity of the shop floor proportionately according to the processing times of jobs. While this appears simple, using more than one norm increases the check period because capacity must be provided for both norms, leading to a greater gross throughput time. A longer period between releases implies a longer pool delay, which cannot be fully compensated for by any resulting gain in performance. To compensate, two solutions have been explored: (1) using different workload norms and check periods for small and large jobs; and, (2) using two different check periods for small and large jobs but the same resources of load capacity. Consider the following:

- (1) Using two different workload norms and check periods for small and large jobs leads to another challenge – how to set them, given that the load capacity and check period are inter-dependent? At each release point for small jobs, a percentage of capacity is kept free for large jobs. The minimum check period for large jobs is the period needed to provide

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3 enough free capacity for the release of large jobs (based on the maximum processing
4 time). The more capacity reserved, the sooner large jobs can be released; this implies a
5 shorter check period for large jobs and a larger check period for small jobs. Each
6 improvement for one job size leads to a deterioration for the other. Moreover, if only
7 large jobs, and thus only large processing times are released, 'load gaps' begin to emerge
8 which would otherwise be filled by jobs with a small workload contribution.
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14 (2) Typical applications of using two different check periods, but where all jobs rely on the
15 same resources of load capacity, favour small jobs; large jobs find it more difficult during
16 the shorter of the two release periods to be released. Small jobs are released and
17 contribute to the shop floor load thus reducing free capacity at the next (and longer)
18 release period, thereby undermining the solution.
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24 The results of applying different norms for small and large jobs did not improve
25 performance. This might be an effect of the short planning horizon and rigid workload norms
26 assumed in the simulations. Applying a long planning horizon, and allowing jobs to
27 occasionally exceed the workload norm where appropriate, as is typical in real-life job shops,
28 neutralizes many of the restrictions which lead to poor performance. Another practical
29 advantage is that this approach, using different resources of capacity for small and large jobs,
30 lessens the detrimental effects which job size variation has on aggregate methods (as
31 described in Section 2.2). Therefore, it is concluded that the methods explored in this section
32 are unlikely to lead to improvements in overall performance but may show more positive
33 effects in practice.
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43 *5.3 Results Based on Prioritization Methods*

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45 Three different prioritization methods have been tested, as outlined below:
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- 47 • Prioritization according to job size: Jobs are considered for release according to size and
48 secondarily according to latest release date. Firstly, all jobs with a processing time greater
49 than 9 time units are considered. Of these, the job with most immediate latest release date
50 is considered first. This continues down through the other groups of job sizes, starting
51 with jobs between 8 and 9 time units, until all jobs have been considered for release once.
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- 53 • Priority according to routing length: Similar to above but according to routing length,
54 starting with all jobs with a routing length of 6 operations.
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- 56 • Converted priority, according to routing length: This aims to guard against the
57 discrimination of small jobs which will occur in the above two prioritization methods.
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3 Release precedence is determined by a combination of priority and slack, where slack is
4 depreciated according to routing length. Thus, jobs with a larger routing length are given
5 priority over jobs with a shorter routing length but with a similar slack. Figure 5 shows
6 the new priority measure, standardized to a scale of [0, 10] for the different slack levels.
7 Jobs are not further prioritized strictly according to routing length. Jobs with short routing
8 lengths and a short slack receive priority over jobs with a larger routing length but longer
9 slack.
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17 [Take in Figure 5]
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19 To analyze the results, the above prioritization rules have been compared to the
20 standard scenario for the three aggregate load approaches. Scenario I represents the standard
21 scenario; in scenario II, prioritization is based on job size; in scenario III, prioritization is
22 based on routing length; and, in scenario IV, prioritization is according to 'converted priority'.
23 Subsections 5.3.1 and 5.3.2 summarise the results of scenarios I-IV for the traditional,
24 corrected and extended aggregate load approaches.
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31 *5.3.1 Results for Release Method B: Traditional Aggregate Load Approach*

32 Figures 6 and 7 show the results obtained using the traditional aggregate load approach for
33 scenarios I-IV for the jobs overall and for small and large jobs individually using the 2-Erlang
34 and exponential distributions. It can be observed that if prioritization is based on job size
35 (scenario II), the performance for 2-Erlang distributed processing times is a slight
36 improvement on the overall results obtained for the standard scenario (scenario I). However,
37 if processing times are exponentially distributed, performance stays the same or deteriorates.
38 Assigning priority according to job size improves performance for large jobs but significantly
39 deteriorates performance for small jobs. This deterioration becomes even worse if processing
40 times are exponentially distributed. There are two possible causes of these poor results, either:
41 (1) the shop floor throughput time increases, caused by the influence of sequence changes at
42 the release stage on the dispatching rule; or, (2) the gross throughput time increases, from a
43 longer pool delay as a result of the difficulties smaller jobs face in being released. As can be
44 seen from the figures, the deterioration in performance of small jobs, and the improvement of
45 large jobs, is mainly caused by the change in pool delay. Small jobs with a high routing length
46 are difficult to release. A small job size does not necessarily imply a short routing length and
47 vice versa. As a result, only considering job size in the release decision does not lead to an
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3 overall improvement. The improvement for large jobs does not fully compensate for the
4 deterioration in small jobs.
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8 [Take in Figure 6 & Figure 7]
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10 If prioritization is based on routing length (scenario III), results are very positive
11 (compared with scenario I). The improvement for large jobs is almost the same as in scenario
12 II, but the negative effect on the performance of small jobs is significantly less. The
13 performance of small jobs is only slightly worse than in the standard scenario. Using the
14 converted measure for prioritization (scenario IV) improves the performance of small jobs
15 compared with giving prioritization strictly according to routing length; however, this
16 improvement does not compensate for the deterioration in performance for large jobs. Hence,
17 results for the traditional approach indicate that the best solution is scenario III, prioritization
18 based on routing length.
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28 *5.3.2 Results for Release Methods B' & C: Corrected and Extended Aggregate Loads*

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30 Figures 8 and 9 summarise the results for release method B' (the corrected load approach) for
31 scenarios I-IV for the jobs overall and for small and large jobs individually. Results are very
32 similar to those for the traditional approach. As previously, basing prioritization on routing
33 length (scenario III) yields the best results. Prioritization according to job size (scenario II)
34 yields slightly better results for large jobs than above but results in extremely poor
35 performance for small jobs; the converted priority approach (scenario IV) leads to a slight
36 improvement in the performance of small jobs but performance is much worse for large jobs.
37 Results for release method C (the extended load approach) are not shown but the same
38 conclusions as for release method B' are also valid here. Through comparison, it can be
39 concluded that the corrected aggregate load approach (B') performs the best out of the three
40 release methods and the best solution remains scenario III, prioritization based on routing
41 length.
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52 [Take in Figure 8 & Figure 9]
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56 *5.4 Results Based on Allowing the Workload Norm to be Exceeded*

