LOAD-BASED ORDER REVIEW/ RELEASE STRATEGIES FOR SHOP FLOOR CONTROL

by

Bulut Aslan

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ABSTRACT

LOAD-BASED ORDER REVIEW/ RELEASE STRATEGIES FOR SHOP FLOOR CONTROL

The basic aim of this thesis is to grasp the notion of order release in terms of system performance and develop a load-based hierarchical order release policy. Basically, order review/ release (ORR) is a decoupling mechanism to manage transitions of orders from planning system to the shop floor and it is a decision point for determining the release time of a job. ORR mechanism used has a two level, load-oriented structure for release of jobs into shop floor. Incidentally, two fundamental manipulation methods are applied in order release phase. In the first level, machine routes of jobs are sorted regarding workload balancing of machines and in the second level, workload bounding method is applied. Besides the classical shop environments used in the literature, releases of orders are achieved in a flexible manufacturing environment as a novel approach. Flexible process plans of jobs are fixed at the release phase, and part routing execution is avoided on the floor. On comparing the results of proposed methods, the results showed that ORR methods do improve performance measures and is an effective tool when used with an appropriate parameter set. Threshold level and period parameters are the critical ones in this set. A proper threshold level is tried to be estimated by inducement of some desired mean queue sizes and predetermined layout and job mix definitions. On the other hand, periodic structure of ORR mechanism is tried to be eliminated by implementing a pull-type and self-triggered structure. Studying the ORR policies under different job flow patterns has been an important aspect of the study that reinforces the conclusions drawn, especially on the effect of introducing process plan flexibility.

ÖZET

ÜRETİM KONTROL İÇİN İŞ YÜKÜ TABANLI İŞ SALMA STRATEJİLERİ

Bu tezin temel amacı performans ölçütleri çerçevesinde iş salma stratejilerini kavramak ve işyükü tabanlı hiyerarşik bir iş salma stratejisi geliştirmektir. Temel olarak iş salma stratejileri, işlerin planlama sisteminden üretim sahasına geçişinde bir karar noktası olmaya ve bu işleri üretim sahasına giriş zamanını tayin etmeye çalışır. Bu tezde kullanılan iki aşamalı, iş yükü merkezli bir yapısı olan bir iş salma stratejisidir. Buna göre içinde iki temel kontrol mekanizması işler. İlk aşamada, işlerin makina rotaları makinaları dengelemek adına sıralanır; ve ikinci aşamada iş yükü kısıtlaması uygulanır. Literatürdeki klasik üretim ortamlarının yanında, yeni bir yaklaşım olrak esnek üretim ortamında da iş salma işlemleri gerçekleştirilmiştir. İşlerin esnek üretim planları salma aşamasında sabitlenir ve üretim sahasında işin yönlendirme işlemi yapılmaz. Önerilen yöntemlerin sonuçlarının karşılaştırılması sonucunda görülen o ki, iş yükü kontrolü ile iş salma stratejileri performans ölçütlerinde iyileşmeler sağlamıştır ve uygun bir parametre seti ile kullanıdığında etkili olmaktadır. Makinalar için iş yükü limiti ve işlerin salınma vaktini belirleyen periyot uzunluğu bu önemli parametrelerdendir. Bu tezde, uygun bir işyükü limiti tahminine giden yolda önceden tayin edilmiş, makinaların kullandığı ortalama kuyruk uzunlukları, fiziksel yerleşim ve iş karışımı bilgileri ile bu limit arasında ilişki irdelenmiştir. Diğer yandan, iş salma stratejileri periyodik yapısı değiştirilerek çekme-tipli ve kendinden harekete geçebilen bir yapıya kavuşturulmuştur. Bu çalışmanın önemli bir bakış açısı, sonuçlarını işlerin esnek üretim planları ile etkileşimli bir şekilde geliştirilen iş salma stratejilerini farklı iş akış modelleriyle işleyebilmesidir.

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LIST OF ABBREVIATIONS

AGV	Automated Guided Vehicle
BFL	Backward Finite Loading
BIL	Backward Infinite Loading
BUFAIM	Boğaziçi University Flexible Automation and Intelligent Manufacturing Systems Laboratory
FFL	Forward Finite Loading
FCFS	First-Come-First-Served
FMC	Flexible Machining Cell
FMS	Flexible Manufacturing Systems
FTL	Flexible Transfer Line
FTML	Flexible Transfer Multi-Line
GD	General Directed
IMM	Immediate Release
IR	Interval Release
LMM	Loading Mathematical Model
LOOR	Load-Oriented Order Release
ORR	Order Review and Release
PBB	Path-Based Bottleneck
SD	Strictly Directed
UD	Undirected
WIP	Work In Process
WLC	Workload Control

1. INTRODUCTION

Shop Floor Control (SFC) is one of the most sophisticated day-to-day tasks in a manufacturing environment. Allocating resources, ensuring that bottlenecks are avoided and generating high levels of shop floor productivity are all part of the challenge. In today's fast moving environment, knowing the current status of jobs out there on the factory floor is essential. To achieve excellence in all these tasks requires capable intelligent systems and their effective operation.

Within the context of SFC systems, Order Review/ Release (ORR) occupies a special place. Simply, ORR is a decoupling mechanism to manage orders' transitions from planning system to shop floor. Order release decisions typically make use of some form of input control to smooth the flow of jobs through the shop by determining which orders are to be released to the shop floor, when they are to be released and conditions of release, if applicable (Figure 1.1):

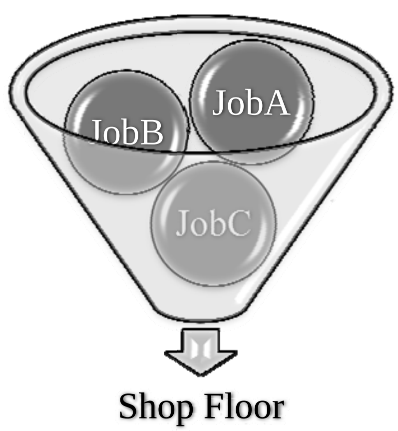

Figure 1.1. Order release pool

These orders are awaited in a pool before being released to the shop floor. The role of ORR during production starts from the identification of a matured order until the release of the orders to the shop floor. It can be imagined as a tap for controlling the flow by analogy. The key point in success of ORR applications compared to do-nothing case (that is directly releasing the incoming work) is not releasing the work immediately. Although other decisions to be tackled prevail on the floor after the release phase, manipulating the orders by a release strategy poses significant importance for effective manufacturing.

Conceptually, ORR mechanisms should have a positive impact on the shop floor operations. By controlling the flow of work and ensuring that shop is not overloaded or underloaded, ORR can help generate stable queues, which are consistent with stable lead times. Since only 'good' jobs are permitted to enter, the shop is always working on jobs which can be completed in a timely and cost effective manner. Main motivations of ORR implementation are to provide input control for smoothing the flow of jobs through the shop; ensuring punctuality in terms of due date performance; reduce investments in raw material inventories; reduce WIP levels; establish a balance between the load released and the amount of unused capacity available on the shop floor. Behind its throughput-oriented aims, it also can be considered as a screening process which identifies problem orders and keeps them off the shop floor (Melnyk and Ragatz 1988).

Another widely used denomination of ORR is implied under the title, *Workload Control (WLC)*. Briefly, WLC is the conceptualization of the manufacturing environment as a queuing system. Main purpose of WLC is to manipulate the queues of workstations of shop floor for some certain measures (i.e. due-date, work in process (WIP), etc.). Release decision is the ground branch of WLC.

Nearly all of the literature is devoted to developing effective release methods for classical manufacturing environments, especially Make-To-Order (MTO) companies with random job arrivals. Modern manufacturing environments however, exhibit various forms of flexibility such as versatile machines that can perform many operations with negligible setup time, easy and quick post-processing program capabilities that enable alternative process plans to be used for a given part type, flexible material handling system that can route parts to several alternative destinations. Such flexibility actually brings both several interesting questions: the process route of a part is no more a static design engineering problem, but possesses a dynamic nature. Furthermore, its timing is important, i.e. should the decision be made at the time of the part release or should flexibility be kept till the last moment by releasing the part immediately and tackling the routing decision step-by-step based on dynamic status?

One of the novelties of this study is its use of FMS as the manufacturing setting as well as classical ones to study the effects of ORR policies. The setting comprises a job mix selected to be processed simultaneously in the forthcoming period with flexible process plans, and machines tooled for processing these jobs. The main goal is to determine the time to release the parts arriving according to this product mix and concurrently determine their processing sequences on releasing.

One general drawback for ORR policies, almost all other than the primitive ones, is that they require some parameters to work properly. Therefore, it requires some effort to find the most suitable parameter set for the manufacturing system under investigation. In the literature, this effort is conducted empirically through extensive pilot runs.

In this study, we put the ORR policy into a dynamic form by dismissing one of the required static parameters as an attempt to alleviate the burden of parameter setting. Namely, periodicity is a widely used property of ORR methods and period length is a critical parameter. Considering the effect of uncertainty in demand and other internal and external dynamics of production environments, a pull system based on continuous monitoring is proposed against classically used periodic push system. Time to pull the jobs from order pool is made dependent on workload updates on workstations to avoid starvation.

The other critical parameter of ORR methods is the workload threshold level used in input control. Another attempt of this thesis has been towards investigating the relationship among the threshold parameter with the other system related characteristics such as the job mix, process plans, and work station utilizations.

Another issue worked on is the aggregate and/or individual buffer spaces of workstations and release pool. The behavior of the system and ORR method is investigated for finite amounts to infinity in terms of buffer spaces.

Bearing the above points in mind, the general aim of this thesis is to investigate the ORR structures to give proper and constructive answers to following questions both in flexible and classical manufacturing settings:

- What is the influence of release methods on Shop Floor performance under different part flow patterns?
- Is it possible to construct a responsive and almost parameter-independent ORR mechanism be constructed?
- Setting out from previous studies, how can these methods be improved (Namely, in terms of workload calculation and route selection)?
- Is offline judgment possible for intelligent release methods contingent on certain input parameters?

The thesis comprises sections for defining the concepts and denominations to expose the problem more explicitly in Chapter 2; expressing the milestone studies so far in the field in Chapter 3, presenting the propositions and empirical evidences worked on during research period in Chapter 4; explaining the methodology in the generation of layout and experimental conditions, simulation results collected and related discussions in Chapter 5 and finally, concluding the subject and suggesting some future studies in Chapter 6.

2. PROBLEM DEFINITION

Within the scope of researches conducted in Boğaziçi University Flexible Automation and Intelligent Manufacturing Systems Laboratory (BUFAIM), there are several types of intelligent algorithms achieving online decision making such as, part routing and dispatching, AGV matching and dispatching, etc. After all, shop floor control activities are not limited by these, but may also include the decision of release of incoming orders. The importance of order release among other decision algorithms in various phases of production is declared by Melnyk and Ragatz (1989) as follows: "The key to effective shop floor control lay not in controlling jobs *after release*, but in *controlling the release* of jobs to the shop floor".

2.1. Definitions for Workload Control Concept and Order Release

Orders to be processed by work stations in the shop floor initially come to a pool. This pool is used to collect and sequence the jobs before the release. ORR determines when to release each job from the pool into the shop floor (either immediately or with a time delay). Work stations possess some buffers used as queues to save time during material handling and accommodate arriving jobs for waiting in order to process them in its processor. The fundamental approach of WLC is to manipulate these queues by keeping them low in WIP level and stable, despite external and internal uncertainty. This manipulation is achieved by setting *workload limits* to work stations. This limit is also named as *Threshold*, or *Workload Norms*. Workload norms can be used in single or distributed form (Only one threshold value, valid for all work stations or different threshold limits for each work station, etc.). If a job is not released due to threshold constraint, then it will wait in the pool till the next ORR determination of jobs in the pool. This determination usually done in periodic cycles, such that at beginning of every period release decision is made. Basically, a job has the following cycle from its entry phase to completion (Figure 2.1):

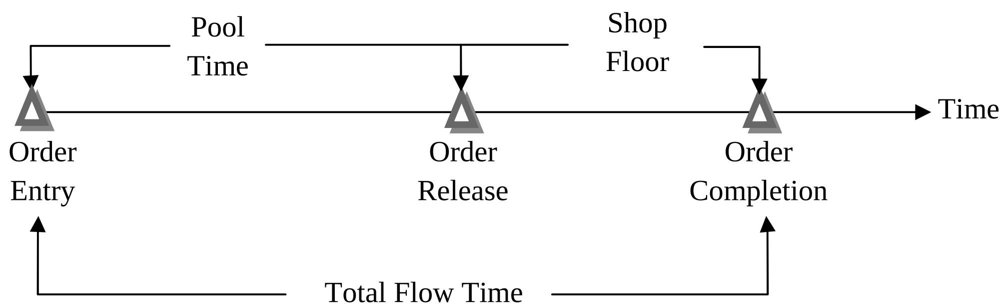

Figure 2.1. Flow time components of a job under WLC

Beside its effectiveness in the control of workload, order review/ release is also a prior quality check mechanism for waiting parts or jobs in the pool, as its name implies through 'review'. Various defects or other inaccuracy can be found before their release to shop floor. This property enables the final review of orders before being released for processing. Bragg, *et al.* (1999) states that, outstanding studies of literature consider capacity availabilities and other concerns by utilization of ORR concept, but not take into account uncertainty in the execution of planned orders. Therefore, this side of the field aids secure production control more empirically. However, this branch is not considered in this thesis as a significant factor.

Bechte (1988) structured WLC concept and designated it as 'load-oriented' order release (LOOR). Despite its name implied, LOOR employs both load-oriented and due date-oriented information in its hierarchical structure. This hierarchy was initially defined in three levels as: order entry, order release and operation sequencing. On being planned by a production planning system (by MRP or other planning instruments), orders are entered to the pool regarding their urgency in terms of due dates by backward scheduling. *Time Limit* depicted in Step 1 of Figure 2.2 is another parameter to be decided beside the period length and workload norm in LOOR. The jobs with schedules falling into this time limit after backward scheduling are treated as urgent ones and other jobs outside the limits as low-priority ones.

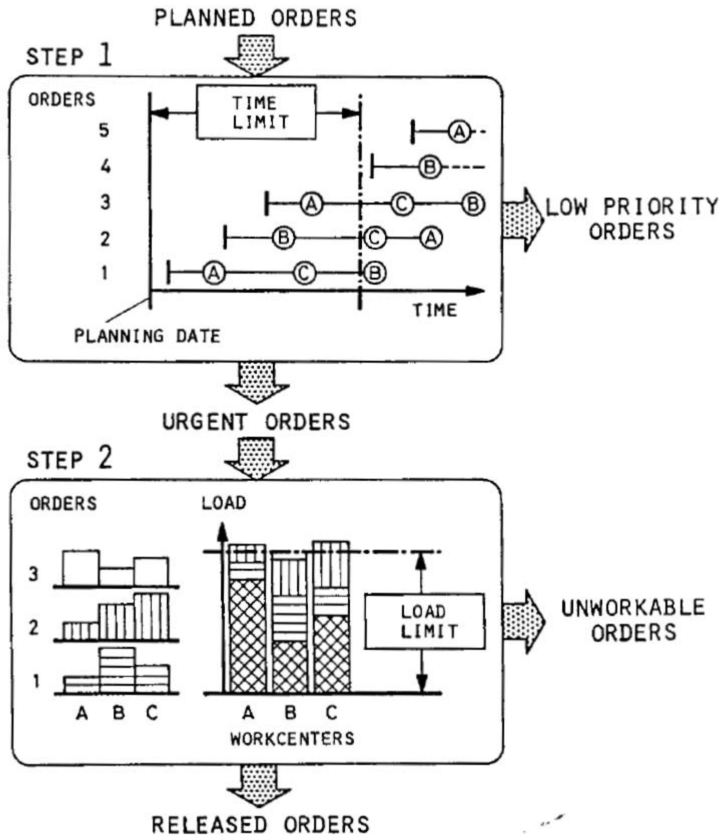

Figure 2.2. First two steps of LOOR after Bechte (1988)

After determining the urgently significant jobs at entry level, order release level enables to select the most appropriate jobs to enter the shop floor. At this stage, workload limiting is performed to enable stable and low-level queues. Workload of operations are distributed to relevant work stations. The jobs fitting the limits are released and non-fitting ones are kept in the pool. At the last step, operation sequencing at queues of work stations are performed due to some chosen rule (Bechte recommends due date-based rule for high level inventory and First-Come-First-Served (FCFS) rule for low level inventories to avoid complexity and enable applicability in operation sequencing).

After this seminal work of Bechte (1988), several researches and practitioners, especially from Europe, extended the content and aims of WLC. Regarding empirical studies, Breithaupt, *et al.* (2002) tabulated them according to order release methods they used. 85% utilized methods regarding due dates and 68% considered availability of system while implementing their own order release method and 28% used LOOR method.

Each job released into the shop floor constitutes (future or immediate) workload for the machines along its processing route. One of the key issues is about the way a job's processing times will be reflected to the workload of specific machines on its route. In the literature, various approaches are used for this purpose. In this study, we denote them as workload determination methods. The approaches aim at calculating the workload of individual machines as jobs enter and progress in the shop floor. For instance; the 'Aggregate Load' approach as the most basic one (Kingsman, *et al.* 1989, Bertrand and Wortmann 1981), reflects the processing time of an operation of a job directly to its related workstation, and this information is kept as a workload level on that machine. By this way, WIP level can be controlled via setting a *workload limit* (*threshold* or *norm*) for that machine. However, reflecting the processing time of downstream operation in the job's processing route, directly to the machine from the moment it is released to the floor might be inflating the workloads unnecessarily. In another workload determination approach, named as 'Corrected Load' (Oosterman, *et al.* 2000), processing time of n^{th} operation of job j (PT_{nj}) to be processed on work station m, WS_m, is reflected via dividing PT_{nj} by the order of the operation n (i.e. PT_{nj}/n). These two are static workload determination methods, where the contribution of an operation to a work station's workload does not change during the flow of the part throughout the system. Figure 2.3 illustrates the two methods in literature. Three more workload determination methods are proposed in this thesis and will be described in Section 4.1.1.

The most widespread problem in implementing and advancing for research on WLC field stems from its parameter-dependent formulation. In Bechte's (1988) study, most critical parameters are *time fence* used in order entry stage, *workload limit* and *release period length* parameters in order release stage. There are various approaches to relax constraints causing from these parameters and to find responsive solutions for attacking this parametrization problem. This thesis employs the latter two of these parameters: workload limit and release period length. To comprehend the reaction of the system to these variables, a parameter search is conducted for both of them. On

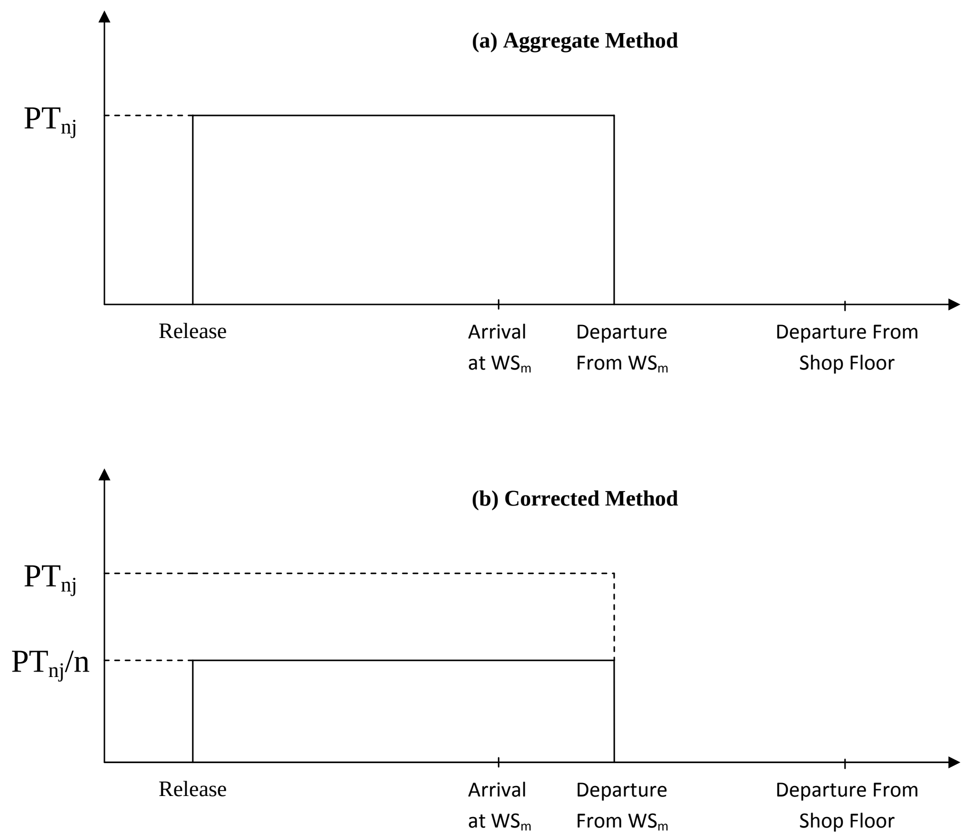

Figure 2.3. Workload determination: aggregate and corrected methods

simulating, workload limits are determined as a single threshold value for each work station and evaluated stepwise down infinity zero. Period Length is also scanned for a reasonable interval. In addition, release period length parameter is proposed to be independent of the off line selection, but dependent on in-progress system transactions, that is determined dynamically during execution.

Stemming from the seminal work of Bechte, it is actually evident that WLC has been developed for job shop production. Through the researches and practical knowledge, it has been implemented into several widely used software such as SAP R/2, debis-PPS (Breithaupt, *et al.* 2002). As WLC concept are developed further, its implementation areas are widened completely over MTO production sector.

This thesis references and is inspired from concepts and approaches of both ORR and WLC lines of research; since ;although their designations distinguish, but their aims resemble. So; the terms from both ORR and WLC choles, are used interchangeably.

2.2. Definitions and Classifications of Work Environment

This section intends to give some definitions and categorization of FMSs, material handling systems, as an inevitable component of FMS, and some designations about flexibility issue in manufacturing. Definitions and classifications about the main subjects, ORR and WLC, will be identified in the next section under the Problem Definition title.

2.2.1. Flexible Manufacturing Systems (FMS)

Individualistic changes in demands of products and rise of computer-integrated manufacturing led to drastic increases in product variations and manufacturing cycle time and production costs. To cope with such obstacles and enhance the spectrum of production volume and variety, Flexible Manufacturing Systems dealing with mid-volume and mid-variety products gained importance seminally in 70s and especially in 90s with integration of computerized systems and automation.

Similar to the name implying *flexibility*, definitions and classifications of FMSs varied certainly as the field gets broader. Chan *et al.*, (2002) states that various kinds of definitions expose common features of FMS as subsystems, which holds:

1. A processing system,
2. A material handling and storage system,
3. A computer control system.

Among several definitions in the literature, the one proposed by Stecke, (1983) covers the three common components of FMS mentioned by Chan *et al.* (2002) and thought to be the most appropriate definition for FMS for this study. According to Stecke (1983); FMS is an integrated, computer controlled complex of automated material handling devices and numerically controlled (NC) machine tools that can simultaneously process medium sized volumes of a variety of part types.

The most known and cited classification based on features and process attributes of FMS is conducted by Browne *et al.*, (1984). Four types of FMSs are identified: (1) Flexible Machining Cell (FMC), (2) Flexible Machining System, (3) Flexible Transfer Line (FTL), and (4) Flexible Transfer Multi-Line (FTML).

FMC is the elementary form of a FMS. The cell comprises a Computer Numerical Control (CNC), material handling system and an automated device for loading and unloading purposes. A Flexible Machining System is a collection of at least two integrated FMCs. FTL is the form of FMS with no routing flexibility, meaning each operation is assigned to only one machine. Conveyors are highly preferred in FTLs instead of mobile vehicles such as AGVs, since the production routes of part types are predetermined. Finally, FTML is the collection of at least two FTLs, which could provide routing flexibility unlike FTLs.

The work environment for the thesis is chosen to be an FMS, accompanied with AGVs for material handling activities. Yet, researches in ORR and WLC fields do not employ any material handling system except a few recent studies, as long as part types are produced in inflexible job shop environments where predetermined routes are used. The aid of flexibility in this study broadened the number of effective strategies of order release and provided the usage of simultaneous leveling activities such as load balancing.

2.2.2. Manufacturing Flexibility

Several definitions of flexibility can be made from different aspects in a goal-dependent fashion. These perspectives has been exhibited by De Toni and Tonchia (1998). In general sense, flexibility can be interpreted as characteristic of the interface between the system and its environment. From production economics perspective, it is an ability of the manufacturing system to adapt and compete against uncertainty both internally (i.e. unexpected machine failures) and externally (i.e. demand fluctuations).

Browne *et al.* (1984) have carried out frequently referred study about eight fundamental dimensions of flexibility. Later, Sethi and Sethi, (1990) suggested this number of dimensions to be eleven; and as the field gets widely utilized in industry and academia, several other new categorizations and definitions are being proposed. Basic types of flexibilities frequently referred in the literature are defined below.

Machine Flexibility can be defined as the capability of a machine to perform more than one operation in a period with limited setup times between consecutive distinct operations. Machine flexibility can be evaluated by both cardinality of set of operations performed on machines or changeover times between consecutive distinct operations, of which this study considers the former one as a measure of machine flexibility.

Process Flexibility is the ability of a manufacturing system to handle the production of different part types for a given configuration. Alternatively named as "mix flexibilities", it can be also thought as a part type flexibility in part selection problem of FMS.

Operation Flexibility is the ability to process a part in different ways, i.e. using alternate process plans. It is clear that this flexibility is rather related with the manufacturability of the part type more than physical aspects of FMS.

Routing Flexibility is the freedom to produce a part type at alternate machines. Routing flexibility can be thought as a combination of operation, material handling (flexibility extension by Sethi and Sethi (1990)) and machine flexibilities. From this study's contemplation, routing flexibility plays a crucial role as an ORR component, which enables effective load level balancing on machines. Browne *et al.* (1984) decomposes this flexibility into two as (a) *potential*; in which the processing routings are fixed, and only in the case of failures are the alternative ones used; and (b) *effective*; in which the same part is processed with different routings, independently of failures.

Product Flexibility is the adaptability to individualistic demand of market by low-cost changeovers or minor design-changes or new products.

Expansion Flexibility is the ease of adding capacity and capability to an existing system.

Volume Flexibility is the ability to produce profitably at variable volumes of products.

Production Flexibility is the potential universe of part types that can be produced.

2.2.3. Flexible Process Plans

A *flexible process plan* explicitly depicts all manufacturing options associated with a product (Benjafaar and Ramakrishnan 1996). These options can be classified into three types: *machining flexibility* is defined as the possibility of performing an operation on more than one machine; *sequencing flexibility* relates to the possibility of interchanging the sequence of operations; and *processing flexibility* is defined as the possibility of producing the same work piece with alternative sequences of operations. In this thesis, we consider all these types of flexibilities when deciding on the route of a given part. Figure 2.4 depicts a flexible process plan for a part with all types flexibility. The nodes in the figure represent different operations on the process plan. Each branch in the figure, starting form the root and ending at a leaf, constitutes a different feasible sequence of operations to produce this part. Furthermore, at each node, candidate alternative machines that can carry out the operation are indicated.

There can be two basic approaches for dealing flexible process plans during execution of the production system: (i) At the point where the job is to be released, fixing the route to a particular option based on the current state of the shop. This leads to giving up flexibility at an early stage; but will be required if one needs to make load-based order release since route and machines should be known for workload calculations. (ii) Delaying decision up to the completion of each operation. In this case, upon completion of an operation, a dynamic part routing decision should be made to choose an appropriate operation-workstation pair among the alternatives offered by the flexible process plan of the product. The dynamic routing approach

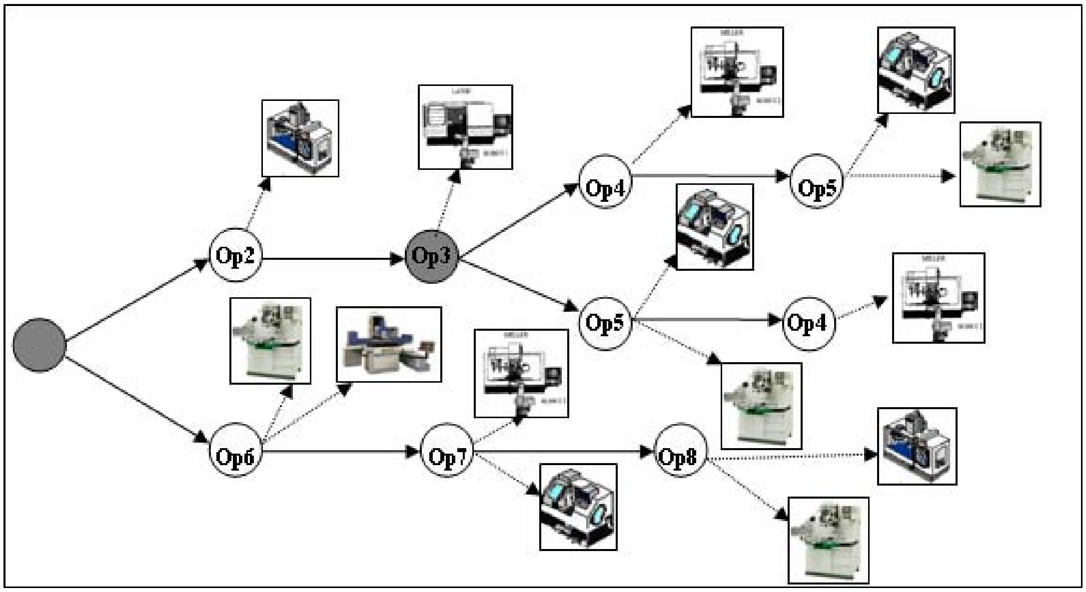

Figure 2.4. Flexible process plan for a part with all Types flexibility

can be complemented with immediate release policy, whereas under an order release strategy that fixes the process route no dynamic routing decision will be required.

One of the aims of the study presented in this thesis is to develop a robust part release strategy to effectively deal with all types of process plan flexibility during real-time control of a flexible manufacturing system (FMS).

2.2.4. Tool Allocation for FMS Setup

Tooling is the task of giving a machine the ability of performing certain operations by making a set of tools available to that machine. Tool allocation is a widely studied subject within the context of FMS. The fundamental objective in tool allocation problem is choosing the right set of tools to be mounted on tool magazines of machines. Most frequently used performance criterion is workload balancing. Basic limitations of this problem are tool magazine capacities of machines and number of available tool copies.

Allocation of tools may also enable the emergence of flexible process plans for job types, such that allocating a tool type having more than a single copy to several machines allows machining flexibility. In this thesis, the allocation of tools to the work stations is achieved by an mixed integer mathematical model, Loading Mathematical Model (LMM), which was developed in BUFAIM by Albey (2006). LMM tries to find the best machine-tool assignment along with allocation of operations to machines. Primary objective is to minimize the unsatisfied demands of part types and secondary objective is to balance the workload among machines in order to minimize the possibility of having bottlenecks in the shop floor (SF). The benefit of having flexible process plans directly arises during the task of balancing the workload. Critical constraints in the model are machine and tool availabilities, machine tool slot capacities and number of tool copies.

2.2.5. Automated Material-Handling and Storage Systems

Material-handling system is basically an integrated system involving activities such as handling, storing, and controlling of materials. The primary objective of material handling utilization in manufacturing environments is to transfer a material safely to its desired destination at the right amount, time and at minimum cost. Singh (1995) classified material-handling equipment into five categories as industrial trucks, conveyors, monorails, automated guided vehicles (AGVs), automated storage and retrieval systems (AS/RS); of from which AGVs are integral part of FMSs. Any kind of technical information, definitions of AGV types and control systems are beyond the scope of this study and thus accordingly skipped.

It appears that almost all studies in the literature use no material-handling equipment in their relevant production environments. In this study, automated material-handling system is used in the FMS environment on the condition that material-handling system, which could step-up the complexity unnecessarily, would not result any serious bottlenecks on the system or affect the performance vitally.

3. LITERATURE REVIEW

Seminal thoughts of Order Review and Release (ORR) and Workload Control (WLC) concepts in production and inventory systems commenced at the beginning of 70s as an eminent Production Planning and Control (PPC) activity via the support of information systems and production technology. This rise of controlled order idea is put forward by Wight (1970) pointing the importance of Input/Output control in job shop manufacturing. Later on, first survey and comparative study were accomplished by Melnyk and Ragatz (1988, 1989). under the keyword: ORR concept.

The discovery of research paradox, that proved the complexity of ORR application to production systems, is again declared by Melnyk, *et al.* (1991). The reason of paradoxical nomination comes from the trade-off gathered from the utility of a job pool mentioned in previous chapter. This pool is designated in various names as *Pre-shop pool* (Bergamaschi, *et al.* 1997) , also named as *Backlog pool* (Melnyk, *et al.* 1994) or *Back order pool* (Baker 1984), or as a more common use *ORR pool*; which assists to minimize congestion within the shop floor, simplifies the management of Work-In-Process (WIP) inventory and further can be used to facilitate production leveling activities such as load balancing, etc. This paradox was tended to be enlightened by several researchers like Kanet (1988) via limiting the load in shop floor and Sabuncuoğlu and Karapınar (1999) via modeling congestion in the system by setting finite buffers in front of work stations. Vast majority of conceptual and analytical studies showed that ORR do not improve overall mean lead time for low utilized systems, which also makes its practical usage obscure. The situation beneath, is the needless waitings of jobs in the pool although system is starving. Most simply constructed ORR mechanisms lead to such ineffective usage of the pool; causing decrease in shop floor time of jobs, but greater overall lead time compared to immediate releasing. This statement can be supported by some counter-arguing authors in the literature. Kanet (1988) is one of the warm advocates putting up these counter-arguments. He suggested that; whilst ORR may reduce the time spent on the shop floor, it could not do the same with the overall lead time, despite its goal is very the same for latter one. This strict and final conclusion is smoothed, conditioned and later on denominated as "Research Paradox" by Melnyk and Ragatz (1988, 1989).

With the foremost activities in the literature up to late 90s in U.S. and Canada, golden era of European research in this field has begun under the title *Workload Control*. Germany, Netherlands and England were the headquarters for the original studies let off by Bertrand and Wortmann (1981), Bechte (1988) and Kingsman, *et al.* (1989), respectively. Several basic implementation methods have been generated for WLC activities such as load-oriented, due-date-oriented, hybrid, etc. whilst some elaborated on order entry level and some on load-oriented order release level. In fact, all of them used a three level hierarchical approach (order entry, order release and priority dispatching) and dissociates from each other with distinct extensions in job releasing methods, dispatching strategy, etc.

These studies were mostly conducted using simulation, while some analytical-based solutions were developed for the sake of performance observations. On the other hand, the number of practical implementations have grown beyond these theoretical studies. Those implementations now become beneficial indicators of new questions; which could not be discovered and raised by well-thought simulation models; and fresh alternative methods for investigating and modeling the environment in healthier fashion.

Another important platform in the literature is the application and data collection environment for research activities within the field. It is understood that, primitive application environments were quite laborious and burdensome without any technological support (e.g. Bechte 1988, Wiendahl 1995). As time went by; achievement of several computations, plottings, and other basic transactions by computers allowed researchers and implementers for efficient usability with effective manipulability with web-functionality (e.g. Stevenson and Hendry 2007). Integration of WLC tools with other commonly used planning and monitoring systems in firms such as ERP systems, gives the impression of tomorrow's reality in this lane of the field.

3.1. Order Release Strategies in Production Systems

Order releasing is one of the important stages among the transactions of complete production cycle of a product, starting from customer quotation and negotiation step to product delivery. Hence, in every kind of manufacturing environment its existence is inevitable.

The great majority of contemporary research in the field is simulation-based, (e.g. Perona and Portioli 1998, Henrich, *et al.* 2006); despite some recent studies reporting some empirical results (e.g. Stevenson 2007, Hendry, *et al.* 2007). Except a specific study on relation between shop characteristics and ORR methods (Oosterman, *et al.* 2000), almost all studies conducted job shop model simulations with variable product specifications and processing procedures, meaning almost all literature devoted to ORR comprise Job Shop type production environment. Basic characteristic of job shop environment is its service for low volume, high variety product spectrum. This property of job shop systems leads to undirected routings of jobs while flowing through and being processed by the facilities in the manufacturing environment.

Generalization of job shop type environment usage in the literature stems from the reason that ORR and WLC concepts have actually been designed for general use, but later found more appropriate and evolved for Make-To-Order (MTO) companies, which are widely known to have job shop production environment (see: Hendry, *et al.* 1998, Oosterman, *et al.* 2000), in which workstations possess the technological capability to accomplish various types of operations in job shops.

The environment having opposite characteristics of job shop is called the flow shop. In flow shop system, routings of jobs are exactly directed and it is widely utilized for products of high volume, and low variety. Flow shops are less prevalent both in simulation-based and case studies. This shop model is also used in this study to investigate the ORR workload aggregation performance on different shop models.

Flexible Manufacturing Systems constitute a special place among those shop models aforementioned. FMS environments for ORR implementation are occasionally handled in the literature. In a recent study published by Henrich, *et al.* (2007), machine and routing flexibilities are investigated for ORR implementation. They called the machining flexibility as semi-interchangeability, which relates to the technical ability of the machines to perform similar operations. In former studies, jobs had their predetermined routes and; from arrival to departure these fixed routes are strictly followed. However, the aforementioned study introduces the existence of alternative machines for some of the operations, and consequently considers machine selection at order release stage. However, it should be noted that Henrich, *et al.* (2007) consider only alternative machines, but not fully flexible process plans (i.e. alternative sequences of operations).

3.1.1. Diverse Classifications of Order Release Methods

Three important review articles of ORR emerge in the literature (e.g. Wisner 1995, Bergamaschi, *et al.* 1997, Sabuncuoğlu and Karapınar 1999) being well-cited surveys.

Wisner (1995) summarized the up-to-date findings and methods of ORR and categorized them as either emphfinite or emphinfinite loading techniques. In infinite loading, orders are released at a predetermined release date, without considering shop loadings. Immediate release (IMM) is the do-nothing case of infinite loading, where jobs are released immediately on arrival into SF. However, in Backward Infinite Loading (BIL) each job's due date is considered for release time of that job into SF by utilizing one of the below BIL loading methods:

$$RD = DD - k_1 P \tag{3.1}$$

$$RD = DD - k_1 P - k_2 Q \tag{3.2}$$

where,

RD	:	Release Date
DD	:	Due Date
k_1	:	process time constant
k_2	:	queue time constant
P	:	expected process time of job
Q	:	current workload on jobs route

In finite loading, orders are released when loadings of the shop are below some predetermined workload norms. Finite loading can consider shop loadings, due dates or both of them. Forward Finite Loading (FFL) assigns jobs to the work stations while taking into the account unassigned capacity at each of them. For instance, release date of a job can be the time whenever a job is completed or realized shop load is below some predetermined desirable shop load, etc. On the other hand, in Backward Finite Loading (BFL), jobs are assigned to work stations starting from last operation to the first one beginning from that job's due date and taking the load planning into account.

Wisner (1995) also classified the studies according to their solution and analysis approach (simulation-based, analytical- or optimization-based, and descriptive) and investigated the relationship of ORR and dispatching policies. The descriptive research characterized controlled order release as a common shop practice and emphasized the importance of leveling shop loads to improve and more easily estimate order lead times. The analytical research, while limited to only a few articles (e.g. Yano 1987, Faaland and Schmitt 1987), illustrated how techniques of optimization or near-optimization could be applied to machine shop models to determine cost minimizing job delay times. Within the simulation classification, a number of approaches to the order release problem were utilized (e.g. Browne and Davies 1984, Shimoyashiro, *et al.* 1984). Most of this research compared IMM to one other release method (either BIL, BFL or FFL).

Bergamaschi, *et al.* (1997) has both classified the existing approaches and provided a detailed literature survey on ORR. Chronological structure of literature review as plain text depicts the evolution and development phases of ORR from seminal thoughts to case studies. They considered eight dimensions that describe the fundamental characteristics and properties of an ORR procedure (Figure 3.1). These are ORR with a limiting mechanism (load-limited, time-limited), timing convention of order release decisions (discrete, continuous), workload measure of jobs (number of jobs, work quantity), aggregation of workload measure (total shop load, bottleneck load, load by each work center), workload accounting overtime (time bucketing, atemporal, probabilistic), workload control (upper bound only, lower bound only, both, workload balancing), capacity planning of which ORR could adjust capacity of workstations or not (active, passive), schedule visibility that could be worked on a single or further period (limited, extended).

The levels used in this thesis (asterisked in Figure 3.1) according to Bergamaschi, *et al.*'s (1997) Dimensional Classification are: Load Limited, Discrete and Continuous, Work Quantity, Load by Each Work Station, Atemporal and Probabilistic, Upper Bound Only and Workload Balancing, Passive, Limited.