57 The Load Oriented Manufacturing Control (LOMC) concept presented by Bechte (1988),
58 based on the probabilistic WLC approach, compensates for large jobs at the release stage. The
59 norm level is relaxed; the first job that exceeds the load limit is still released to the shop-floor,
60 allowing very large jobs at the front of the queue in the pool to be released. In experimenting

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3 with using this idea in an aggregate load context, it has been difficult to control the emerging
4 overload. Allowing workload restrictions to be exceeded can result in the shop spiralling out
5 of control as, for example, the overload released at release time ' t_x ' has a negative influence
6 on what can be released at release time: ' t_{x+1} '. The extra (potentially very large) job that is
7 released has to leave a given work centre before its workload is withdrawn and the capacity is
8 made available for other jobs. The shop floor has to compensate for the overload and thus the
9 capacity available for the release of other jobs is less. This hinders the release of especially
10 large jobs in future periods; thus each time a job is released in this way, it stores up problems
11 for the next release. No positive results have been obtained for release methods B, B' and C.
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21 *5.5 Results for the Load Correction Approach*

22 Under the traditional aggregate load approach, jobs which are in-process at a given work
23 centre at release time ' t ' contribute as a whole to the workload of the resource, adversely
24 affecting the release of jobs from the pool, even though a proportion of the work has been
25 completed and is thus hypothetically downstream. The workload of a work centre is only
26 reduced when the whole of a job has left the work centre and this information has been fed-
27 back from the shop floor. Under the load correction approach, the release procedure
28 compensates for in-process jobs and corrects the load by deducting the hypothetical
29 downstream load. Correcting the load should increase the capacity available for other jobs and
30 make it easier for large jobs to be released. Despite this, no positive results have been
31 obtained. Correcting the load showed no, or only a slight, improvement compared with the
32 traditional approach.
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43 *5.6 Discussion of Results*

44 Results show that using different norms for small and large jobs and dividing the capacity of
45 the shop floor according to job size or routing length is inadequate: it increases the check
46 period and thus the pool delay. This effect could be improved by using a longer planning
47 horizon, and a relaxed norm level, and is worthy of further exploration. Allowing jobs to
48 exceed the workload norm once is also unsuitable for aggregate load methods: it causes an
49 overload which is difficult to handle and to 'get under control'. Similarly, the load correction
50 method has shown no positive effects.
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58 The best approach is prioritization; all scenarios based on prioritization led to an
59 improvement in overall performance compared to the standard scenario. Small jobs find it
60 more difficult to be released but the increase in pool delay for small jobs is overshadowed by

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3 the pool delay reduction for large jobs. The question is: can deterioration in the performance
4 of small jobs be accepted? In practice, perhaps the answer depends on the proportion of small
5 and large jobs in the company's current job mix and the way in which the performance of the
6 company is measured (i.e., is one on-time small job evaluated in the same way as one on-time
7 large job or is the total work content of a job considered in determining performance?).
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12 A small performance loss for small jobs may be acceptable if the performance of large
13 jobs is clearly improved. It also seems practical to consider larger jobs for release first and
14 then to fill the emerging gaps of free capacity with small jobs. Choosing which jobs are
15 considered for release first has a significant influence on the pool delay and thus on the gross
16 throughput time. In addition to the influence on the pool delay, prioritization did not have a
17 negative influence on shop floor throughput time performance. It was expected that the
18 combination of changing the sequencing at the release and the FCFS dispatching rule would
19 deteriorate the performance of small jobs at the direct load level. The jobs that are first
20 released are also the first jobs to arrive in the queue in front of the work centre. It was
21 expected that this would lead to deterioration in the performance of small jobs on the floor
22 because there is always likely to be a large job being processed first. However, the negative
23 influence is on the direct load, which is typically small and thus of less influence than the
24 indirect load if the routing length is long. To summarise, consider the following:
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- 36 • If jobs are prioritized according to size (scenario II), large jobs benefit the most. Jobs
37 with a large routing length but small job size are unlikely to ever be released; this is a
38 major contributing factor to the high average loss in performance for small jobs.
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- 40 • If jobs are prioritized according to routing length (scenario III), a less significant
41 improvement in performance for large jobs is observed but the deterioration of small
42 jobs is much less, and the best overall performance is obtained.
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- 44 • The performance of small jobs can be slightly improved using the converted priority
45 method (scenario IV); however, much of the benefit for large jobs that results from
46 prioritization according to size or routing length is lost.
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53 The way in which processing times are distributed is also important. If processing
54 times follow a 2-Erlang distribution, overall performance is significantly better than if
55 processing times follow an exponential distribution. Prioritization according to routing length
56 improved performance if processing times are exponentially distributed and thus if job size
57 variation is high. Using this method, there is almost no difference in performance compared
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3 with a 2-Erlang distribution. For all approaches, release method B' (the corrected approach)
4 performed best and method C (the extended approach) performed the worst.
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9 10 **6. Handling Rush Orders**

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14 Despite the importance of rush orders in real-life job shops, where a company may receive an
15 important urgent order at short notice, the topic has received little attention in the wider
16 literature. A rare contribution is made by Wu & Chen (1997) who developed a model to
17 estimate the cost of producing a rush order in an assemble-to-order context. Handling rush
18 orders has not been adequately explored in the WLC literature. The question of how the
19 emergence of rush orders can best be handled within the structure of the WLC concept is an
20 important implementation issue highlighted by Hendry *et al.* (2008). While Hendry *et al.*
21 (2008) suggest reserving a percentage of capacity for rush orders (based on their arrival rate)
22 to cope with the problem, this idea has been rejected as it raises the check period - the same
23 problem as identified in Section 5 when capacity was reserved for small and large jobs
24 respectively. Therefore, following the results outlined in Section 5, this section briefly
25 explores whether prioritization, the best solution to handling job size variation, could play a
26 similar role in handling rush orders or if allowing rush orders to exceed workload norms
27 provides a better solution.
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40 Figures 10 and 11 summarise the results obtained for release method B, the traditional
41 approach, under three scenarios, for rush orders and the overall remaining orders. Scenario I
42 represents the standard scenario without rush orders; in scenario II, priority is given to rush
43 orders; and, in scenario III, rush orders are allowed to exceed workload norms. The results for
44 method B', the corrected aggregate load, and method C, the extended aggregate load, are
45 similar but not shown here. Method B' performed best and method C the worst. From this
46 brief extension to the analysis, it is concluded that prioritization (scenario II) performs the
47 best, especially if processing times are exponentially distributed. If rush orders are allowed to
48 exceed the norm (scenario III), they cause the same uncontrollable overload as outlined in the
49 previous section. The shop floor throughput time performance of rush orders deteriorates due
50 to the uncontrolled load on the shop floor and the remaining jobs have a much longer pool
51 delay caused by the disturbed feedback from the shop floor. Prioritization has been tested up
52 to a rush order proportion of 30%. This is considered a very high - Hendry *et al.* (2008)
53 suggested a rush order proportion of between 10 and 20% - however, the performance of rush
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3 orders remained relatively stable irrespective of changes in the rush order percentage. For the
4 overall remaining orders, the lower the percentage of rush orders, the better the performance
5 of non-rush orders.
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9 [Take in Figure 10 & Figure 11]
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12 In an additional approach (scenario IIIi), rush orders were allowed to exceed the norm
13 without contributing to the load – on arrival, they were released directly to the shop floor and
14 neglected by the WLC system. The occupation of the shop floor was maintained at the same
15 level, meaning the WLC system parameters were adapted to the new lower load. Rush orders
16 resulted in a significant loss in shop floor throughput time performance due to the
17 uncontrolled overload on the shop floor. Hence, it is not possible to control only part of the
18 shop floor using a WLC system; if WLC is to be effective, the whole shop floor must be
19 controlled.
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29 7. Conclusion

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33 The order release stage of the Workload Control (WLC) concept has received much attention.
34 Despite this, research has failed to address many of the practical considerations involved in
35 the release of jobs that affect the ability to apply the concept in practice. This paper
36 contributes to the available literature by representing a return from field work to a theory
37 testing environment, demonstrating the complementary roles which case and modelling
38 research can play in the development of theory. An original attempt to address the issue of
39 variations in job size is presented. Several approaches have been tested to satisfy the special
40 requirements of both small and large jobs and to improve the practical applicability of the
41 WLC methodology.
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49 Considering the research questions that were raised in Section 3.2: prioritization
50 appears to be the best solution to incorporating small and large job sizes within the release
51 mechanism of the WLC concept, providing the best balance between the differing needs of
52 the two job sizes. This improves the performance of large jobs while simultaneously allowing
53 a short check period to be used, as favoured by small jobs. The results obtained for this
54 solution also show greater stability and less deviation among the single results for each
55 simulation run. Although this was not the intention of the work, we can conclude that the
56 robustness of the system has also been improved.
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3 In conclusion, giving priority to jobs with a large routing length is a more effective
4 solution to the problem than reserving capacity for each job size or allowing jobs to exceed
5 the norm. The same conclusion is also shown to be valid for rush orders, where prioritization
6 proved to be the best solution in order to handle the arrival of rush orders within the WLC
7 concept. While the proposed solution for job size variation is consistent with the suggestion
8 made by Land (2004), the solution for rush orders is in contrast to the suggestion made by
9 Hendry *et al.* (2008). The results have implications for practice by showing that relatively
10 simple methods can improve the performance of release mechanisms. Prioritization is likely
11 to be the solution that can be most realistically applied in practice – an important driver of
12 theory. However, while prioritization is considered a relatively simple method of improving
13 the effectiveness of the release mechanism, whether the advantages prioritization provides
14 outweigh a slight increase in sophistication for the production planner can only be determined
15 by returning to a case study setting - and so the cycle continues.
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Authors	Routing	Work Centres	Operations	System	Processing Times
Bertrand (1983)	R	5	U~[1,10]	H	Exp. Distribution, (1/λ) = 1 hour AND < 5
Shimoyashiro <i>et al.</i> 1984)	SR	33 (80)	[1, 15] mean 6	R	Mean 1; min. 0.1; max. 14 hours
Onur & Fabricky (1987)	R	6	U~[4, 10]	H	Uniform Distribution [3, 9] hours
Ragatz & Mabert (1988)	R	5	U~[1, 8]	H	Exp. Distribution, (1/λ) = 1 hour AND < 4
Melnyk & Ragatz (1989)	R	6	U~[1, 6]	H	Exp. Distribution, (1/λ) = 1 time unit
Park & Bobrowski (1989)	R	5 (10)	U~[1, 5]	H	Exp. Distribution, (1/λ) = 2.5 hours AND < 4 hours
Melnyk <i>et al.</i> (1991)	R	6	U~[2, 6]	H	Normal Distribution, μ = 1.5, σ = 0.1 hours.
Ahmed & Fisher (1992)	R	5	U~[1, 8]	H	Exp. Distribution, (1/λ) = 1 hour AND < 4
Philipoom & Fry (1992)	F	5 (12)	5	H	Exp. Distribution selected such that 90% capacity utilisation rate is obtained.
Philipoom <i>et al.</i> (1993)	R	15	U~[3, 7]	H	Exp. Distribution selected such that 87% or 92% capacity utilisation rate is obtained.
Hendry & Wong (1994)	R	6	U~[1, 6]	H	Exp. Distribution (1/λ) = 1.5 time units
Melnyk <i>et al.</i> (1994)	R	6	U~[2, 6]	H	Exp. Distribution (1/λ) = 1.5 and (1/λ) = 1.5 bounded between 1.4 and 1.6 hours.
Fredendall & Melnyk (1995)	R	6 (12)	U~[2, 6]	H	Exp. Distribution, (1/λ) = 1 time unit
Park & Salegna (1995)	SR	6	U~[1,6]	H	Exp. Distribution selected such that the first WC has a utilisation level of 92% and the others 86%.
Cigolini <i>et al.</i> (1998)	R	11	U~[1,12]	H	30 job types.
Hendry <i>et al.</i> (1998)	SR	15	[3, 13] mean 9	R	μ = 41 hours.
Land & Gaalman (1998)	R	6	U~ [1,6]	R	2-Erlang Distribution, μ = 0.75 days.
Oosterman <i>et al.</i> (2000)	R, SR, F	6	U~ [1,6]	R	2-Erlang Distribution, μ = 1 day.
Kingsman & Hendry (2002)	SR	15 (4)	[3, 13]	R	μ = 41 hours.
Bertrand & van de Wakker (2002)	R	15	Geometric function, μ = 5, max = 39	H	Negative Exponential Distribution, μ = 1 time unit.
Bertrand & Van Ooijen (2002)	R	10	U~ [1,10]	H	Exp. Distribution, (1/λ) = 1 time unit
Henrich <i>et al.</i> (2004)	R, F	12	U~ [1,12]	H	Gamma Distribution, alpha = 2, beta = 0.5, μ = 1, and variance = 0.5.
Land (2006)	R	6	U~[1, 6]	H	2-Erlang Distribution, μ = 1 time unit.

Routing: Random Routing (R); Semi-Random / Dominant Flow Routing (SR); Flow Shop Routing (F).
System: Real System Characteristics (R); Hypothetical System Characteristics (H).