As the authors of the most up-to-date review study, Sabuncuoğlu and Karapınar (1999) widened and modified the classification of Wisner (1995) and conducted some experiments to attack research paradox put forth by Melnyk and Ragatz (1989). One dimension devoted to ORR policies which do not use of any information about shop status or characteristics of jobs (i.e. immediate [IMM]- releasing the jobs direct without any delay or interval release [IR] -). Another one is about load limiting approach such as aggregate loading (releasing jobs until a total limit is reached), workstation information based (detailed information is utilized then aggregate). A third one is based on calculation of release times (infinite and finite loading), and finally the fourth one considering both workload level and due date criteria for job releasing).

Table 3.1. Eight dimensions denominated by Bergamaschi, *et al.* (1997) for ORR procedure.

ORR Mechanism	Load Limited*	Order release may occur based upon job's features and workload in the shop.
	Time Phased	A release date is computed for each job regardless of the shop load.
Timing convention	Discrete*	Order release may occur at periodic intervals.
	Continuous*	Order release may occur at any time.
Workload Measure	Number of jobs	Workload is expressed in terms of number of jobs.
	Work Quantity*	Workload is expressed in terms of work quantity.
Aggregation of Workload Measure	Total Shop Load	All workload in shop floor is aggregated to a single value for release decisions
	Bottleneck Load	Workload is computed and controlled for only selected bottleneck work stations.
	Load by each work station*	Workload is computed and controlled for each work stations.
Workload accounting over time	Atemporal*	Total workload is summed up without differentiating its distribution over time.
	Time bucketing	Workload profile for each machine is distributed over time.
	Probabilistic*	Total workload is summed up by assigning probabilities to the operations.
Workload Control	Upper/Lower bound only*	Order release occurs if it does not exceed an upper/lower workload limit.
	Upper and lower bounds	Order release occurs to keep shop load within certain limits.
	Workload Balancing*	Load distribution balancing among work stations rather than direct bounding.
Capacity Planning	Active	ORR model may adjust work station capacity (output control).
	Passive*	No output control exists.
Schedule Visibility	Limited*	Controlled workload during the next closest planning period.
	Extended	Controlled workload more than a single planning period.

Another point in recent review of Sabuncuoğlu and Karapınar was the modeling of shop congestion for the attempt of enlightening research paradox, namely the trade-off state between overall lead time (total flow time in the system) and shop floor time (flow time in shop floor environment after release) due to the release of orders. From the seminal literary to that time, classical job shop models had been utilized having no material handling activity and infinite input and output buffer spaces for work stations. By modeling material handling activity and finite buffer cases, they concluded the effectiveness of ORR activities is significant for highly utilized systems, on the other hand insignificant and even aggravating for low utilized systems.

Among the ORR mechanisms developed to date; a load-oriented, work station information-based ORR mechanism, proposed by Philipoom, *et al.* (1993) called Path-Based Bottleneck (PBB) is used for several goals of order releasing in simulation experimentation of this thesis. This is a load-oriented method having a periodic structure. Besides, its objectives are overlapping with the machine-tool allocation model used for setting up the FMS environment. Both of them are aiming to minimize the total flow time of parts (namely, maximize the throughput) whilst balancing the workload of work stations simultaneously. Thus, PBB will be adapted for use in full routing flexibility in this thesis. The following paragraphs explain PBB in its original form.

Path-Based Bottleneck algorithm was proposed as a periodic ORR procedure based on workload bounding for the control of part flow to capacity constrained work stations, which likely to become bottlenecks in the future. The release of jobs are only permitted if no work station on the job's path will be loaded over a pre-determined threshold (workload limit). All jobs which would cause to exceed of this threshold in case of a release are held in the pool for later evaluation. On the other hand, due to accumulation of jobs in the pool, a priority rule has to be applied for releasing a set of the candidate jobs. This prioritization is based on a capacity slack-based priority rule for balancing the workload of work stations. After this sequencing of jobs within the pool, eligible jobs not exceeding the threshold level of work stations are evaluated for the release.

Under this framework, releasing procedure is performed in two steps. At first, the jobs waiting for entry are sequenced in increasing order of each job route's slack ratio (SR_j). This ratio is the difference between its pre-determined threshold and workload already committed to it in form of time units. Slack ratio attempts to identify the average proportion of slack of all work stations visited by a job which is consumed by that job. So, the route consuming the smallest proportion of slack of work stations on its path on average would be the most desirable candidate to enter the shop floor. This slack ratio also penalizes the jobs having large processing times at temporarily constrained work stations. Slack ratio is calculated by the following formula:

$$SR_r = \frac{\displaystyle\sum_{m \in M(r)} \frac{PT_{mr}}{T - L_m}}{N_r} \tag{3.3}$$

where,

SR_r	:	Slack Ratio of route r
PT_{mr}	:	Processing Time of route r at work station m, ($PT_{mr} = 0$ if machine m is not on job route r)
T	:	Capacity threshold
L_m	:	Current workload on work station m
N_r	:	Number of operations on route r of job
$M(r)$	:	Machine set for route r of job

All slack ratios for machine routes of jobs waiting in the pool are calculated one-by-one and sorted by increasing order. As a tie breaker in case of an identical slack ratio value, route having the least average processing times of operations is chosen to be at the top among matches. Job sequence located at first place in the list symbolizes the most desirable machine sequence of a job type among all job sequences in the pool.

The second step begins by evaluating the unique path starting from the first route in the ordered list. If the sum of current load of each machine along the job's route and job's processing time at that machine is below the threshold, then the job having that route is released into the shop floor. Upon releasing that proper job, if implemented, would cause to increase workloads of all machines on that job route according to a workload determination method as defined in Section 2.1.

The modifications proposed over this basic structure of PBB will be explained in Section 4.1.1.

4. PROPOSED ORDER RELEASE METHODS

The impression obtained from the literature is that, there are certain ORR mechanisms (load or, due date-based or hybrid) performing well for certain shop characteristics, release period and job mix properties via proper parameter setting, and not so well performing for other than their matches. The aim of the thesis is to comprehend the behavior of the ORR mechanism regarding workload bounding (threshold level), release periodicity and route characteristics effects; and make some constructive suggestions such as a self-triggering parameter-independent aperiodic release structure, an offline threshold level calculation method for different shop flow pattern.

As the first step, PBB algorithm is modified in a way to handle flexible process plans, and different workload calculation methods are discussed. In the next step, in order to seek for a more adaptive approach to avoid acting according to shop floor characteristics, period length parameter is dismissed. The release method is invoked by triggers of certain dynamics related with workload changes on the shop floor, namely continuous monitoring and automated release mechanism is formed. The final section dwells on the other critical parameter (a common or distributed workload threshold for work stations) by investigating its relation with shop and job mix properties.

4.1. Modeling of Path-Based Bottleneck Algorithm

Philipoom, *et al.*'s (1993) basic Path-Based Bottleneck frame and the reasons for using it in this thesis are described in Chapter 3. However, for more effective and diverse use of this algorithm some modifications are performed in its hierarchical arrangement, and this new form is named as PBB/r (indicating its extension of routing flexibility and other modifications).

4.1.1. Modifications in Path-Based Bottleneck Algorithm Structure

Before mentioning the modifications performed on PBB, it is better to explain the method and procedure in handling the flexibility issue within PBB structure. In Section 2.2.3, flexible process plans and ways of utilizing them for route selection are described. One is dynamic part routing handled on the floor, and other is in the pool. While executing PBB/r algorithm, the latter method is used for part routing activity, such that the machine route of a job is decided and fixed before the release. However, in the definition of flexibility the routes of jobs are determined as operation-machine pair; such that alternative process route of a job constitutes a sequence of operations, which could be performed by their relevant tool types. Therefore, for fixing the job's route path in terms of machines, all possible machine routes (namely, job sequences) are derived from alternative process routes. The instance of derivation is shown in Figure 4.1. Alternative process route of a job has three operations, of which first operation could be performed on vertical milling machine (VMM) or turret milling machine (TMM), second operation could be performed on horizontal milling machine (HMM) or centre lathe (CL) and finally a shaping operation that could be only performed on a shaping machine (SHP).

The modifications made on PBB are handled in both steps of the algorithm. Two ranking methods are used in the first step. After each job release, this list is updated according to workload changes on the machines. First one is the Slack-Based listing method as defined by Philipoom, *et al.* (1993) adapted to accomodate job routes instead of job types, such as in Equation 3.3:

$$W_r = \frac{\sum\limits_{m \in M(r)} L_m}{N_r} \tag{4.1}$$

where W_j is the average workload along route r and L_m is the current workload on work station m. The aim in suggestion beside the slack ratio is to simplify the listing approach by only observing the workloads of its machines on the job's route, whilst balancing and increasing the utilizations of low-utilized work stations. Another inten-

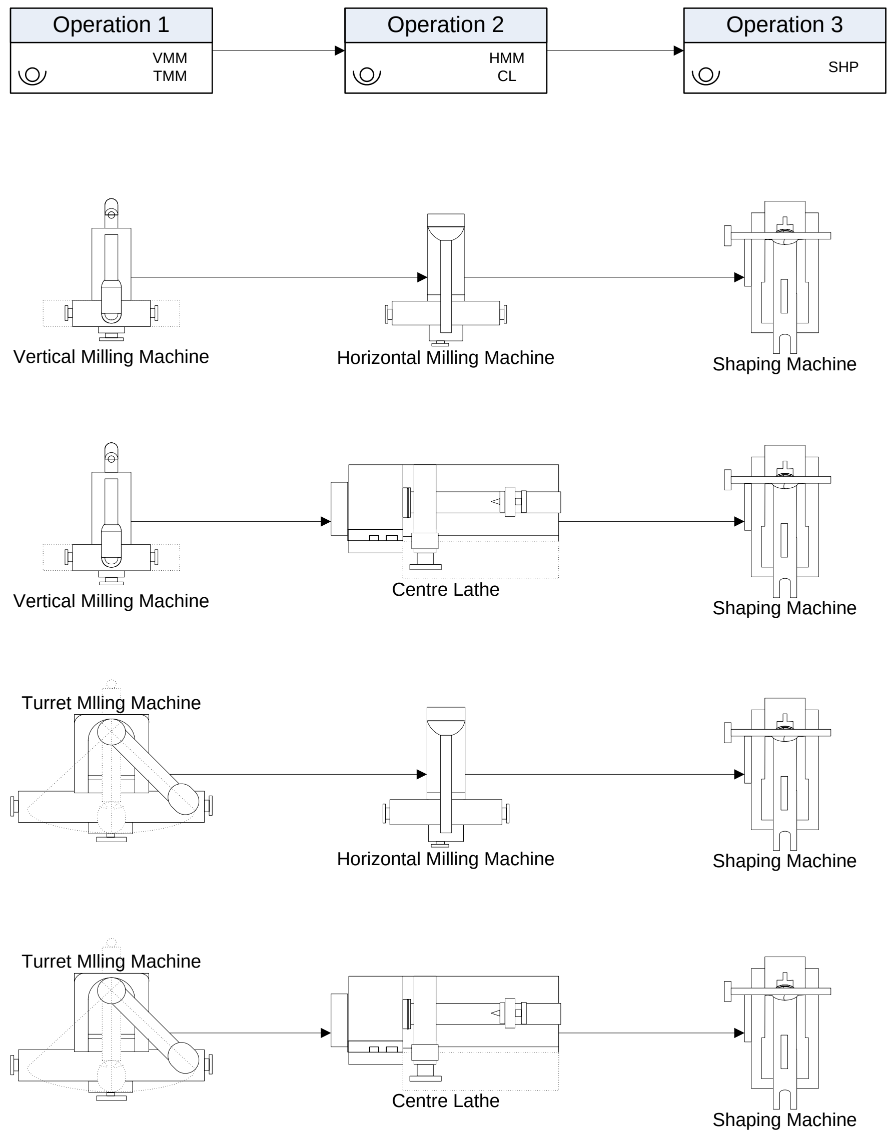

Figure 4.1. Derivation of job sequences from an alternative process route

tion for using this simplified approach is to eliminate discrimination of jobs (choosing the jobs with smallest processing times for shared work stations) in releasing them into shop floor. In addition, tie breaker in this listing approach is chosen to be the same as in slack ratio method's tie breaker (Average processing times for all operations of a job sequence). This method is named as *Load-based Listing* method throughout this study.

At this step, all possible job sequences in the list are sorted according to their slack ratios or workload sums in an increasing order. The job sequence at the top is the most desirable one to be evaluated for release at first. The jobs waiting in the pool belonging to that job sequence are let flow through the system, until the machines of that job sequence are bounded by the threshold level. Then, the job sequence in the second place can only be evaluated if job types belonging to the top job sequence do not exist in the pool or any machine on that job sequence reached its threshold limit. This process goes on until the evaluation of last job sequence in the list, if relevant job types exist in the pool.

In the very same step; Philipoom, *et al.* (1993) suggested updating loads of work stations in case of a release into the shop floor, but did not mention about the update of slack ratios in the slack ratio list. If workloads of work stations are updated in case of a release, then slack ratios must also be updated.

Briefly, the second step is about load limiting and workload determination on work stations. When the system is suitable to release a job into shop floor, this would lead to updates of workload levels for each machine on that job's route. At this point, together with previous two methods (Corrected and Aggregate) totally four machine load determination methods are implemented PT_{nm} symbolizes the processing time of n^{th} operation of a job on machine m. (Table 4.1):

Table 4.1. Workload load determination methods

Method	**Description**	**Form**
Aggregate	PT_{nm} is directly reflected to its machine workload	Static
Adjusted	PT_{nm} is reflected to its machine workload via dividing by n	Dynamic
Corrected	PT_{nm} is reflected to its machine workload via dividing by n	Static
Lagged	PT_{nm} is reflected to its machine workload via multiplying by $f(n, n_{max})$	Dynamic

The columns from left hand of Table 4.1 depict the machine load determination method, their brief descriptions and their altering statuses whilst being processed on shop floor, respectively. The last column reflects the characteristics of load determination while the jobs are on the shop. In static form, workloads of jobs on their downstream machines do not change; although jobs' operations are processed. While in dynamic form, as operations of a job are being processed, its related processing time coefficient alters. Corrected and Adjusted methods can be compared such that: a job having 5 operations is released to the shop floor. Upon release moment, both method depicts same workload on machines along the job's route. When first operation of the job is finished, corrected method does not change workload on remaining downstream machines but only whole load of first operation is removed from first machine. On the other hand; for adjusted method, although the same load for first operation on first machine on the route is removed remaining workloads of operations on downstream machines are increased. At that moment, load of second operation is completely reflected on second machine and coefficients of other remaining downstream machines are updated due to current sequence of operations. (Figure 4.2)

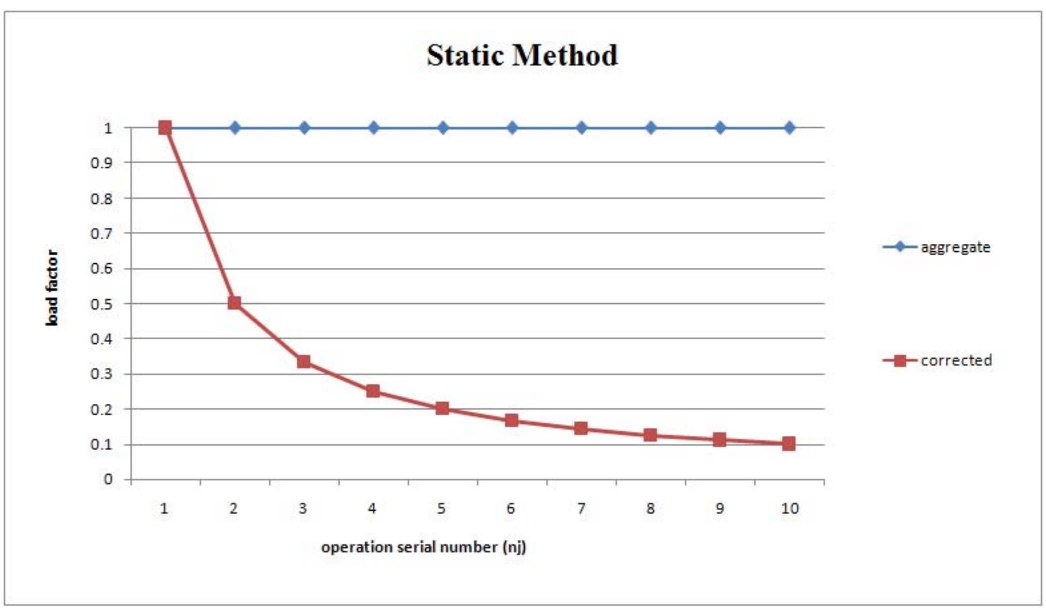

Figure 4.2. Static machine workload determination

The Lagged method is formed to have the opposite structure of Corrected and Adjusted methods. Such that, the latter pair show a concave-up characteristic (a decreasing function with a negative second derivative) in n vs. $f(n, n_{max})$ plane, where

$f(n, n_{max})$ is the processing time coefficient of an operation that will be reflected to its corresponding work station as workload and n_{max} is the maximum number of operations a job has in the job mix (equation 4.2):

$$f(n, n_{max}) = e^{\alpha(n_{max})\cdot(n-1)^{\beta(n_{max})}} \tag{4.2}$$

Contrary to this frame, the former one a concave-down characteristic (a decreasing function with a positive second derivative) tried to be formed in n vs. $f(n, n_{max})$ plane. The belief in this formulation is: the more upstream the work station, the larger the processing time coefficient is and; the more downstream the work station, the smaller the processing time coefficient is. To illustrate, as can be observed from Figure 4.3 the system of a Lagged method with n_{max} equals to ten, would multiply the processing time of first operation with 1, the second one with 0.9995 and third one with 0.905, etc. Contrary, the same system will have these coefficients as 1, 0.5, 0.33, etc.

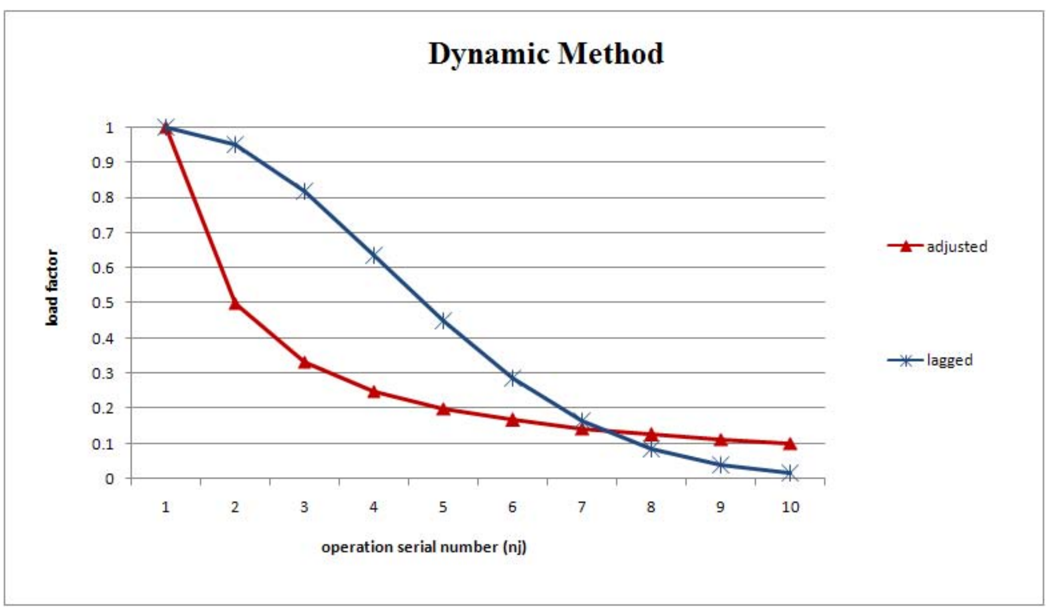

Figure 4.3. Dynamic machine workload determination

The formulation used for Lagged method has two constants $\alpha(n_{max})$ and $\beta(n_{max})$;

and inspired by the normal distribution formulation. They are adjusted to determine them off line and manually, due to job mix properties of the system according to n_{max}. α is the scale parameter and β is the skewness parameter of this function, the location parameter is fixed to zero. Due to its dynamic form, load factor of Lagged and Adjusted methods are altering as operations of jobs are completed. Figure 4.3 depicts these two methods when a job, having 10 operations for its shipment, initially enters the system. As operations are completed one by one, Figure 4.4 depicts load factors of that job when it is in a time interval such that, the job finishes its 4^{th} operation and not arrived to start 5^{th} operation yet.