Table 1: Sample of Previous Approaches to Modelling Processing Times in WLC Simulation Studies

Shop Characteristics	
Shop Type	Pure job shop
Shop Characteristics (Real or Hypothetical)	Hypothetical
Routing Variability	Random routing, no re-entrant flows
No. of Machines	6
Interchange-ability of Machines	No interchange-ability between machines
Machine Capacities	All equal
Machine Utilisation Rate	90%
Shop Floor Dispatching Policy	First-Come-First-Served

Table 2: Summary of Simulated Shop Characteristics

Job Characteristics	
No. of Operations per Job	Uniform[1, 6]
Operation Processing Times (Exponential)	Exp. Distribution, $(1/\lambda) = 1$
Operation Processing Times (2-Erlang)	2-Erlang, $\mu = 1$
Inter-Arrival Times	Exp. Distribution, $(1/\lambda) = 0.633$
Set-up Times	Not considered
Due Date Determination Procedure	Job entry time + a; a U~[35, 60]
Complexity of Product Structures	Simple independent product structures
Job Characteristics (Real or Hypothetical)	Hypothetical

Table 3: Summary of Simulated Job Characteristics

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For Peer Review Only

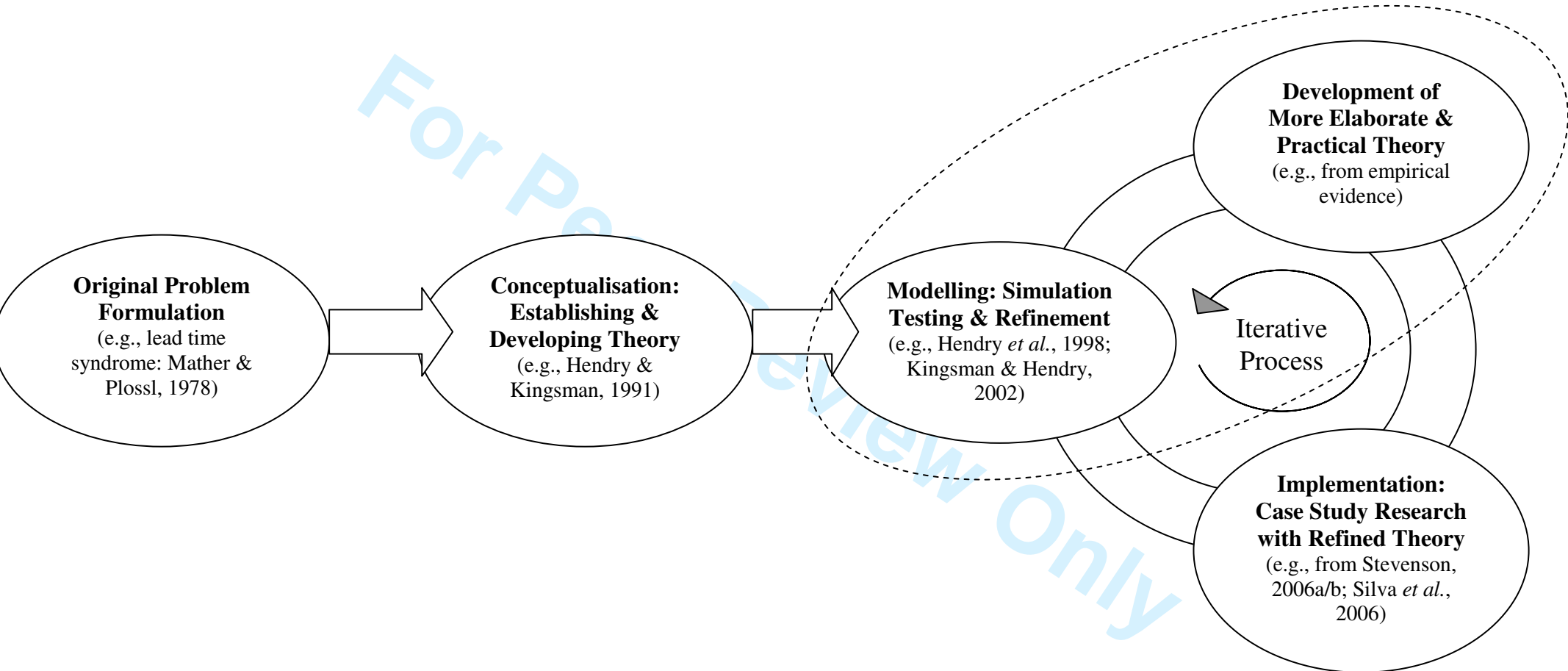


Figure 1: Theory-Practice Iterative Research Cycle

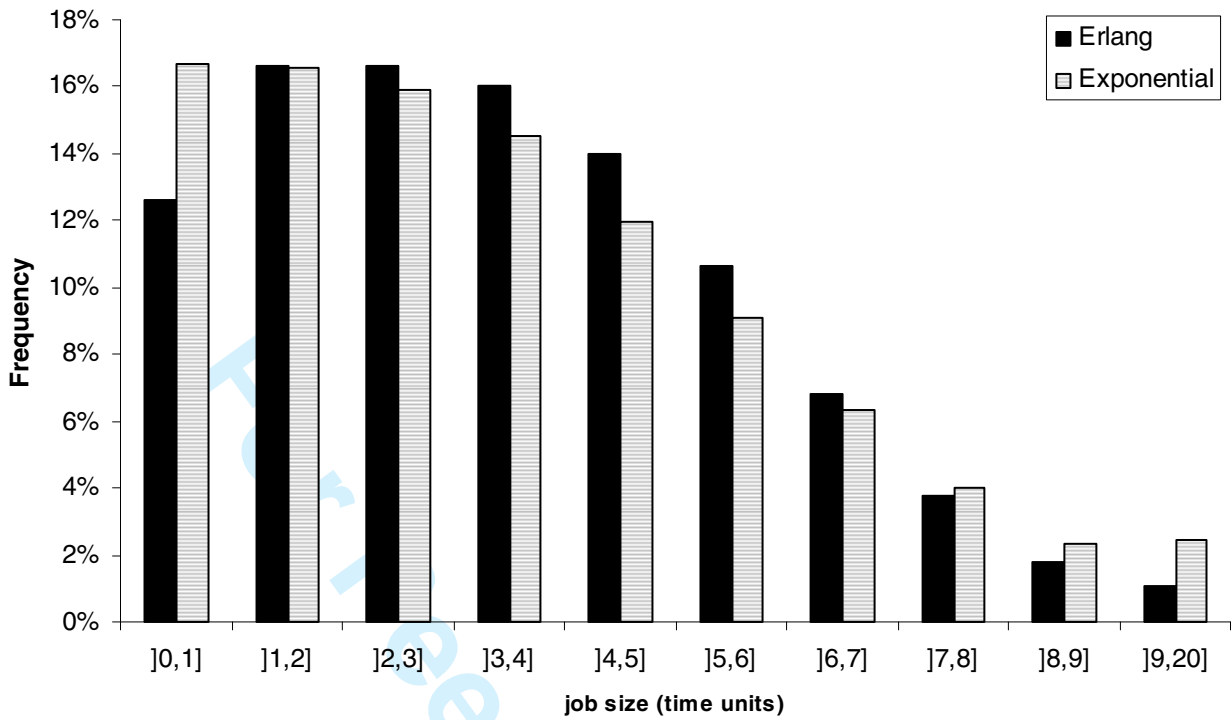


Figure 2: Job Size Distribution: Exponential v Erlang

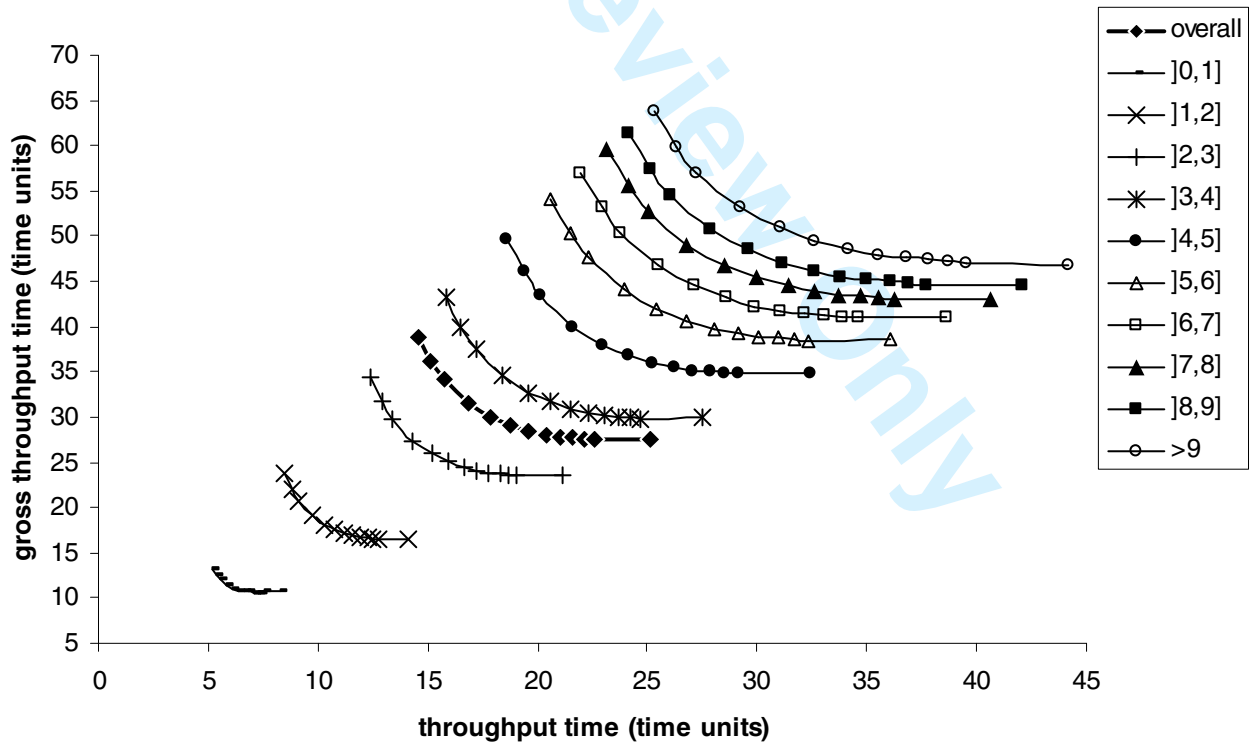


Figure 3: Performance of Approach B under Standard Scenario (2-Erlang)

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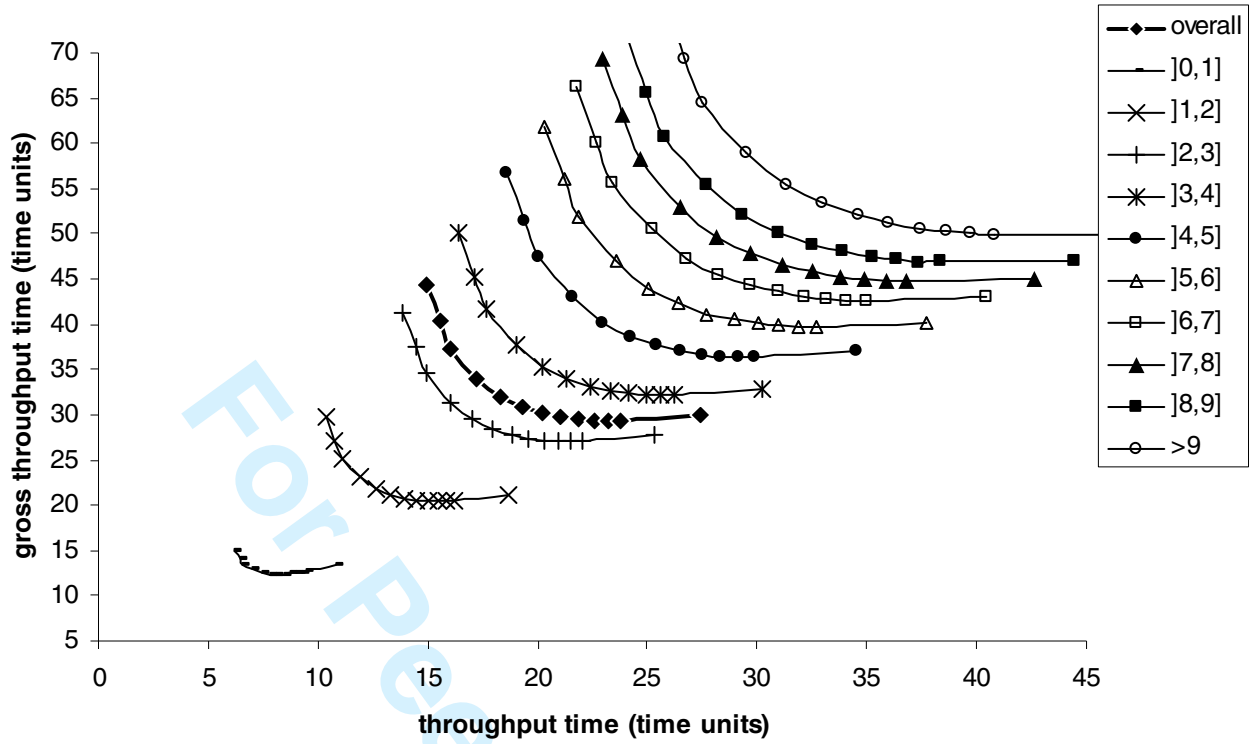


Figure 4: Performance of Approach B under Standard Scenario (Exponential)

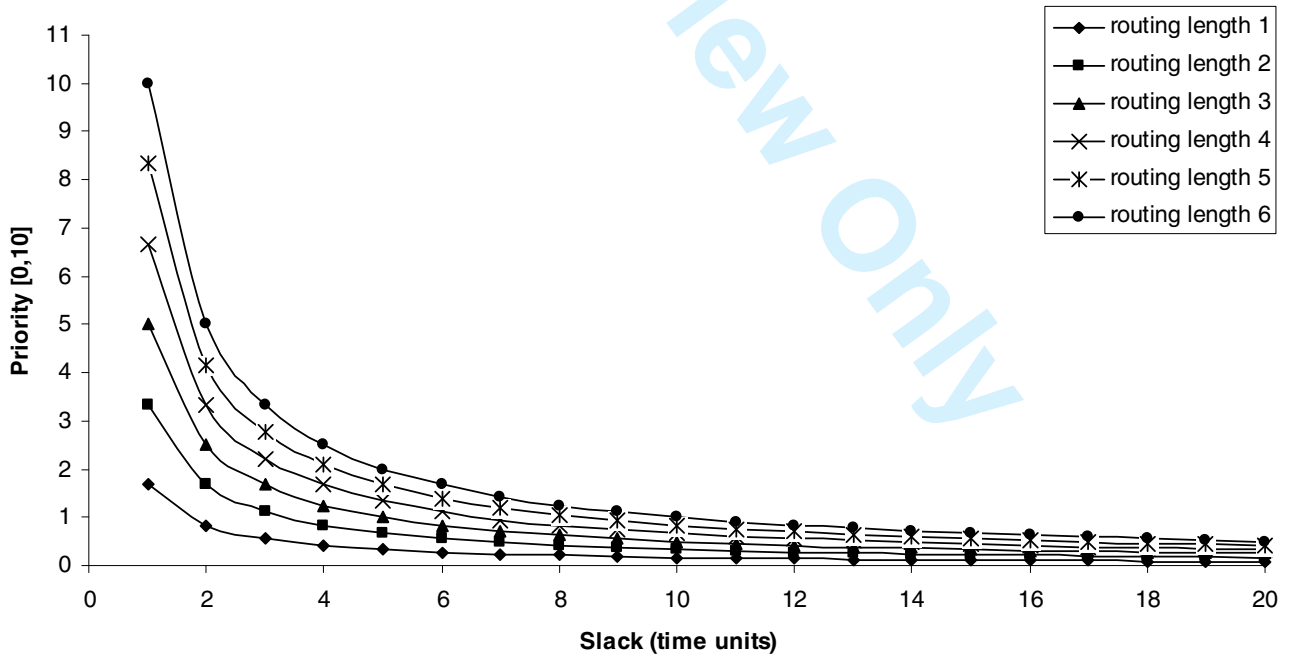


Figure 5: Conversion of Priority According to Routing Length

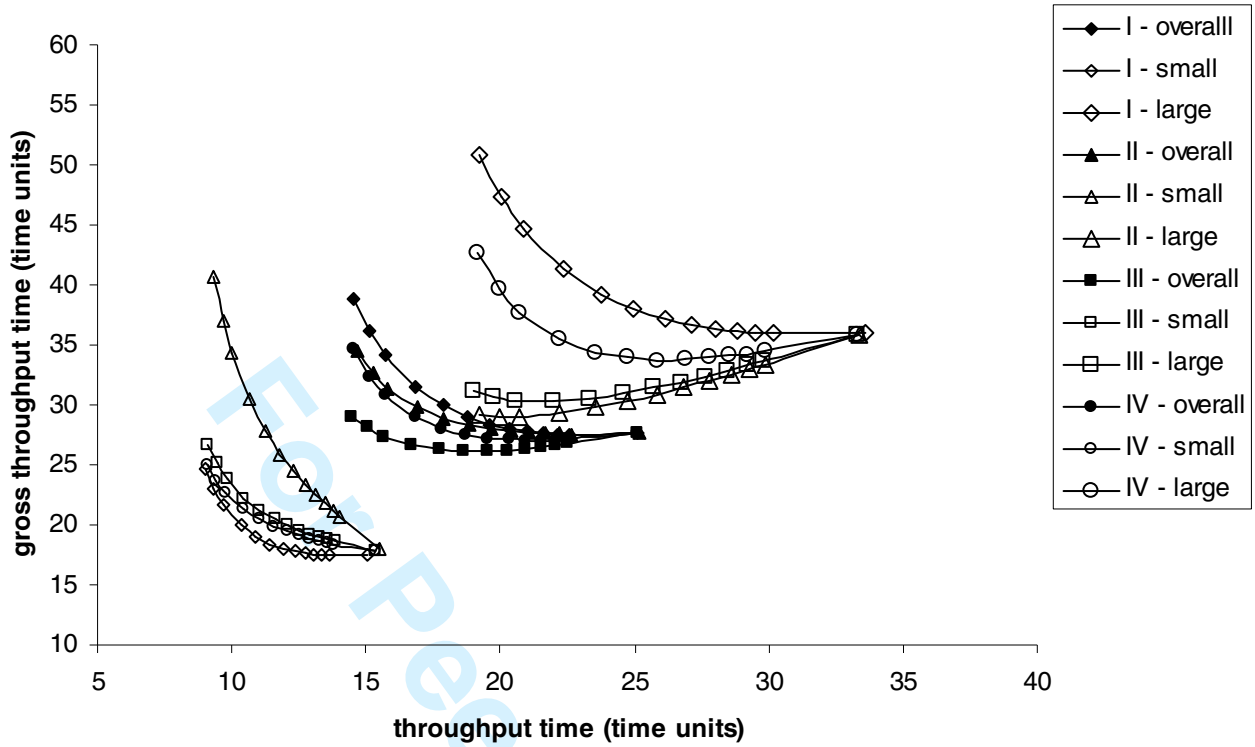


Figure 6: Performance of Approach B with Prioritisation (2-Erlang)