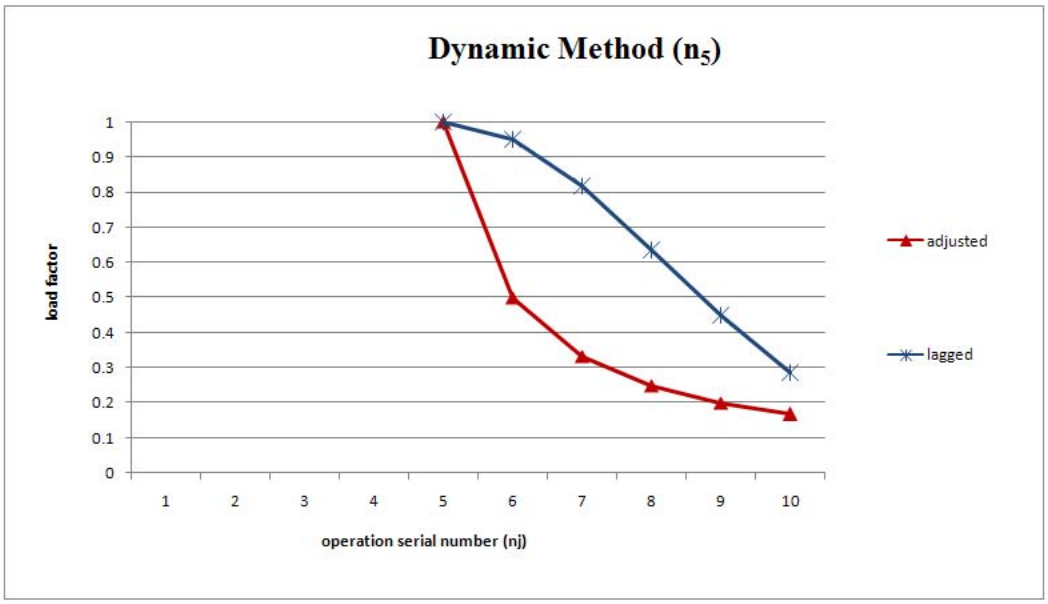

Figure 4.4. Dynamic machine workload determination

Beside its internal structure, the invoke of PBB is also modified for certain purposes. As mentioned earlier in WLC definition, the critical parameters for PBB are period cycle length of job release and threshold (workload limit) level of work stations. A thorough parametric search is conducted for examining the behavior of the system and the best threshold value in terms of least total mean flow time for all jobs is tried to be found empirically, as being done in this way within all literary content. All literary works find the best workload limit in terms of their chosen performance measure through experiencing pilot simulation runs. In the scope of this thesis, a near-optimal value this parameter is also tried to be estimated offline by a proposed method using system information in Section 4.3.

Parametric search for threshold parameter was performed for two types of order release timing: periodic and pull-type. In periodic order release simulation runs, a set of period lengths is used to see actions and reactions of the system. This parameter is also considered as critical and hard-to-achieve to find a near-optimal value. Also, for stochastic job arrivals setting a constant period length for order release decisions seems non-responsive to demands of market. Therefore, a parameter-independent pull system is implemented in the simulation using workload updates of work stations as informative supports. Detailed information for progressing of Process-Triggered Pull System (PTPS) is explained in the next section (Section 4.2).

4.2. Process-Triggered Pull System (PTPS)

The main concern in converting the periodic structure of order release method is to eliminate the decision attempt for evaluation of this crucial parameter.

To design a pull-type order release system, some decision points when an order release decision is require should be identified and some trigger mechanism that invokes the PBB/r must be defined. During execution of manufacturing (or its simulation) certain events may change the status such that the PBB/r which stopped job release at previous decision point should now reconsider the situation. For instance, the pool which was emptied may have a new arrival to be considered, or an operation may be completed on a machine whose workload was at the threshold. The updates of workloads on the machines determine whether it is worth to call the algorithm or not. Therefore it is required to provide continuous monitoring of workloads on machines, job arrivals and call the algorithm in the most appropriate points.

By evaluating some relevant status information about the system, the decision procedure depicted in Figure 4.5 and described below decides whether to call the method (*ExecutePBB/r*) or not at each discrete time point.

- Has workload of any machine been updated before the last call of this order release method? Workload update information is turned on (to be true) when any machine finishes an operation on its processor and pulls the job into its output buffer. Since, this activity declines the workload on that machine and possibly enables it to open up some space for new jobs to be entered into the shop floor from the release pool. (Update information is turned off (to be false) at the beginning of this transaction)
- Is the output buffer of order release pool empty? It is impossible to release any jobs if that output buffer is not available.
- Are there any jobs in order release pool to be evaluated for release decision? It makes no sense to execute algorithm method if no jobs are present in the pool.
- Has any new arrival been known before the last call of this order release method? On arrival of a new job, it may be possible to release it though workloads of machines are not updated since last call of this order release method.
- Is threshold flag ON? When threshold flag is ON (true); it means that at previous call of *ExecutePBB/r* method, at least one of the machines has prevented a job to be released from the pool. Despite the fact that nothing affecting the workload distribution on machines (either a new job arrival or finish of a process) has happened there still exists a probability to achieve a release of a job into the shop floor. Although nothing has occurred relating the workloads; a job, which could not been released previously, may have a chance to be released if no load limiting exists on the machines in its job's route.

4.3. An Analytical Method to Describe the Relation between Threshold and Other System Parameters

This section presents an analytical framework that explains the relationship between the workload threshold used in ORR and other system parameters.

Let $P_m^{r,l}$ be the probability that, a part currently on machine m is on route r and visiting that machine for operation l of r , where r is a machine route, which is an element of set of routes R. The machine route (or alternatively job sequence) of

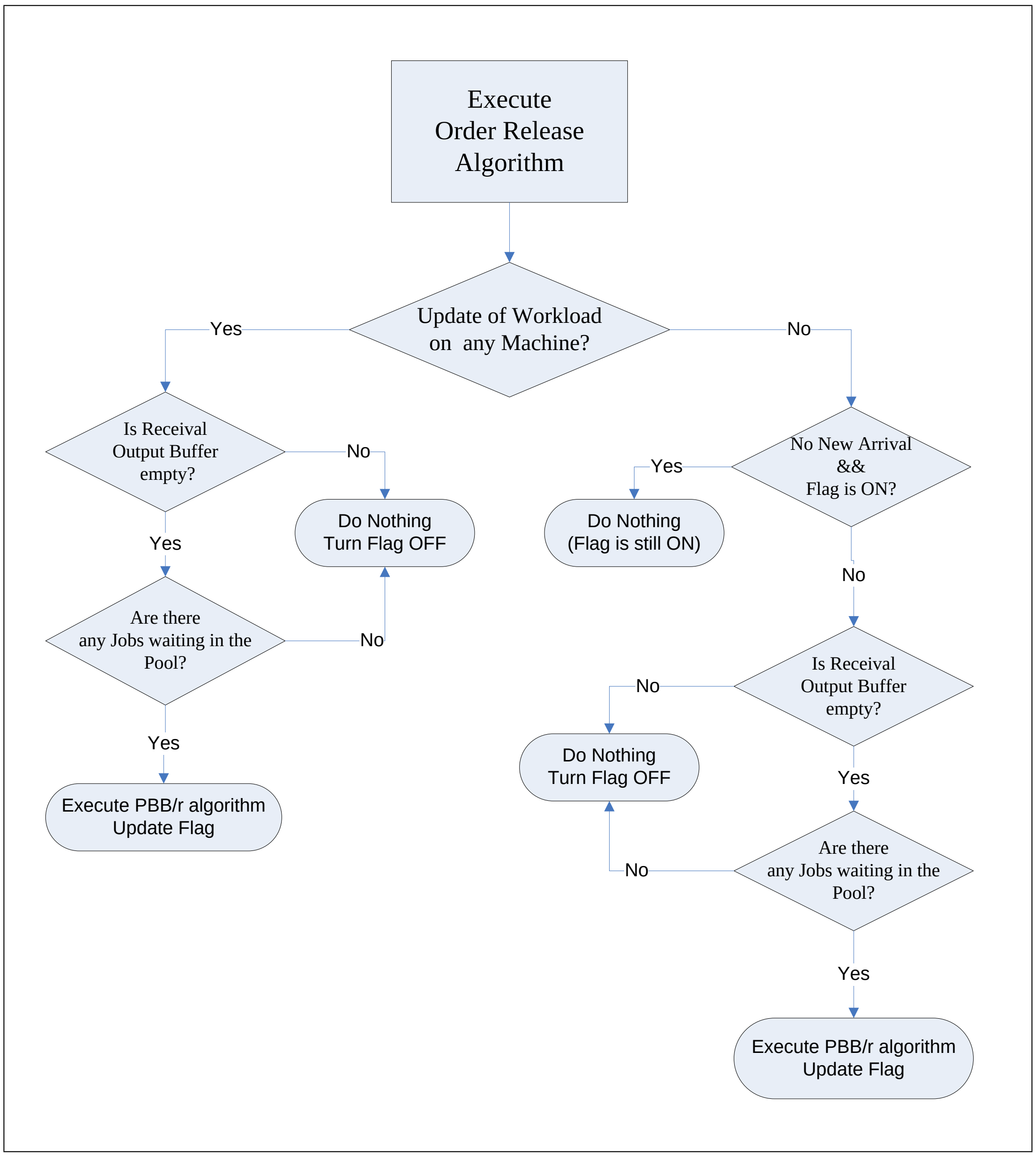

Figure 4.5. Path-based bottleneck execution

a job constitutes the order of machines that operations of the job will be performed sequentially. All possible routes of a job are sequentialized in terms of possible combinations of operations and machines. For instance; a job can be completed by milling and shaping operations sequentially and milling operation could be performed by a certain tool, which is mounted on more than one machine in the shop floor (i.e two work stations), then that job would have two job sequences, if shaping operation can be performed by only one work station.

To illustrate, there exist JobA and JobB having a product mix ratio of 30%, and 70%, respectively. These two jobs have the specifications depicted in Table 4.2 and the job sequences derived from this job mix is: JobA only follows the machine route as Lathe-Grinder; JobB could either follow Lathe-Grinder or Drill-Grinder path. Thus, for this example route r can take on the values $R = \{A, B1, B2\}$. The probability that a part is of type j can be based on the job mix ratio. However, it is still needed to estimate the probability that a particular route of that part will be used. For simplicity, it is assumed here that all routes of a part type are equally probable. Thus, for the example, it is 0.30 for the single route of job A and 0.35 for each route of job B.

Product Name	**Operations**	Mix Ratio
JobA	Receival-JAO1-JAO2-Shipment	30%
JobB	Receival-JBO1-JBO2-Shipment	70%

Operation Name	**Tool Name**
JAO1	Tool1
JAO2	Tool3
JBO1	Tool2
JBO2	Tool3

Work Station	**Loaded Tool**
Lathe	Tool1
Lathe	Tool2
Drill	Tool2
Grinder	Tool3

Table 4.2. Job mix example for probability calculations

By the help of these ratios, $P_m^{r,l}$ values are calculated as follows for the case given in Table 4.2:

$$
\begin{aligned}
P^{A1,0}_{Receival} &= 0.30 & P^{A1,1}_{Lathe} &= \frac{0.30}{0.30+0.35} & P^{A1,1}_{Grinder} &= 0 \\
& & P^{A1,2}_{Lathe} &= 0 & P^{A1,2}_{Grinder} &= \frac{0.30}{0.30+0.35+0.35}
\end{aligned}
$$

$$
\begin{aligned}
P^{B1,0}_{Receival} &= 0.35 & P^{B1,1}_{Lathe} &= \frac{0.35}{0.30+0.35} & P^{B1,1}_{Grinder} &= 0 \\
& & P^{B1,2}_{Lathe} &= 0 & P^{B1,2}_{Grinder} &= \frac{0.35}{0.30+0.35+0.35}
\end{aligned}
$$

$$
\begin{aligned}
P^{B2,0}_{Receival} &= 0.35 & P^{B2,1}_{Drill} &= \frac{0.35}{0.35} & P^{B2,1}_{Grinder} &= 0 \\
& & P^{B2,2}_{Drill} &= 0 & P^{B2,2}_{Grinder} &= \frac{0.35}{0.30+0.35+0.35}
\end{aligned}
$$

Direct load (D_m) of a machine can be defined as the total amount of workload waiting in that machine's input buffer queue, namely the operations of jobs that are to be processed in the very nearest future by that machine. Figure 4.6 illustrates the direct loads of each work station.

$$D_m = inQ_m(\sum_{r \in R} \sum_{l=1} t^{r,l}_L P^{r,l}_m) \tag{4.3}$$

where inQ_m is the expected input buffer length of machine m and $t^{r,l}_l$ is the processing time of l^{th} operation of route r on machine m. L is the maximum number of operations on the routes.

Indirect load (I_m) of a machine can be defined as the workload amount of jobs waiting or being processed in some places other than the buffers of that machine and going to visit that machine in the future. Indirect loads of each work station is illustrated in Figure 4.6.

$$I_m = \sum_{k \in M, k \neq m} I_{k,m} + I_{Rec,m} \tag{4.4}$$

where M is the set of all machines, $I_{k,m}$ is the indirect workload of machine m resulting

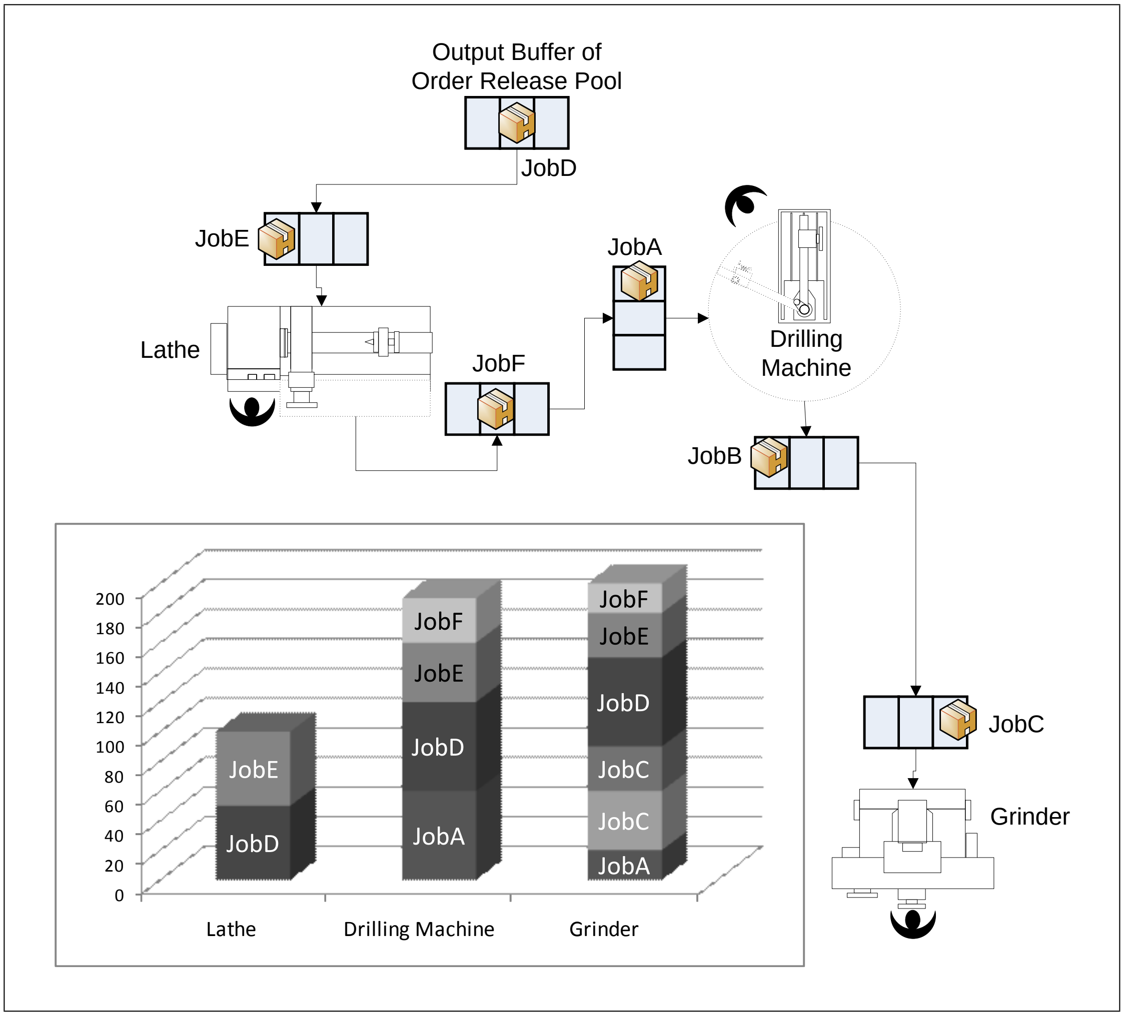

Figure 4.6. Representation of direct and indirect loads

from the jobs on machine k.

$$I_{k,m} = (inQ_k + U_k + outQ_k)(\sum_{r \in R} \sum_{i=1}^{L} \sum_{l<i} t_m^{r,l} P_m^{r,l}) \tag{4.5}$$

where inQ_k, U_k and $outQ_k$ are the expected input buffer lengths, expected utilization percentage and expected output buffer lengths of machine k; respectively. $I_{Rec,m}$ is the indirect workload machine m due to jobs on output buffer of order release pool, which are waiting to be transferred and processed for its very first operation.

$$I_{r,m} = outQ_{Rec}(\sum_{l} t_m^{r,l} P_{Rec}^{r,0}) \tag{4.6}$$

where $outQ_{Rec}$ is the expected output-buffer usage of order release pool.

The sum of indirect and direct loads of a machine results the total workload of that machine. The machine having the maximum amount of workload is anticipated to be the bottleneck machine in the system and threshold level is thought to be near to this maximum value.

There are certain assumptions and requirements while applying this method. They are route usage ratios of jobs, machine utilizations, and mean input and output buffer lengths of machines. First two of these identified parameters can be estimated via the help of LMM. On the other hand, as mentioned earlier, probability distribution of jobs over job sequences are performed uniformly and preliminary runs are conducted for other parameters. Results of this approach can be found in Section 4.3 of numerical experimentation chapter.

5. NUMERICAL EXPERIMENTATION

Proposed ORR mechanisms and other comparative base cases are tested for part flow patterns under some assumptions (Section 5.1) by extensive simulation runs on a simulation package, described in Section 5.2. After giving information about simulated manufacturing layout and, job mix properties of part flow patterns in Section 5.3, experimental results are presented with supporting tables and figures for each flow pattern. In the next section (Section 4.3) another numerical study about seeking a relation between threshold level and system parameters is presented. Finally, all ORR mechanisms are compared and overall results are discussed in Section 5.4.4.

5.1. Assumptions and Performance Measures

For the sake of simplicity and easily comprehensibility of the system to settle it an easy-to-analyze form, some assumptions were made to avoid any external or internal complexity. By this way, lean structure of the model assisted to manipulate certain parameters and policies to achieve certain performance measures. These assumptions valid for all simulation experiments are as follows:

- A small FMS environment, that is convertible into any manufacturing environment model ranging from undirected to strictly directed flow patterns, with a number of cells, buffers and AGVs.
- No assembly operations.
- No breakdown on cells.
- No breakdown or battery shortage on AGVs.
- No explicit set-up times (may be included in processing times).
- No tool changes. Tools are allocated at the beginning of production and not re-allocated.
- Materials or other equipments are available when needed.
- Process plans of job types (flexible or fixed) are available in advance.

The main functions of order release policies proposed in Chapter 4 comprises load balancing and load limiting activities for effective machine exploitation, and for reduced WIP inventory respectively. The performance measures used in judging these methods are accordingly selected as:

- Flow time statistics of job types
- Completion amounts of job types within time limits
- Machine utilizations
- Work-in-Process Inventory

These constitute the most popular performance measures in the literature excluding the due date related ones. The first two are attached more importance as primary performance measures. Note that, sometimes these measures may be conflicting with each other.

5.2. FMS.NET as an Object-Oriented FMS Simulator

FMS.NET is an object-oriented discrete event FMS Simulator developed by Gönen, (2005) as a part of his thesis for research purposes of BUFAIM. It composes of movable objects like AGVs as material handling instruments, unitloads as jobs being transferred and processed, tools as instruments of processors of cells; static objects like cells as flexible processing work stations, queues as buffers for cells, lanes as roads for AGVs, nodes as junctions, borders and corners of traffic area.

FMS.NET requires three separate information from the user as inputs for FMS to simulate it properly: Layout Definition, Job Mix Definition and Simulation Parameters in Extensible Markup Language (XML) format. Layout definition consists of properties of material handling and machining systems. Job mix specifies job definitions that are produced in this FMS layout. Simulation parameters are composed of selected decision algorithm names and run parameters that will be used in a given simulation experiment such as simulation end time, seed for randomization and warm up time for collecting steady-state statistics. Based on the object-oriented architecture of the FMS.NET simulator, order release decision model is implemented within this structure. An order release algorithm class included in general algorithm class and PBB/r is coded as an instance of this class and inserted in the decision tools library. Other decision algorithms within general decision algorithm class, which affect the results directly or indirectly and correlates with order release activities are as follows:

- AGV Dispatching
- AGV Matching
- AGV Routing
- Blockage Solving
- FMS Loading
- Junction Management
- Operation Aggregation
- Operation Selection
- Process Order
- Traffic Routing

Following are the descriptions of these decision algorithm classes:

AGV Matching is the process of assigning eligible AGVs to parts to be transported.. A unitload is transferred to output queue when its operation is completed in current machine and this part should be transferred to another machine. This part is assigned to one of the AGVs which have empty position. If there is no eligible AGV, this part is not assigned to any AGV and waits for an AGV to become eligible.

AGV Dispatching is the process of deciding the next destination of an AGV. After an AGV arrives to its destination and completes delivery or pick-up tasks, its new destination should be provided. This is also required when a part is assigned to an AGV.

AGV Routing is the process of selecting a route between an AGV's current location and its destination.

Blockage Solving is the process of deciding what action will be performed when AGV is arrived to a cell with full input buffer. It is used to avoid blockages in the system. If an AGV arrives to its destination to deliver a part and the input queue of the machine is full, AGV becomes blocked. If no action is taken, this may result in system deadlock depending on the layout.

FMS Loading is the process of selecting job types to be processed simultaneously and allocating the necessary tools to magazines (not activated in this study's experimentation).

Junction Management is the process of deciding which AGV will pass through a junction node first, when more than one AGV want to seize that node to pass through.

Operation Aggregation is the process of deciding whether consequent operations will be performed in the same cell. It aids to save time if a unitload has finished one of its operations and could perform the next operation still on that work station.

Operation Selection is the process of deciding next operation and the machine to process that operation for a part. When an operation is completed, next operation for this part is selected by using alternate operation routes of the part.

Process Order is the process of deciding which part is processed first from an input buffer of a cell. When a processor becomes empty, one of the parts that are in input queue and wait for the processor is selected and transferred to processor.

Traffic Routing is the process of deciding whether a unitload will be sent to its destination via AGV or conveyor.

FMS.NET simulator has an event calendar whose events are sorted in increasing time order. Simulator executes the event with the minimum time, this event can cause new events to be created and simulator add these newly created events to its event calendar. Execution goes on like that till simulation end time is reached. There are several types of events for AGV movements and handles, cell processes, etc. An additional event type also created for periodic and pull-type order release purposes. In periodic release; after initial invoke of order release algorithm, the very next call time of the order release event is inserted to the event calender. In pull-type release; there exists no order release event, but it is invoked at each discrete event call.

5.3. Design of Test Problems and Layout

The manufacturing environment under consideration is a FMS, where a finite set of job types in a given job mix are produced on a number of workstations. The processing capabilities of the workstations are determined by the set of tools that are mounted on their tool magazines. This allocation of tools to specific machines is assumed to be performed off-line (i.e. via a LMM as described in subsection 2.2.4). Parts are carried by Automated Guided Vehicles (AGV) among workstations. A part whose processing is complete at a workstation is transferred to its output buffer, and generates a transport call. Then, it is matched with an eligible AGV to be taken to its next workstation's input buffer. The destination workstation has either been fixed in advance at part's release, or, if this is not the case, it is fixed by a dynamic routing algorithm before the part is matched with the AGV. To avoid possible deadlock situations, a central buffer station (CB) can be used as temporary storage. The experiments are conducted on a hypothetical FMS environment with six workstations. The layout for the hypothetical facility can be seen in Figure 5.1.

Process plans for the job types to be processed on the above layout are arranged to generate three general part flow patterns. These part flow patterns are *Strictly Directed* (SD), *General Directed*(GD) and *Undirected* (UD) (Figure 5.2).

In UD, almost all machines are both upstream or downstream (or mid-level) machines in operation sequences of job types. The very same work station might perform the first operation in the routing of one job, while it performs the final operation in the routing of another job. In other words, the routing sequence is completely random and the flows through the shop are undirected. Beside the routing sequence, the route step

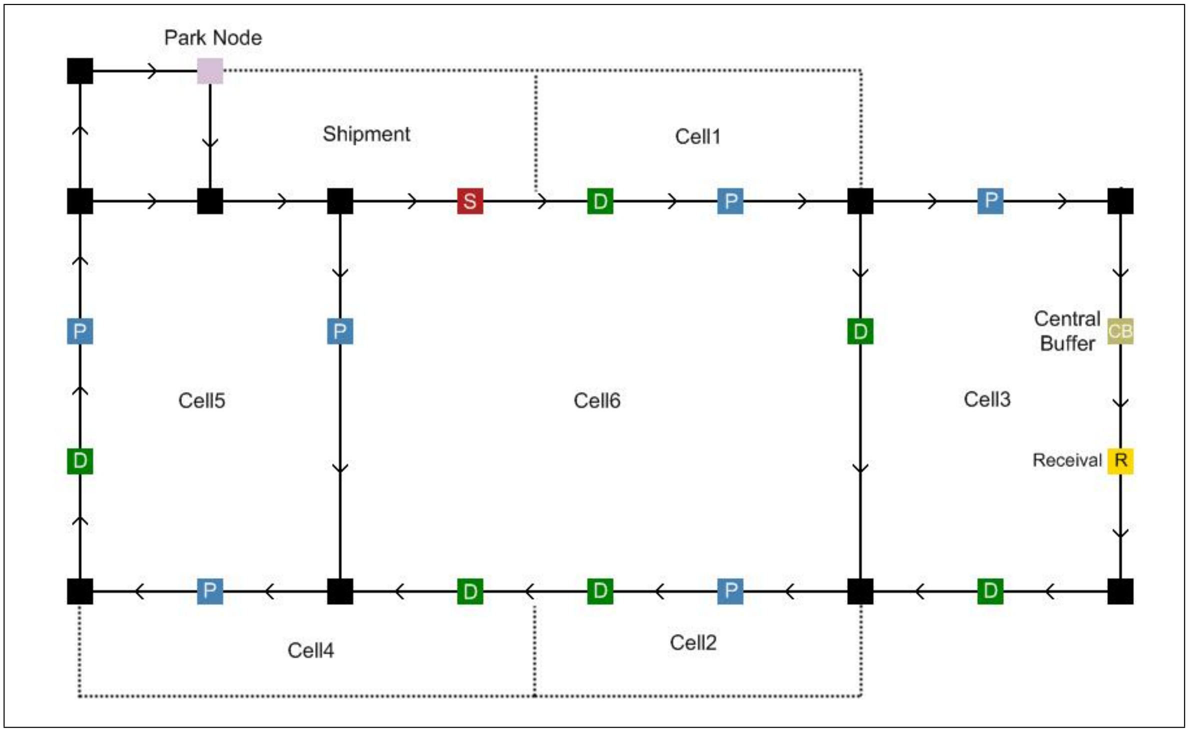

Figure 5.1. Physical layout

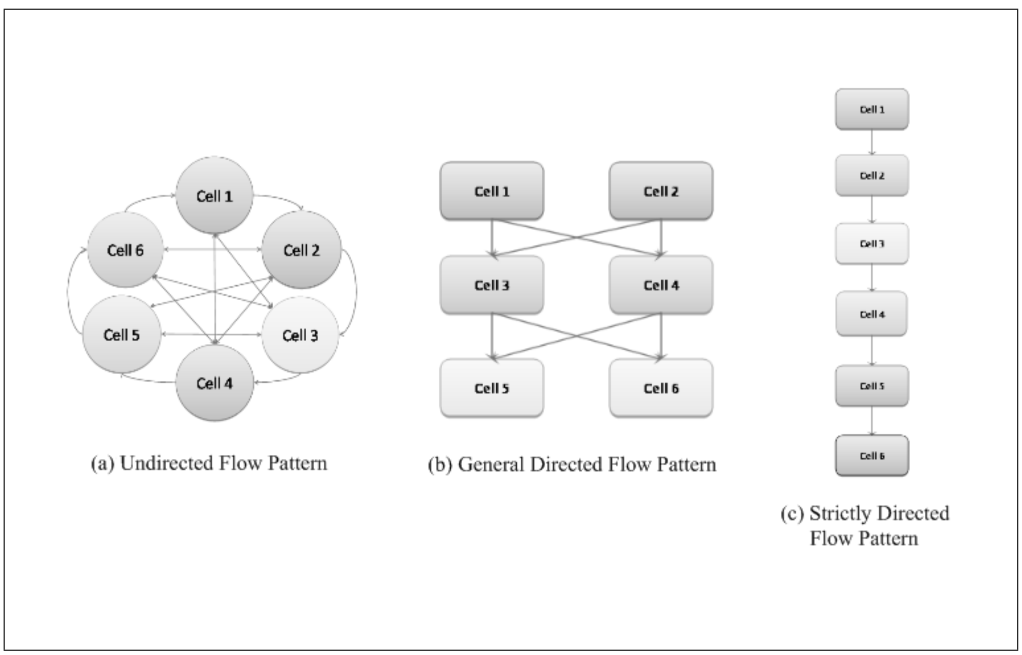

Figure 5.2. Three part flow patterns

size (number of operations of each job type) varies strongly. Some jobs may have only one operation to be performed, while other jobs visit all stations in the shop. Route and machine flexibilities are available in this case.

In SD, each job has exactly the same routing direction and step size. The volume of jobs are high, but job type variety is low (i.e. 3 job types). All three jobs must be routed in order of increasing work station number (Cell1 - ...- Cell6) to be shipped successfully. It is evident that process plans are not flexible in this case.

In GD, a movement between any combination of two stations may occur, but the flows always have the same direction. Compared to the strictly directed routing, any set of stations might be excluded from the routing. Thus, GD may still show routing variety with respect to routing lengths, though there exist a unique flow direction. This is the case in which machine and processing flexibilities are inserted, that enable the release mechanism to handle part routing and balancing decisions prior to shop floor.

In problem generation, following set of parameters are decided to be selected:

1. *Layout dependent parameters*:
    - Number of cells, I/O. Buffer sizes of cells, Output buffer size of ORR pool, Layout design (locations of cells, lanes and nodes), AGV fleet size, Speed and capacity of AGVs,
    - Tool magazine capacities of cells, Number of tools, Slot requirement of tools, Availability of tools.
2. *Part dependent parameters*: Number of part types, Process routes for each part, Number of operations in each part routes, operations, Processing times of operations, Product mix and demands of part types.
3. *Algorithms*: Simulator decision rules (AGV dispatching, AGV routing, operation selection, blockage solving, etc.)

In addition, machine slot capacities, tool slot requirements along with number of available tool copies are some other key parameters of machine and routing flexibilities.

These parameters are also generated in order to have reasonable sample problems regarding the shop models.

Keeping the layout dependent parameters constant as symbolized in Figure 5.1; AGV fleet size, AGV speed and output buffer size of ORR pool are adjusted according to characteristic of shop model by pilot runs before actual replicated simulation results. In pilot runs, AGV fleet size and speed are set according to an average AGV utilization between 75% and 85% in order not to erect barriers for healthy observation of system measures. AGV capacities are set to one unit.

Parts in the output buffers are processed on First-Come-First-Served (FCFS) basis. The AGVs can carry one unit at a time and they are always routed along the shortest path to their destination. When dynamic part routing algorithm is required Smallest Queue Workload (SQW) algorithm is used. SQW selects the machine having the minimum workload on its input buffer queue among the alternatives.

Part dependent parameters are determined regarding flow patterns since all other physical properties are fixed. Job route alternates and number of part types are chosen to be high in UD, but low in GD and SD. First number of routes and then number of operations in each route are generated. Operations of routes are not defined up to this point.

Processing times of operations are generated and inter arrival times of jobs are selected such that the workload of the shop will be around 90%. Processing times are randomized via normal distribution with a 5% standard deviation around the mean.

Number of tool types, tools slot requirements and available tool copies are randomly generated, from user defined discrete uniform distributions and operations are randomly matched with one of the tool types belonging the set of generated tool types. As the final step, magazine capacities of machines, all of which are identical to each other, are determined. This is achieved by assigning a total number of magazine as a percentage of total slot requirement of all tools, but averaging over all alternative process routes of all part types.

After completely generating all required input data in XML formats, final step is to allocate the generated tools to the located cells. This step is achieved by Loading Mathematical Model (LMM), which was previously mentioned in Section 2.2.4. It takes up a negligible amount of time (less than a half minute) to find the solutions for tested layout definition and job mixes, since job mix and layout definitions used for the experiments do not constitute a large database.

The objectives of LMM and ORR mechanism used in this thesis overlap, since both of them intend to maximize the completion amount of part types and balance the workload among cells. So, intuitively it could be claimed that simulation results could not be affected negatively by utilization of LMM. Even the tiny manual changes after gathering a solution from LMM leads to poor results both in do-nothing case (immediate release - IMM), or order release mechanism (Path-Based Bottleneck/r).

Two cases with different job mix definitions and tool allocations for each of SD, UD and GD flow patterns are generated for numerical experimentation. The details for these cases can be found in Appendix A.2, A.4 and A.3, respectively.

A single simulation run constitutes 75,600 units of time with a transient period of 10,000 which is observed to be quite sufficient for all replications. Ten replications are collected for each level of factors (i.e. ten replications for ‘Aggregate’ Workload Determination method in SD flow pattern).

5.4. Experimental Results

Simulation results are presented and discussed in this section. The presentation method used to depict the simulation results in the figures in this chapter is similar to (Oosterman, *et al.* 2000). The curves (i.e. those in Figure 5.4) are the performance curves. The horizontal axis shows the average time an order spends on the shop floor from the time of its release to its completion; and its is used as an indicator of threshold tightness. The vertical axis shows the average total throughput time which is our main performance measure to compare alternative release methods. To determine total throughput time, the pool waiting time is added to the floor time. Thus, total throughput time performance is depicted for different threshold tightness levels. A mark on the curves is obtained by simulating a release method with a specific threshold level for 10 replications. If a curve remains below another one, it may be concluded that it has a better total flow time performance. To retrieve each release method's best performing threshold level we have to look up the threshold value yielding the minimum point of the corresponding curve.

Effects of workload determination methods, ORR period, and pull-type self-triggered mechanism on system performance are investigated for SD, GD and UD part flow patterns and reported in the following subsections.

Analyses of these effects on a flow pattern begin with the impact of workload determination methods. In this step, figures depict the performance curves of different workload determination methods and tables show total throughput of jobs, threshold level and sum of all I/O. Buffer mean lengths corresponding to the best average total flow time for period length of 50. At the second step, ORR period effect on the performance is investigated for period lengths of 50, 100, 500 and 1000 time units with the same tabular convention. Performance curve characteristics show similarities while examining ORR period effect, so selected ones are exhibited within the subsections and the results for the remainder of the experiments can be found in Appendix B. At the third step, results of pull-type ORR check mechanism for each flow pattern are presented as an alternative approach to periodic one.

At the last step, immediate and interval order release (IMM and IR) results are depicted under these flow pattern subsections. Recall that, IMM can be considered as the do-nothing case of a continuous ORR mechanism such that, when an order arrives into the system, it is directly released to shop floor without evaluating any system information. Therefore, average flow times of jobs are equal to their average shop floor times. Interval Release (IR) resembles IMM except its timing convention, namely it is the periodic form of immediate release. One important distinction for IMM and IR is that, they use SQW for dynamically selecting the machines, the parts will visit.

Although I/O. Buffer sizes are kept infinite in workload control mechanisms (since they already have the power of controlling sizes of buffers), IMM and IR are found to be affected by these buffer sizes. Actually, restricting the system with finite buffer sizes can also be considered as a primitive workload control strategy. So, before comparing IMM and IR with ORR mechanisms, their behaviors under finite buffer sizes are analyzed.

After analyzing SD, GD and UD flow patterns seperately in this fashion, in another section these results are summarized and discussd in a combined manner to give an overall view.

Finally, as the last section of this chapter, we give a numerical example for each analytical model that explains the relation between threshold and other system parameters.

5.4.1. Results for the Strictly Directed (SD) Part Flow Pattern

Best average total flow time of jobs is found from Figure 5.5 and corresponding statistics are depicted in Table 5.1 with different workload determination methods for period length of 50 time units. Special to the job mix structure of SD, the two job sequence desirability listing methods, slack and load, using equations 4.1 and 3.3 respectively give totally identical results.This is expected since there are only three part types all of which use the same fixed route (all machines sequentially ordered with increasing cell numbers).

There are no significant differences between the methods in terms of average total flow times and total throughput for the jobs (Hypothesis testings can be found in Appendix C.1). However, average queue lengths (in other words, WIP) differ. Corrected method results to higher amount of total average queue length, especially at bottleneck machines, since it permits more jobs for intermediate and downstream machines.

Table 5.1. Best total flow time points for figure 5.3

	Best Average Total Flow Time	Total Throughput	Total Mean WIP	Best Threshold
Aggregate	30,498	731	4.59	850
Adjusted	30,501	731.5	4.04	400
Corrected	30,383	731.7	11.69	225
Lagged	30,690	731.9	5.74	550

It may be concluded that SD flow pattern does not affected significantly by workload determination methods from aspect of the primary performance measure, so it may be better to seek for better results in terms of other measures, since total throughput results also resemble. Then, in terms of total average queue length either aggregate could be chosen to exhibit here (remainder are given in Appendix B.1).

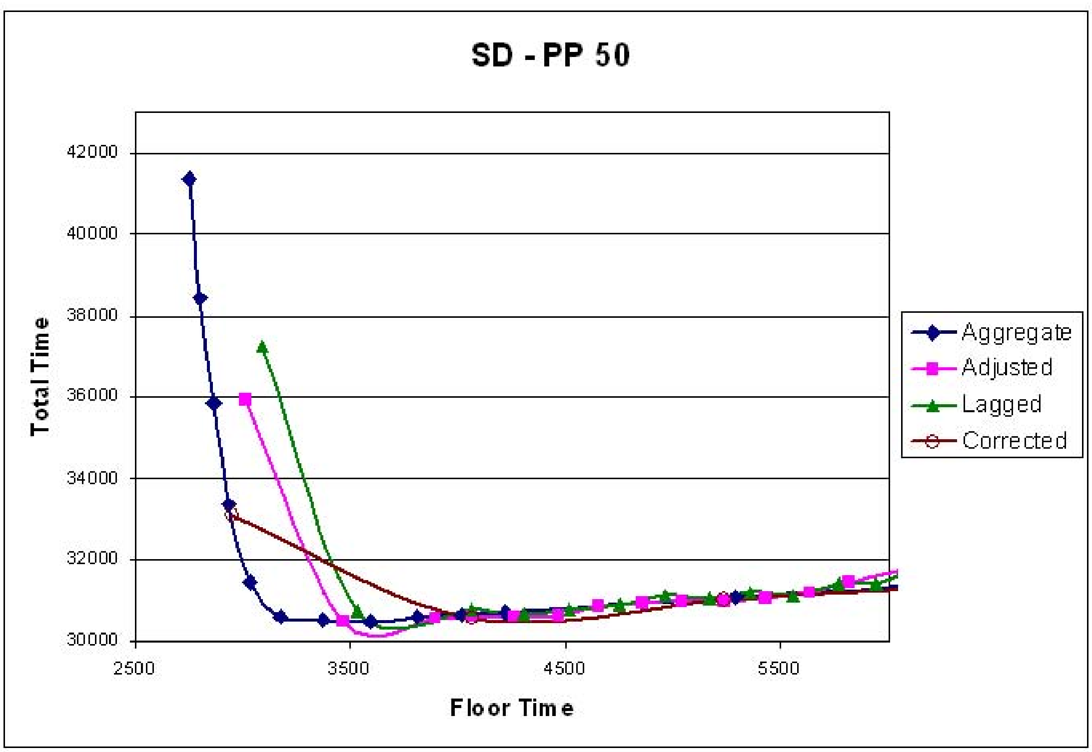

Figure 5.3. SD model with effect of workload determination methods

ORR period length is a critical parameter for periodic ORR mechanisms. The gradual increments in the value of the period length show that it effects the total flow performance significantly. First figure is the one with Aggregate method and Load approach in SD flow pattern (Figure 5.4 and Table 5.2):

Table 5.2. Best average total flow time points for figure 5.4

ORR period length	Best Average Total Flow Time	Total Throughput	Total Mean Q. Lengths	Best Threshold
PP 50	30,498	731.0	4.59	850
PP 100	30,781	644.3	4.28	850
PP 500	31,471	554.5	3.28	1250
PP 1000	32,376	392.8	1.86	1500

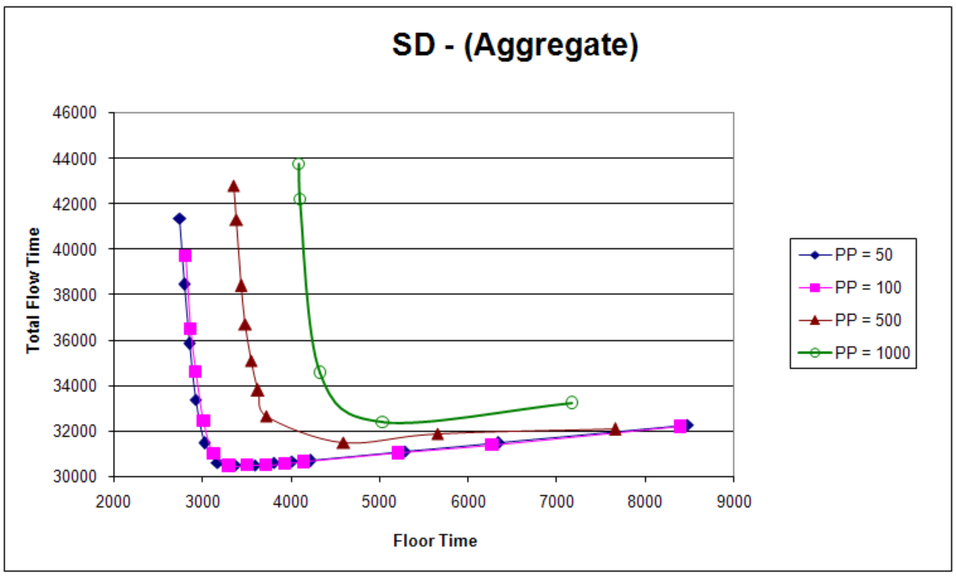

Figure 5.4. SD model with aggregate method for four levels of ORR period length

The basic remarks that could be drawn from Figure 5.4 and Table 5.2 are as follows:

- Average total throughput of jobs decreases drastically as the period length rises. However it can be observed that there exists a critical interval where increasing the ORR checking frequency would not contribute to performance measures, instead would cause computation burden. So, period length is a parameter to be decided carefully.
- Total WIP level declines due to starvation caused by infrequency of ORR check. So, it is evident that decreasing the frequency would prevent the jobs to be

released on time and cause starvation on the machines beside the latency. The situation is worse with a restricted pool output buffer, such that when the time comes to release a vast amount of job due to the starvation, the restricted output buffer would not permit to release as much as required number of jobs into the shop floor.