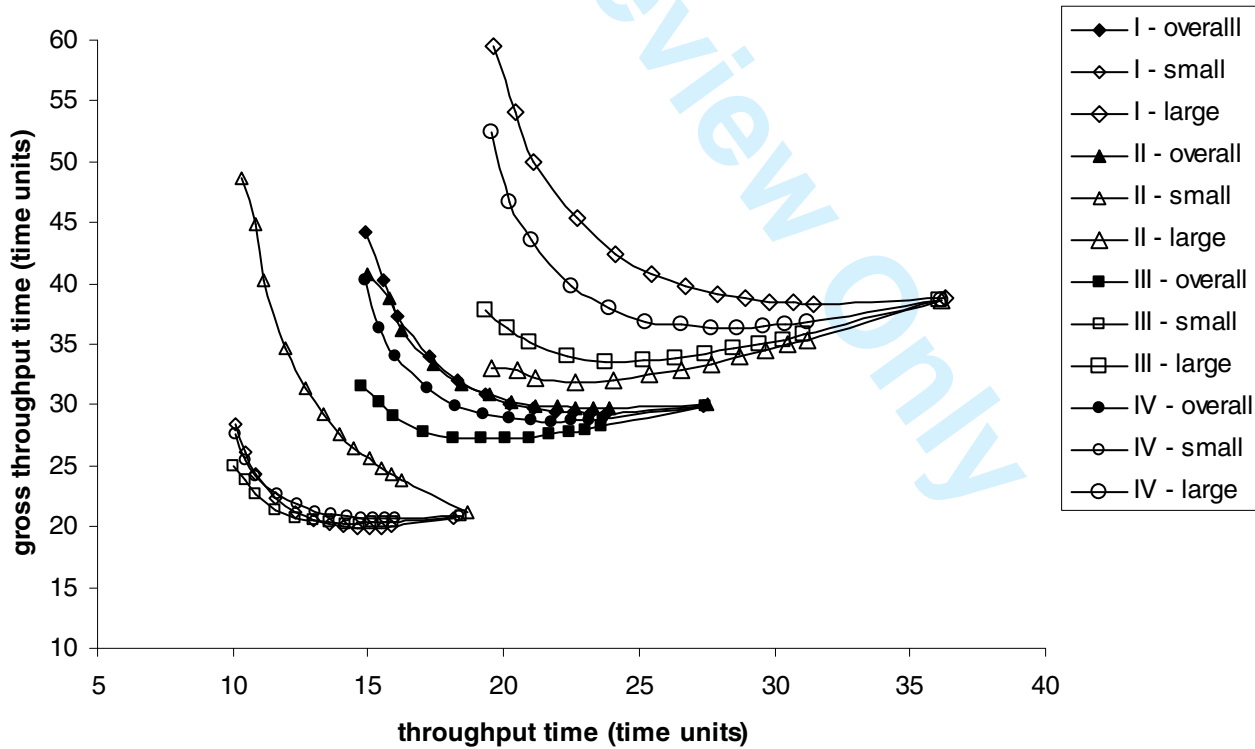


Figure 7: Performance of Approach B with Prioritisation (Exponential)

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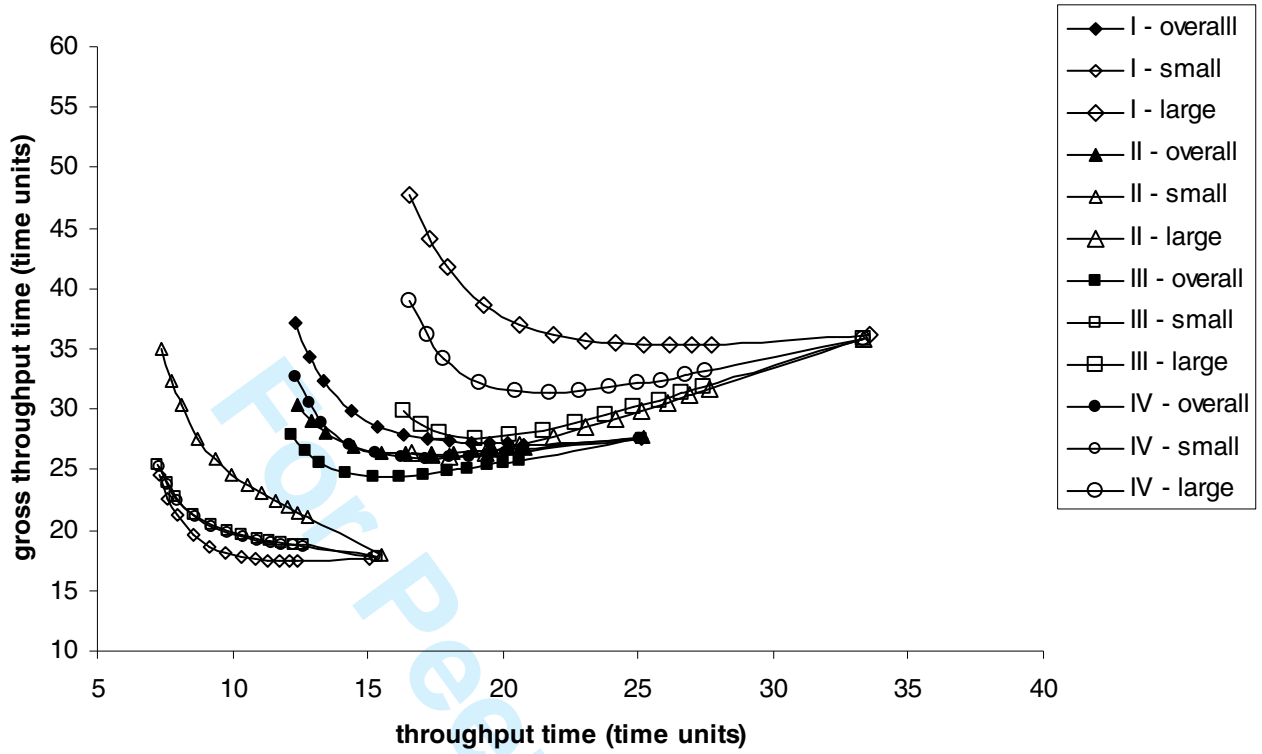


Figure 8: Performance of Approach B' with Prioritisation (2-Erlang)

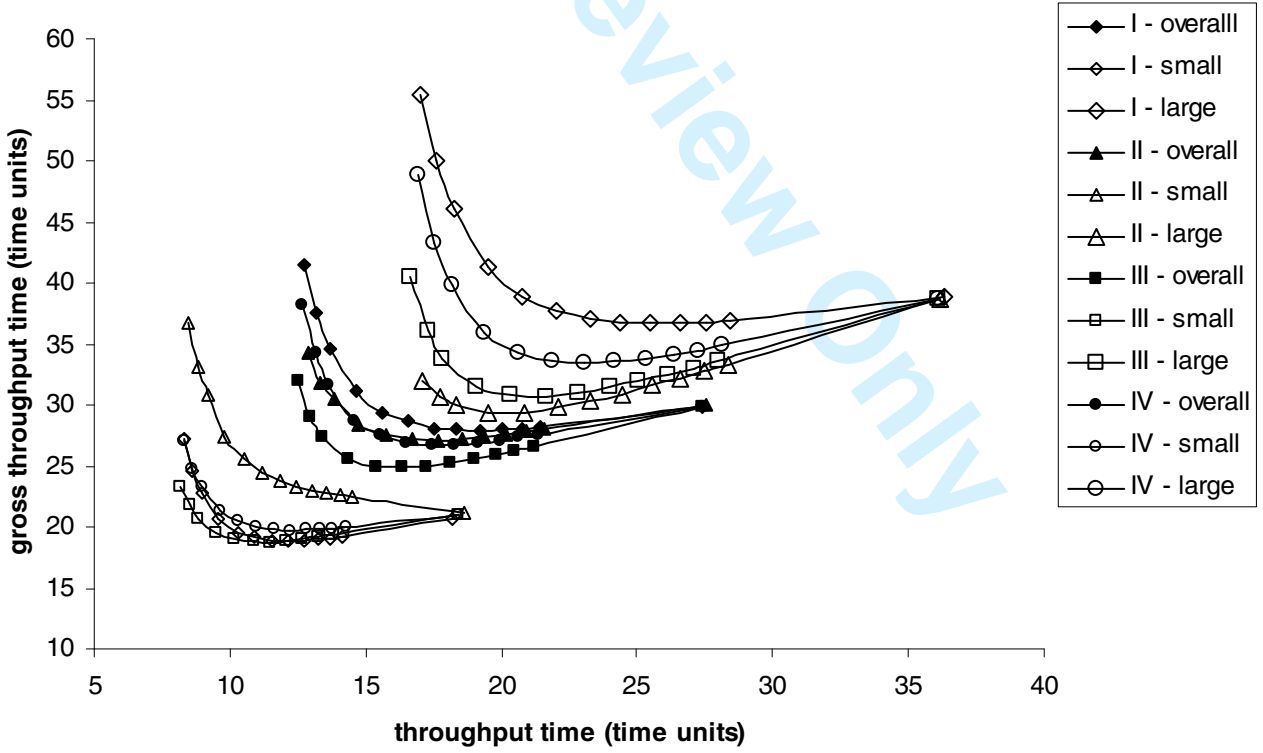


Figure 9: Performance of Approach B' with Prioritisation (Exponential)