Very similar behaviors are observed for other machine workload determination methods in SD flow pattern. These charts and tables are exhibited in Appendix B.1.

Regarding the pull system for SD compared to its periodic form at first glance the results are similar (Table 5.5 and Figure 5.3). Nonetheless, there exists a slight improvement in best average total flow time or total throughput of jobs. The main reason can be due to high frequency ORR checks (will be quantified in 5.4.4) compared to most frequent periodic case (PP50). Total mean WIP levels are close to each other and reasonable from a realistic perspective (e.g. using Lagged method, 3 jobs in average for input buffer of each work station; neglecting the output buffers, since they resulted in very insignificant amounts).

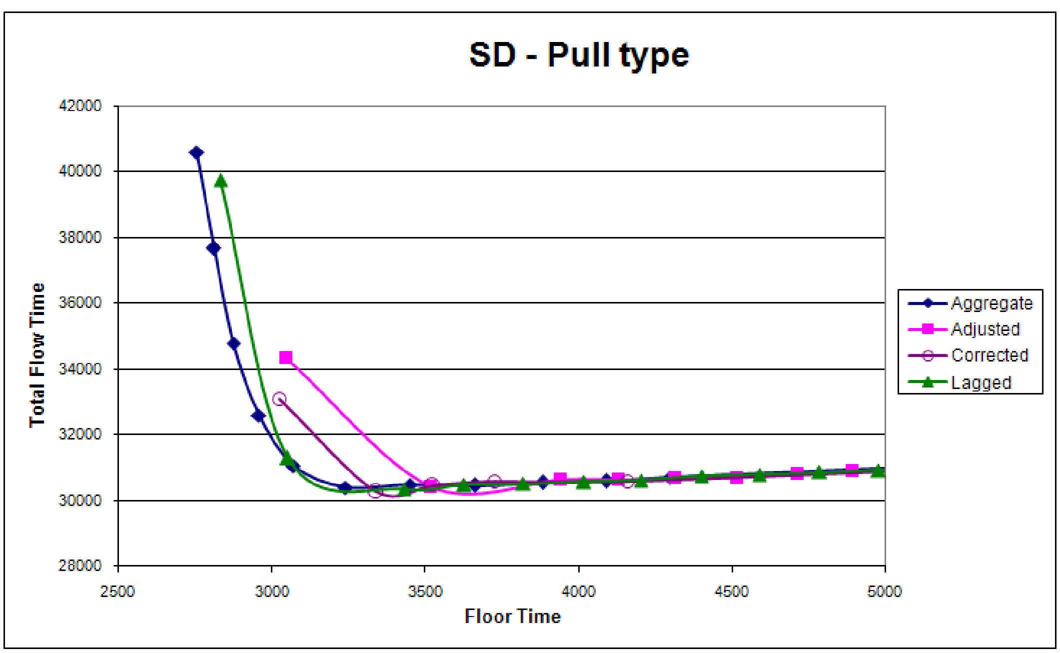

Figure 5.5. SD model pull-type simulated with effect of workload determination methods

Table 5.3. Best total flow time points for figure 5.5

	Best Average Total Flow Time	Total Throughput	Total Mean WIP	Best Threshold
Aggregate	30,408	734.125	20.6	750
Adjusted	30,445	733.5556	15.18	400
Corrected	30,587	733.3333	15.5	300
Lagged	30,363	734.4444	18.15	500

There exists an interesting case for SD flow pattern in terms of do-nothing cases (IMM and IR). Although a convex curve is built, up to a finite queue size, the best average total flow time can only be reached for infinite I/O. Buffer queue sizes (Figure 5.6). The same behavior is observed for IR case of SD for each period length (Table 5.4 and Figure 5.7). The main reason for such a situation can be the completely strict flow paths of jobs. So, buffers are of paramount importance for such a specific flow pattern.

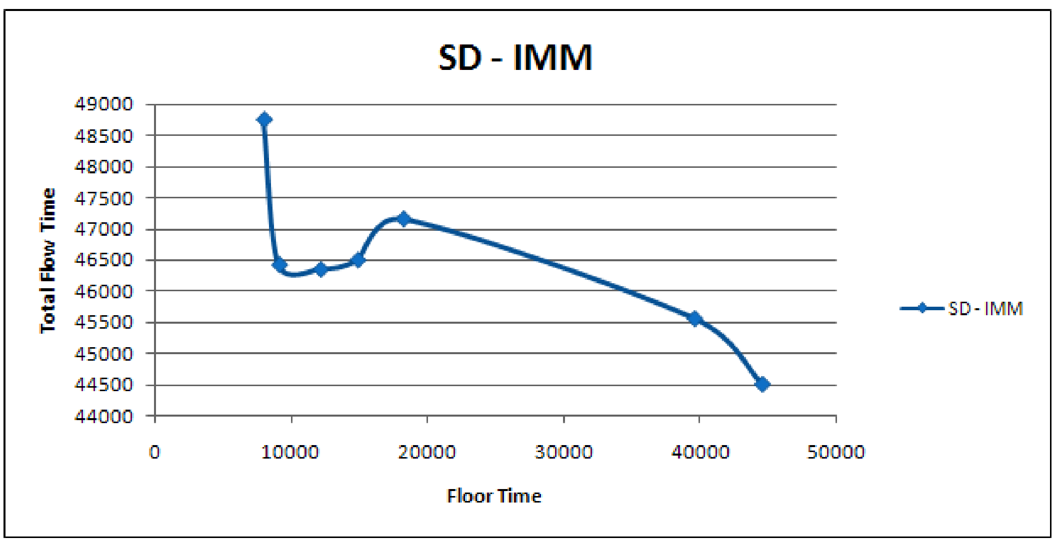

Figure 5.6. SD immediate release with variable I/O. Buffer sizes

Table 5.4. Best average total flow time of jobs with relevant I/O. Buffer size at different period lengths for SD

SD - IR	Average Total Flow Time	I/O. Buffer Queue Size
PP50	46,377.42051	10
PP100	46,390.03064	10
PP500	47,308.47292	10
PP1000	48,501.98352	15

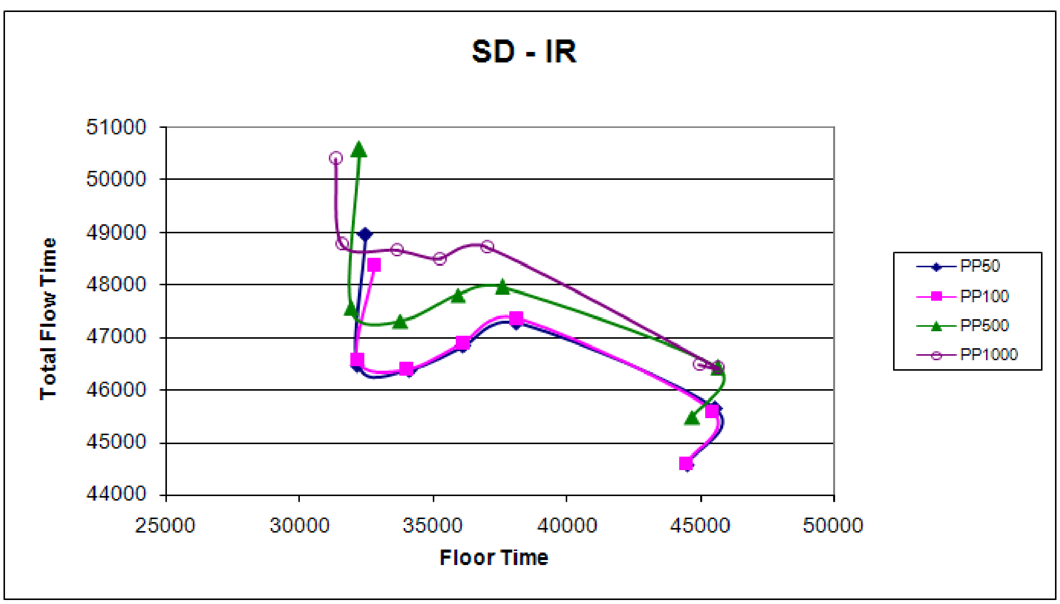

Figure 5.7. IR on SD with period effects

5.4.2. Results for the General Directed (GD) Part Flow Pattern

The fundamental alteration of GD from SD is the flexibility issue. The structure and flow of jobs has been modified but, directions of routings are kept still the same. Unlike SD flow pattern, Load- and Slack-based listings of job sequences do differ in results (Table 5.5, Figure 5.8 and Table 5.6, Figure 5.9; respectively). However, no significant superiority could be observed between these two listing methods except lagged and adjusted methods (Hypothesis testings can be found in Appendix C.2).

Table 5.5. Best total flow time points for figure 5.8

	Best Average Total Flow Time	**Total Throughput**	**Total Mean WIP**	**Best Threshold**
Aggregate	54,229	980.1	91.49	5000
Adjusted	55,335	982.78	29.08	1250
Corrected	53,873	997.89	16.98	700
Lagged	54,105	994.78	83.86	4000

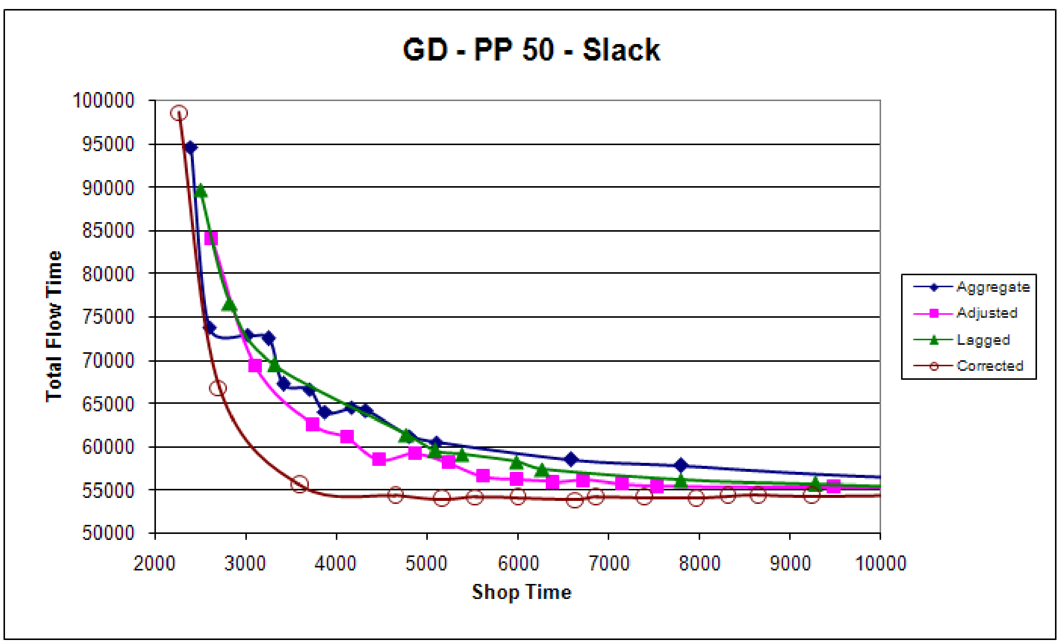

Figure 5.8. GD model with effect of workload determination methods for slack-based listing

Corrected workload determination method outperforms all other methods in both listing approaches regarding the primary measures. The differences between the other methods are statistically significant, especially for slack-based listing (Hypothesis testings can be found in Appendix C.2). Work-In-Process (WIP) level is also very low and preferable compared to other approaches.

Adjusted (dynamic form of Corrected method), performed as the second best one. The reason may be to be the particular dynamic form of the best performing method. Actually, corrected method could enable more jobs to enter into shop floor. Especially, downstream work stations would not be monitored as having high workload. This situation could lead the upstream work stations not to starve at most of the time during simulation.

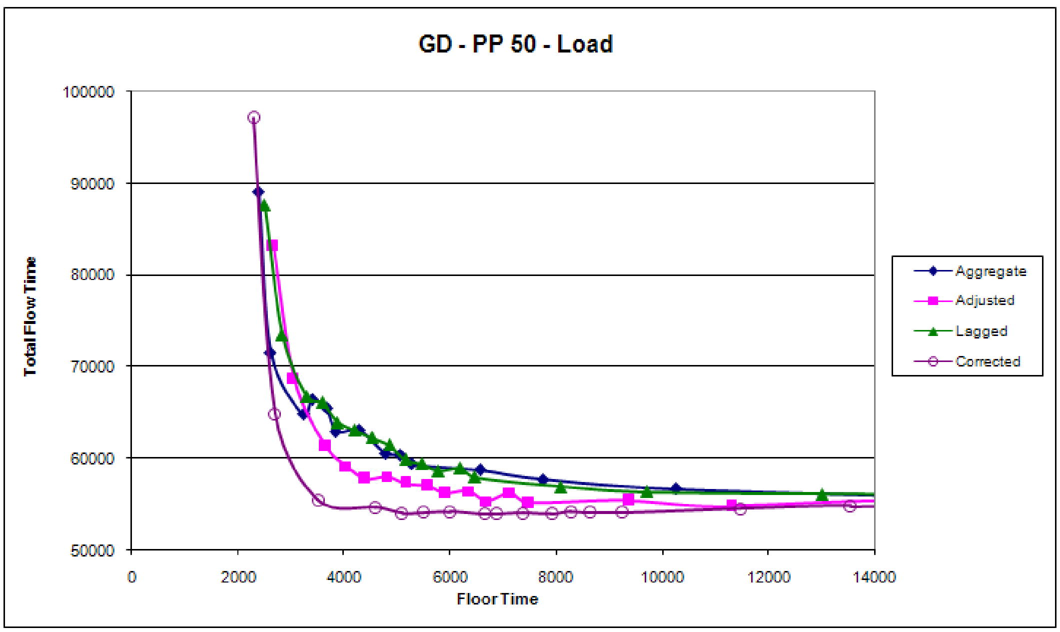

Figure 5.9. GD model with effect of workload determination methods for load-based listing

Aggregate and Lagged method could only reach their best average total flow times of jobs at high threshold levels. The reason lies beneath is their blockages on downstream work stations. As the jobs are penetrating through their loads on downstream machines remains high, so they prevent other jobs in the pool to enter the system.

So, Corrected workload determination method is selected for demonstration of further analysis in this section and the remaining results are given in Appendix B.2.

Table 5.6. Best total flow time points for figure 5.9

	Best Average Total Flow Time	**Total Throughput**	**Total Mean WIP**	**Best Threshold**
Aggregate	55,139	973	71.76	4000
Adjusted	54,798	976	36.61	1500
Corrected	53,921	990	17.02	700
Lagged	55,947	981	67.62	3000

Within the selected period lengths, 50 and 100 period lengths do not differ so much like in SD and UD part flow patterns (Table 5.7 and Figure 5.10). An interesting point in this case is that, periods of 500 and 1000 shows the same tendency like the pair of periods 50 and 100. This shows that determination of an appropriate period length is much harder, since gradual increments of this length do not reveal a linear behavior in terms of average total flow time vs. average shop floor time plots.

Table 5.7. Best total flow time points for figure 5.10

ORR Period Length	**Best Average Total Flow Time**	**Total Throughput**	**Total Mean WIP**	**Best Threshold**
PP 50	53,873	997.89	16.98	700
PP 100	53,974	997.56	10.53	550
PP 500	76,042	575.44	1.71	5000
PP 1000	79,460	290	0.96	7000

Although both listing methods put forward the Corrected as the best performing workload determination method, the situation is not the same with pull-type results of slack-based listing (Table 5.8 and Figure 5.11). Two convex curves are formed as the candidates of best performing threshold level intervals. Flexible structure of GD flow pattern may permit such a result, that the system may perform close at two distinct intervals of threshold levels because of jobs switching from one set of route preferences to another. Here, the interval of higher threshold levels performed better.

GD flow pattern structured in pull-type and using Load-based listing resulted

Figure 5.10. GD model with corrected and slack-based listing method for four levels of ORR period length

Table 5.8. Best total flow time points for figure 5.11

	Best Average Total Flow Time	**Total Throughput**	**Total Mean WIP**	**Best Threshold**
Aggregate	52,613	983.7143	91.69	5000
Adjusted	54,951	991.7857	30.81	3000
Corrected	53,418	1004.786	18.01	4000
Lagged	55,937	983.5714	44.46	3000

similar to its periodic form (Table 5.9 and Figure 5.12). Corrected workload determination method is the superior one in terms of primary performance criterion besides its leading values in total throughput and total average WIP.

The same analogies for period effect of order release and workload bounding can be observed at the same time in results of Interval Release (Table 5.10 and Figure 5.13). Period length and workload limiting affect system performance of WLC strategies seriously.