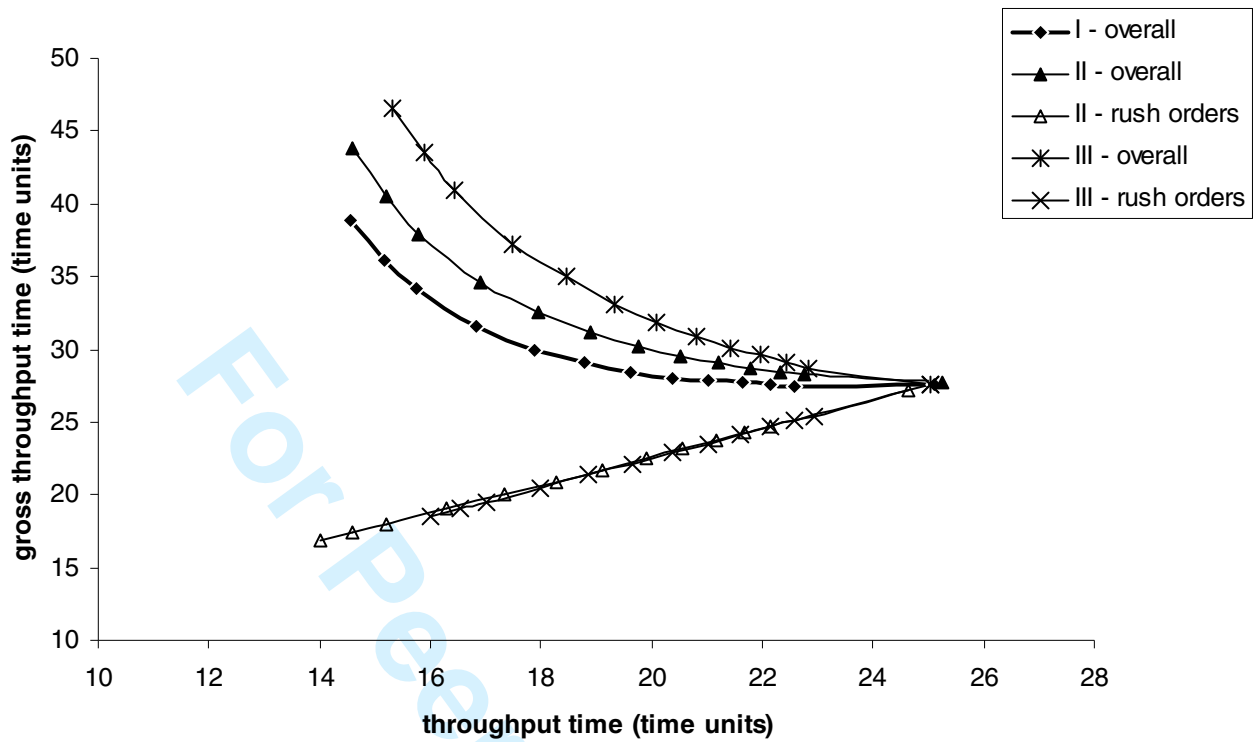


Figure 10: Performance of Approach B for Rush Orders (2-Erlang)

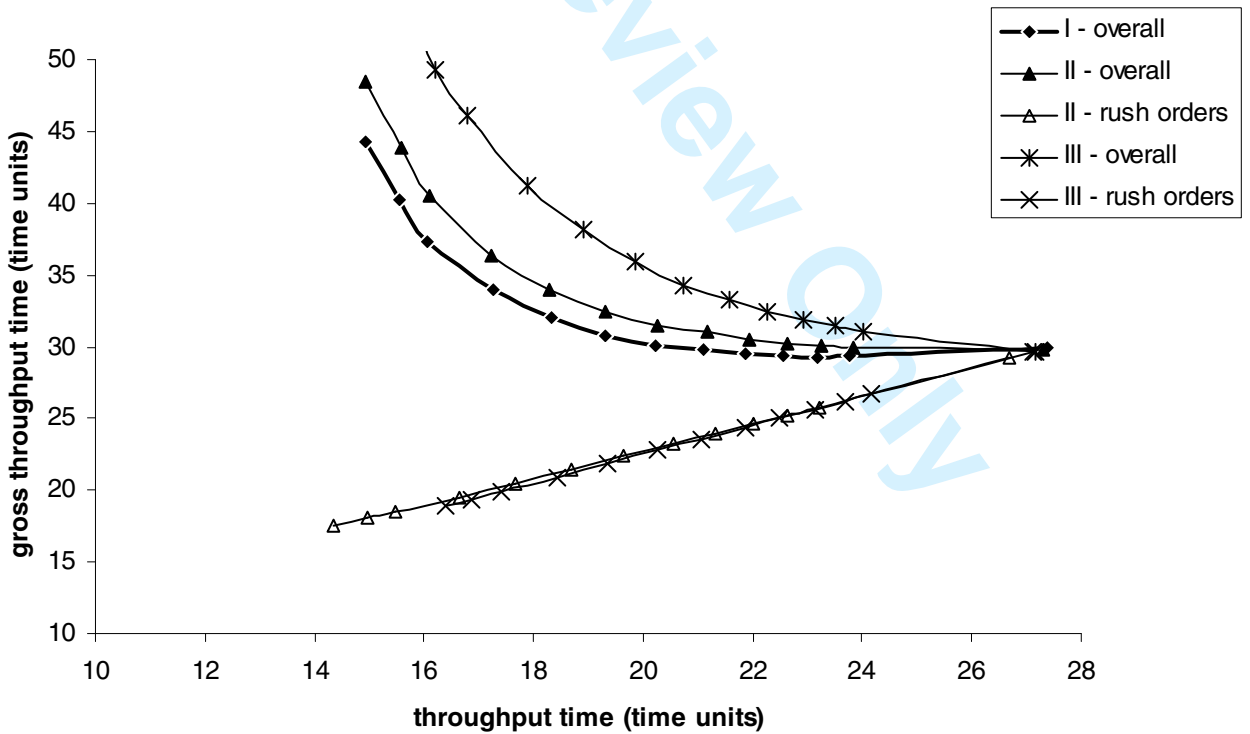


Figure 11: Performance of Approach B for Rush Orders (Exponential)