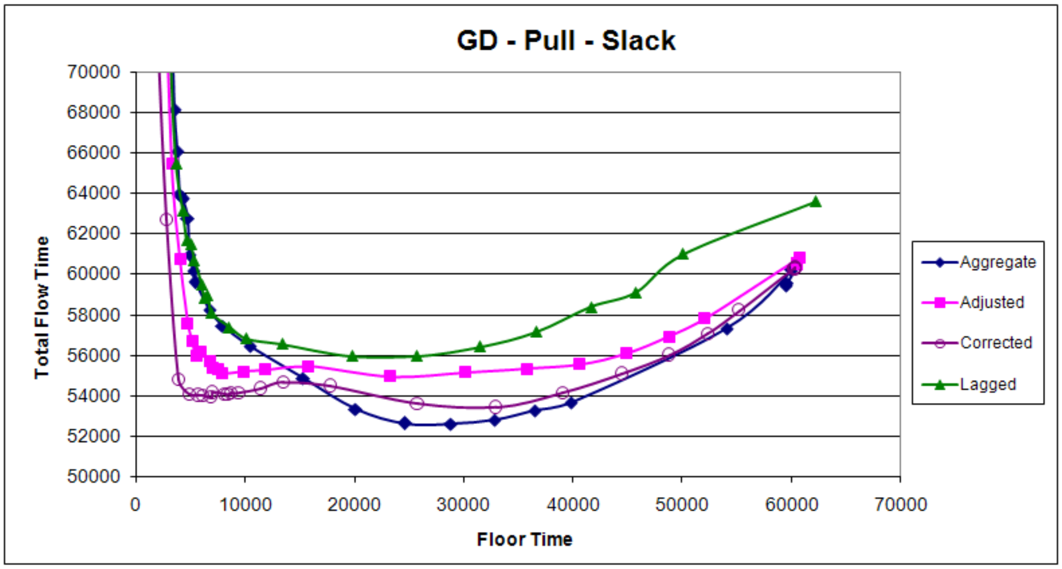

Figure 5.11. GD model pull-type simulated with effect of workload determination methods for slack-based listing

Table 5.9. Best total flow time points for figure 5.12

	Best Average Total Flow Time	Total Throughput	Total Mean WIP	Best Threshold
Aggregate	54,944	978.5714	72.35	4000
Adjusted	55,203	991.7143	38.46	3000
Corrected	53,837	1004.429	27.63	700
Lagged	56,153	987.2857	45.16	4000

Table 5.10. Best average total flow time of jobs with relevant I/O. Buffer size at different period lengths for GD

	Best Average Total Flow Time	Total Throughput	Total Mean WIP	Best Threshold
PP50	61,042	927.5	131.8	15
PP100	60,983	926.5	122.9	10
PP500	61,735	926.7	129.3	15
PP1000	62,976	925.3	116.8	10

Figure 5.12. GD model pull-type simulated with effect of workload determination methods for load-based listing

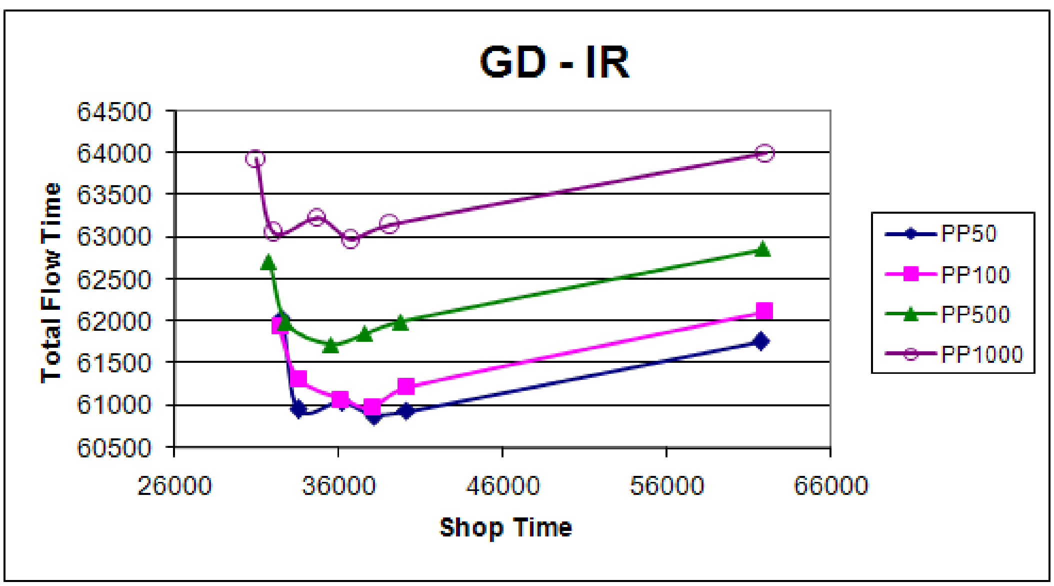

Figure 5.13. IR on GD with period effects

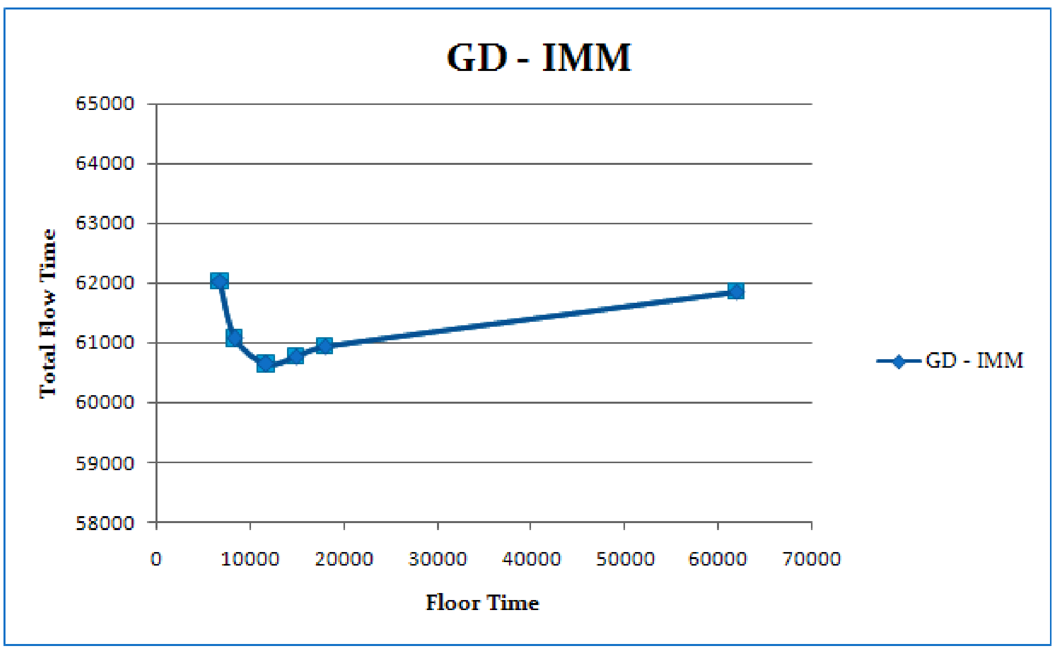

Figure 5.14. GD immediate release with variable I/O. Buffer Sizes

5.4.3. Results for the Undirected (UD) Part Flow Pattern

Undirected part flow pattern has intricate flow paths of jobs among the machines. On the other hand, it is the case where flexibility issue could be utilized completely by PBB/r for part routing activity. Workload determination methods are depicted for slack-based listing in Table 5.15 and Figure 5.11.

Table 5.11. Best total flow time points for figure 5.15

	Best Average Total Flow Time	Total Throughput	Total Mean WIP	Best Threshold
Aggregate	71,606	930	29.09	1500
Adjusted	70,359	940	24.79	950
Corrected	67,468	942	25.36	700
Lagged	70,209	938	21.18	1000

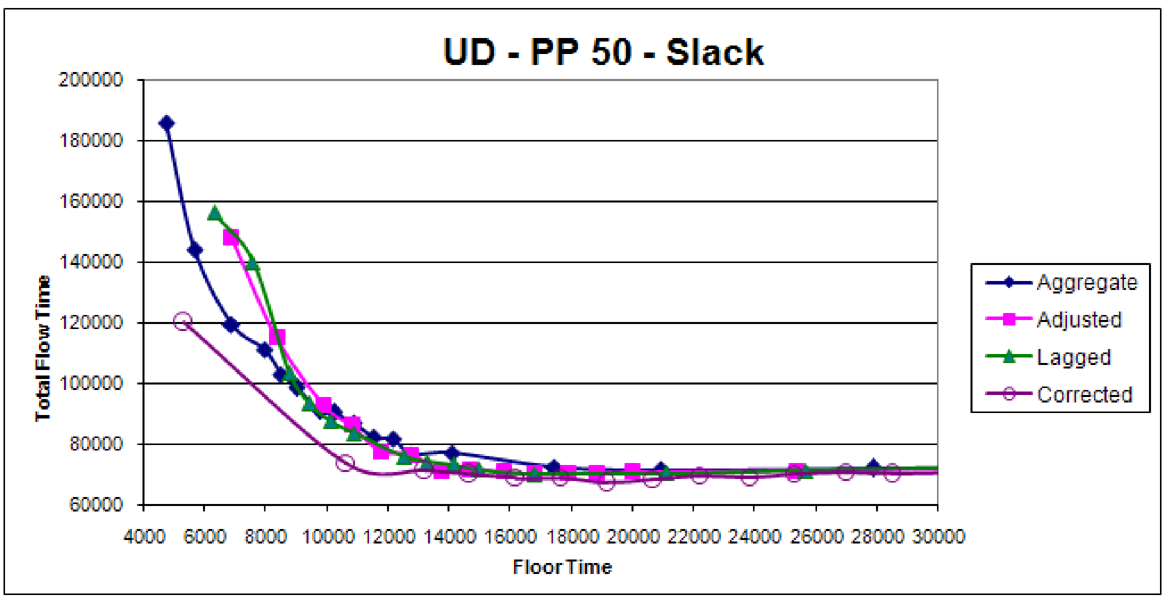

Figure 5.15. The effect of workload determination methods with slack-based listing for UD model

The worst performing workload determination method in terms of all criteria is the Aggregate method, since it is not suitable for undirected flow patterns and flexible manufacturing structure.

Table 5.12. Best total flow time points for figure 5.16

	Best Average Total Flow Time	**Total Throughput**	**Total Mean WIP**	**Best Threshold**
Aggregate	72,482	925	66.81	3000
Adjusted	70,523	933.4	20.81	950
Corrected	69,141	941.3	19.75	600
Lagged	69,589	935.33	48.7	1250

A sensible contrast between listing method arises in UD flow pattern. The main difference between two approaches come across in the total mean WIP level. Slack-based listing resulted some more stable and lower mean queue lengths than the load-based listing (Table 5.12 and Figure 5.16).

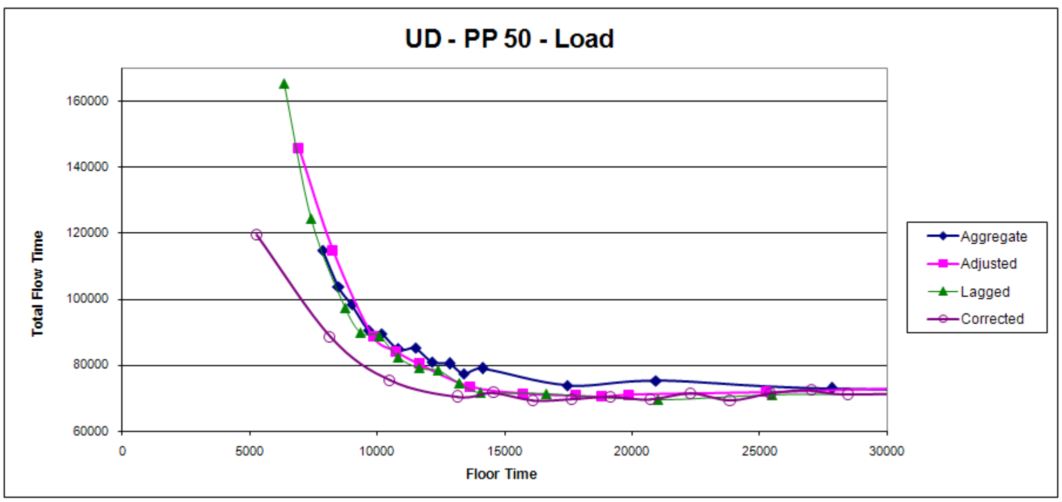

Figure 5.16. UD model with effect of workload determination methods for load-based listing

Job sequence listing is performed in the first level of PBB/r algorithm, and workload bounding in the second level. Slack-based listing interacts with workload bounding since it considers threshold level before workload limiting activity steps in. However, load-based listing only considers balancing the loads of machines without concerning about fitting that job sequence to the remaining workload spaces of machines. So, better performance of slack-based listing could be explained by its utilization of slack information of machines.

In the existence of flexibility, Corrected method is again superior than other methods, especially when listing method is slack-based (See Appendix C.3 for hypothesis testing). The main reason could be the same with GD flow pattern, that slack-based have a structure to enable a certain amount of buffer storage, to avoid starvation. So, Corrected workload determination method is selected for demonstration of further analysis in this section (Table 5.13 and Figure 5.17) and the remaining results are given in Appendix A.4.

Table 5.13. Best total flow time points for figure 5.17

	Best Average Total Flow Time	**Total Throughput**	**Total Mean WIP**	**Best Threshold**
PP 50	67,468	942.7	25.36	700
PP 100	68,653	941.5	33.28	850
PP 500	75,571	553.4	3.87	1000
PP 1000	82,368	287.5	0.97	1500

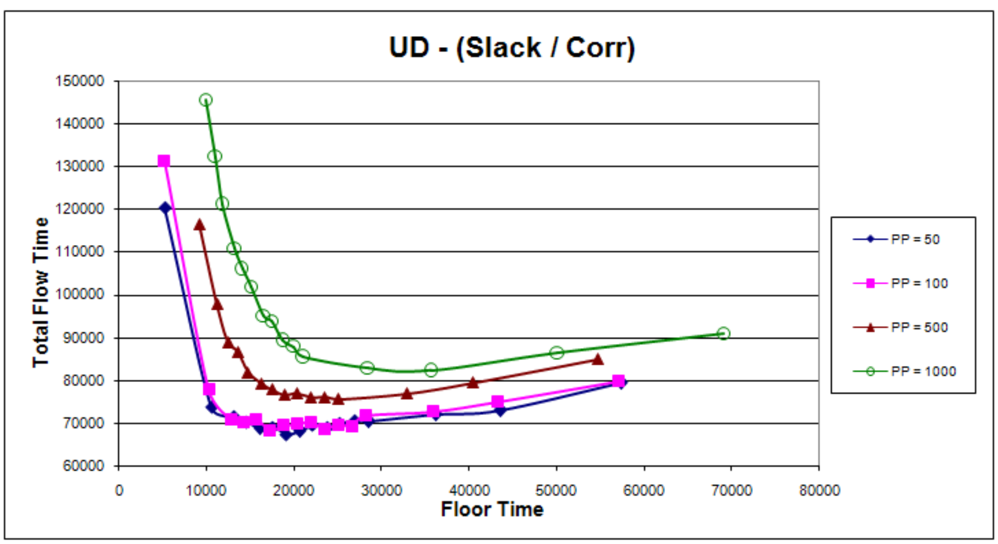

Figure 5.17. UD model with corrected and slack-based listing methods for four levels of ORR period length

When the periodic structure of PBB/r converted into pull-type self-triggered mechanism for UD flow pattern, analogous observations to periodic case are extracted (Table 5.14, Figure 5.18 and Table 5.15, Figure 5.19). For instance, best performing threshold level of Aggregate method is worse than and away from the other methods.

This is from dissonance determination method of Aggregate, such that it creates unnecessarily vast workloads on its very downstream machines. However, the machines do not have a constant upstream or downstream status in UD flow pattern.

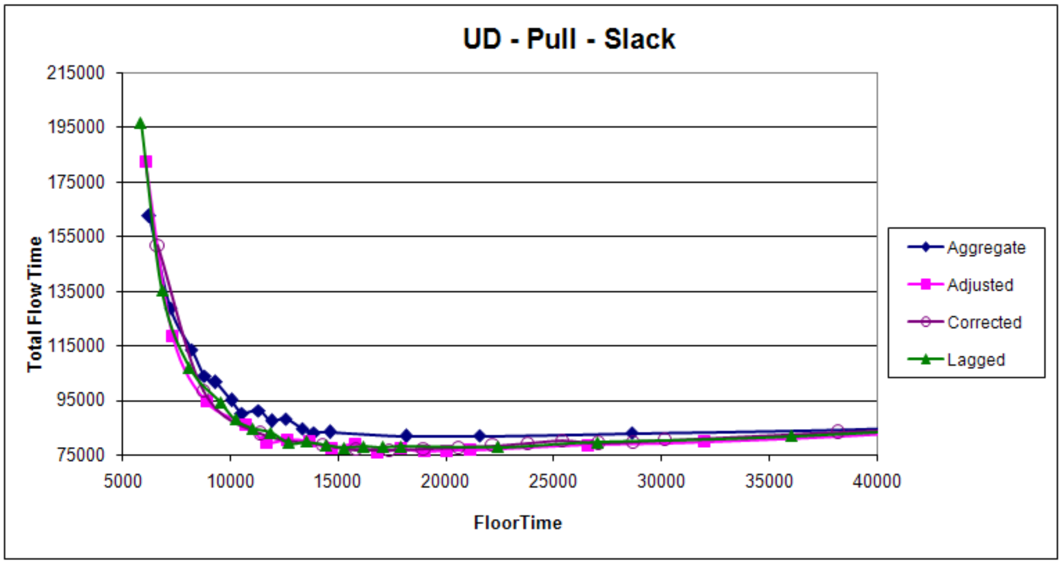

Figure 5.18. UD model pull-type simulated with effect of workload determination methods for slack-based listing

Table 5.14. Best total flow time points for figure 5.18

	Best Average Total Flow Time	Total Throughput	Total Mean WIP	Best Threshold
Aggregate	81,989	905.875	41.55	1250
Adjusted	76,246	920.25	26.5	800
Corrected	76,613	917.625	29.94	600
Lagged	77,976	918.125	30.76	950

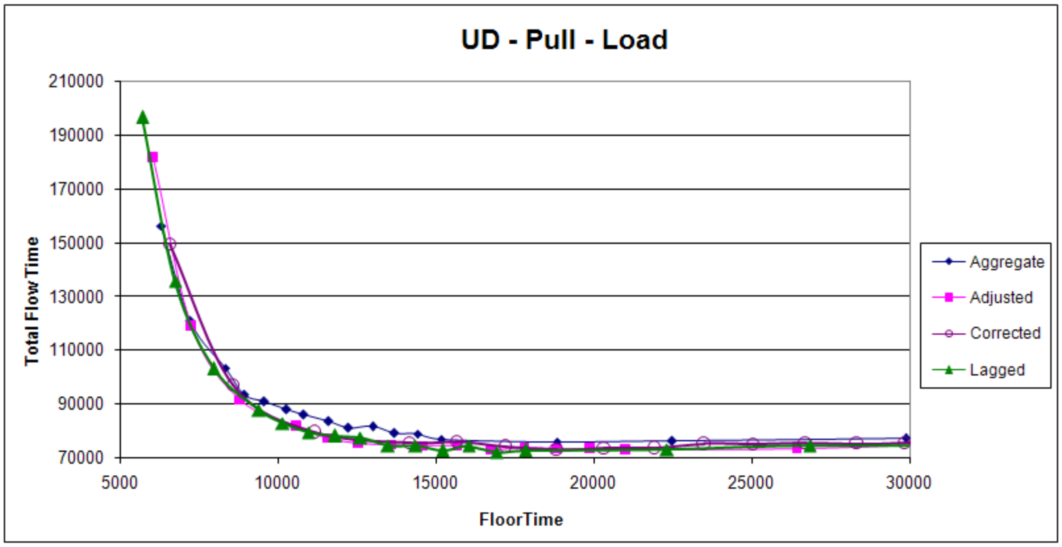

Figure 5.19. UD model pull-type simulated with effect of workload determination methods for load-based listing

Table 5.15. Best total flow time points for figure 5.19

	Best Average Total Flow Time	**Total Throughput**	**Total Mean WIP**	**Best Threshold**
Aggregate	76,008	921.625	28.21	1250
Adjusted	72,954	910.25	41.46	1000
Corrected	73,042	921.75	32.2	650
Lagged	72,110	921.125	30.56	950

Table 5.16. Best average total flow time of jobs with relevant I/O. Buffer size at different period lengths for UD

	Best Average Total Flow Time	**Total Throughput**	**Total Mean WIP**	**Best Threshold**
PP50	87,695	885.4	60.28	15
PP100	88,015	887.5	60.64	15
PP500	90,015	261.2	6.1	15
PP1000	93,015	524.9	2.66	15

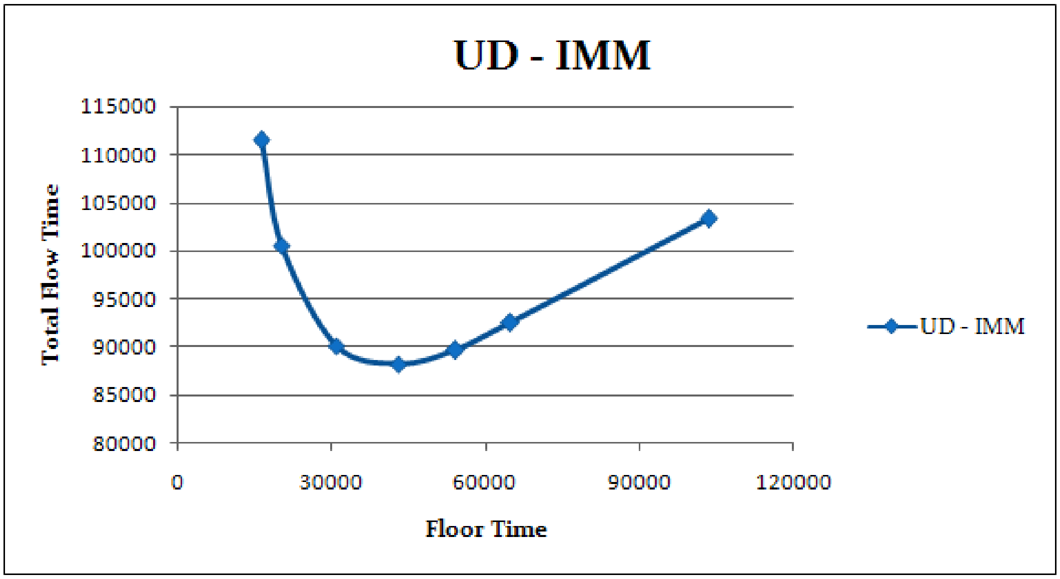

Figure 5.20. UD immediate release with variable I/O. Buffer sizes

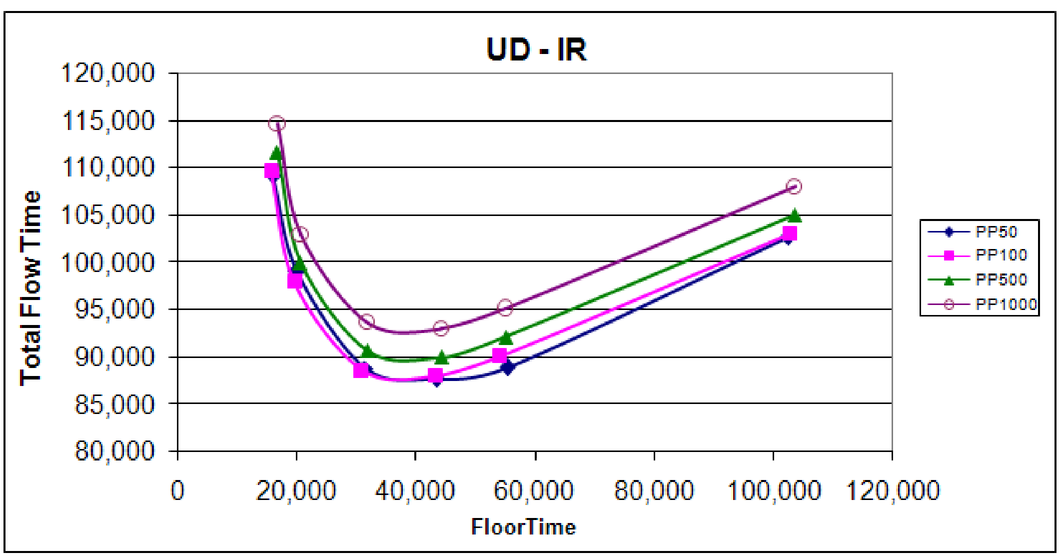

Figure 5.21. IR on UD with period effects

5.4.4. Summary of results

In this subsection, an overall evaluation of the previously presented numerical results will be conducted. Initially, best performing components of all ORR mechanisms are compared for each part flow pattern on the same performance curve. Then, quantitative facts of pull-type self-triggered mechanism will be presented with its pros and cons.

As mentioned previously in Section 5.4.1; SD flow patterns have interesting performance curves both for IR and IMM, although periodic and pull-type PBB/r mechanisms display regular and close results of performance. At this moment, an overall picture to combine and compare the results will be beneficial (Table 5.17 and Figure 5.22). Regarding strict flow paths of jobs in SD part flow pattern, IMM and IR can only reach their best average total flow time when all I/O. Buffer sizes are infinite.

Table 5.17. Comparison of best performing ORR mechanisms with relevant statistics for SD part flow pattern

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Lengths	Best Threshold (or Q. Size)
IMM	46,355	682.44	21.64	10
IR	46,377	686.66	26.15	10
Agg - Periodic	30,498	731.01	4.59	850
Lagg - Pull	30,363	734.44	18.15	500

When threshold levels are set to infinity for both periodic and pull-type mechanisms, all four mechanisms would give exactly the same results. Due to inflexible feature of SD, PBB/r could not perform part routing activity but achieve workload limiting activity like IR and IMM do. So, it turns out to be a pure load balancing activity while ORR decides which job to enter into the shop floor. This is the main reason for good performance of PBB/r mechanism compared to IMM and IR.

In GD part flow pattern, the critical change is the introduction of flexibility into

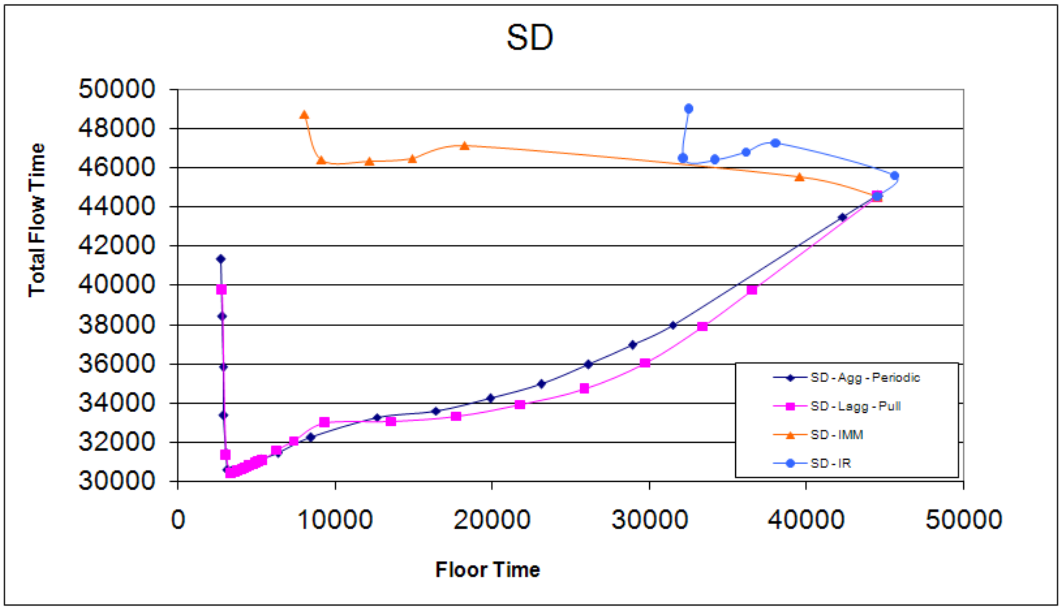

Figure 5.22. Best performing ORR mechanisms for SD part flow pattern

the system. As mentioned earlier, IMM uses Smallest Queue Workload (SQW) part routing algorithm. IMM has a superior relative performance with flexible process plans of GD, compared to SD. However, IR shows even worse performance, most probably due to its periodic structure (Table 5.18 and Figure 5.23). Similar to SD case, pull-type and periodic PBB/r mechanisms have statistically indifferent average total flow time measure (See Appendix C.4 for hypothesis testing).

Table 5.18. Comparison of best performing ORR mechanisms with relevant statistics for GD part flow pattern

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Lengths	Best Threshold (or Q. Size)
IMM	60,640	928.2222	30.088	10
IR	61,042	927.5	131.8	15
Slack/Corr - Periodic	53,873	997.89	16.98	700
Slack/Agg - Pull	52,614	983.7143	91.69	5000

The undirected (UD) flow pattern case, used in our experiments introduces full flexibility in routes. This flexibility is fixed in advance in PBB/r and kpt until last minute in IR and IMM (Table 5.19 and Figure 5.24). In UD flow pattern, periodic

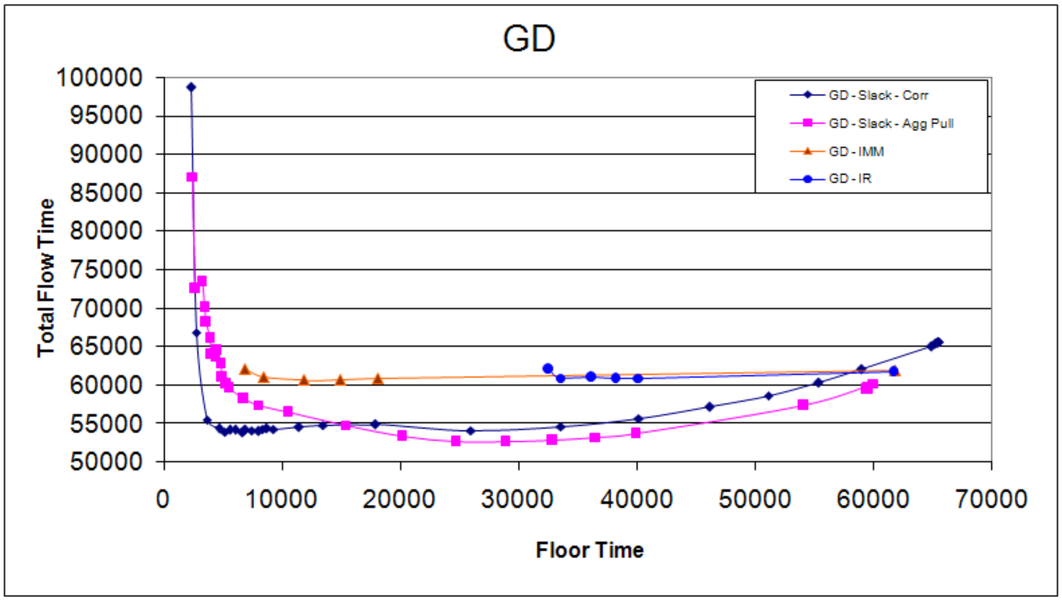

Figure 5.23. Best performing ORR mechanisms for GD part flow pattern

Slack-based listed Corrected method is the best performing one among the best performers (See Appendix C.4 for hypothesis testing). The inferior performance of pull-type PBB/r mechanism may be caused by job discrimination during slack-based listing. Job discrimination can be defined as continuously selecting the same job type to enter the system because of small processing times of its operations. The ORR frequency check, that will be quantified in the next subsection, shows that pull-system has generally a high frequency ORR invoke. It is evident that when period length of PBB/r mechanism decreases, it will try to fit the most suitable job sequence, namely the job sequence having smaller processing times, to the slacks of the machine. So shorter jobs would be finished completely during the simulation period and longer jobs would not.

Table 5.19. Comparison of best performing ORR mechanisms with relevant statistics for UD part flow pattern

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Lengths	Best Threshold (or Q. Size)
IMM	87,695	885.4	60.28	15
IR	87,550	885.1	62.55	15
Slack/Corr- Periodic	67,468	942.70	25.36	700
Slack/Adj - Pull	76,247	920.25	26.5	800

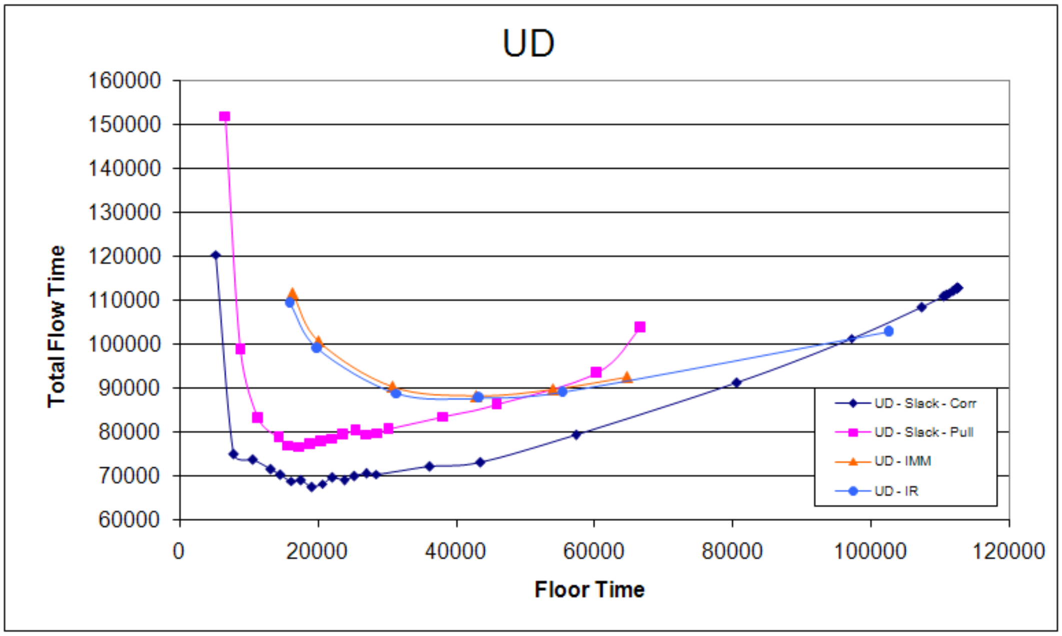

Figure 5.24. Best performing ORR mechanisms for UD part flow pattern

Process-Triggered Pull System enabled the system to make the release decisions when necessary. This would achieve a good performance especially with very uncertain demand structure. But, in cases of this thesis product arrivals are so stable that, at every fixed amount of time one part type with a certain probability arrives the system and operative properties of these parts do not have an extreme variation. The following one is a comparative table for periodic and pull-type ORR structures (Figure 5.25). These figures depict the number of ORR checks in 1000 time units. For instance, for previous periodic cases these values are 20, 10, 2, 1 for periods 50, 100, 500, 1000; respectively.

Table 5.20 show the properties of time lines in Figure 5.25. To illustrate; the first row depicts, time line named 'Pull_SD-Slack-Agg' in Figure 5.20is drawn for Threshold Level of 850 and resulted an average of 82 ORR checks within 1000 time units, namely a check in every 12 time units in steady state (Average number of ORR checks per 1000 time units).

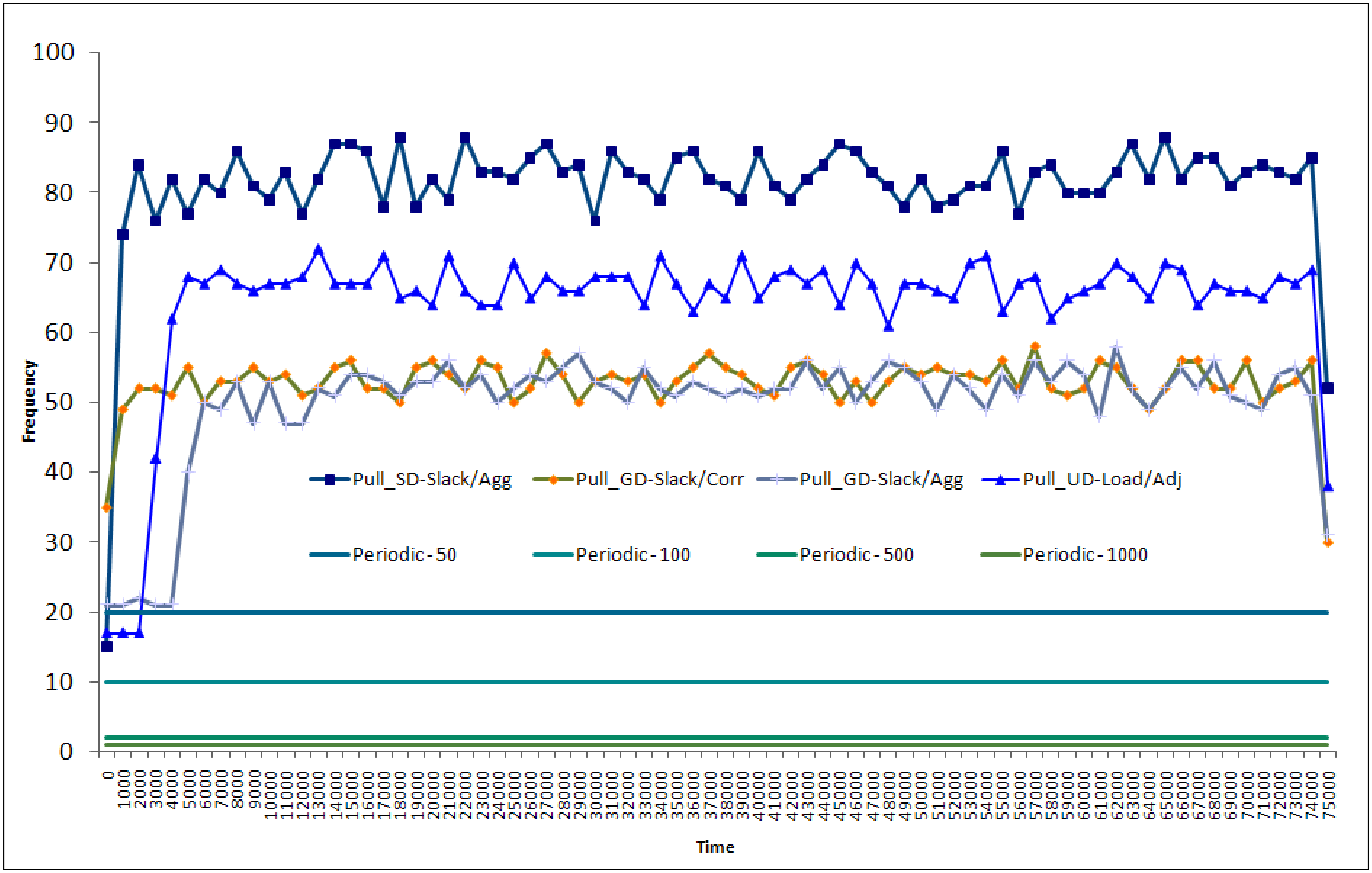

Figure 5.25. Number of ORR mechanism calls per 1000 time units for one of the seeds

Table 5.20. Tested threshold levels, ORR check frequency and average ORR interval for one of the seeds

Timeline	**Tested Threshold**	**ORR Check Frequency**	**Average ORR Interval (in time units)**
Pull_SD-Slack-Agg	850	82	12
Pull_GD-Slack-Corr	500	53	19
Pull_GD-Slack-Agg	6000	51	20
Pull_UD-Load-Adj	1000	67	15

5.4.5. Numerical Demonstration for the Relation Between Threshold and Other System Parameters

As mentioned at the beginning of Section 4.3, offline threshold estimation could be handled by two approaches. Actually, the one using the simulation results (mean queue sizes of I/O. Buffers) is an attempt for verification of this estimation method. Such that, it turns out to be a conversion method of queue length into workload. Table 5.21, 5.22 and 5.23 depict the input and output values of threshold estimation by preliminary simulation runs for SD, GD and UD flow patterns.

Table 5.21. Inputs and outputs for SD, when target is 850 (Exp. I).

	Mean Input Values			**Output Values**		
	I. Buffer Length	**Utilization**	**O. Buffer Length**	**Direct Load**	**Indirect Load**	**Total Load**
M1	0.37	0.773	0.60	24.2	31.0	55.2
M2	0.23	0.723	0.60	13.9	132.0	145.9
M3	2.67	0.888	1.85	203.3	286.6	489.9
M4	0.14	0.612	0.53	7.3	483.6	490.9
M5	0.33	0.775	0.60	21.6	690.1	711.7
M6	0.43	0.813	1.17	29.5	834.1	**863.6**

The basic approach in these verifications is that, by preliminary simulation runs a parametric search is conducted for best threshold value (namely, target threshold level) to minimize average total flow time of jobs. Then, mean queue lengths of I/O. Buffers and utilization averages of machines are collected for that best threshold level. By comparing the computed (maximum of total workload of machines) and simulated threshold value, it can be observed that the values are quite close each other. For a more healthy verification, another replication is simulated with different inter arrival times of jobs and processing times of operations.

Table 5.22. Inputs and outputs for GD, when target is 4000 (Exp. I).

	Mean Input Values			**Output Values**		
	I. Buffer Length	**Utilization**	**O. Buffer Length**	**Direct Load**	**Indirect Load**	**Total Load**
M1	24.96	0.939	0.16	3736.7	35.3	3772.0
M2	25.93	0.938	0.20	3772.2	35.3	3807.5
M3	14.73	0.928	0.22	1658.2	2172.6	3830.8
M4	2.70	0.910	0.17	299.7	3583.2	**3882.9**
M5	2.09	0.895	0.20	241.9	3528.9	3770.8
M6	0.68	0.711	0.20	75.9	3100.9	3176.8

Table 5.23. Inputs and outputs for UD, when target is 3000 (Exp. I).

	Mean Input Values			**Output Values**		
	I. Buffer Length	**Utilization**	**O. Buffer Length**	**Direct Load**	**Indirect Load**	**Total Load**
M1	6.14	0.914	0.22	536.1	2133.3	2669.4
M2	14.64	0.930	0.20	1615.5	956.3	2571.8
M3	2.10	0.862	0.22	384.3	2816.6	3200.9
M4	24.10	0.914	0.20	1945.9	835.7	2781.6
M5	11.79	0.924	0.20	1417.4	801.2	2218.6
M6	7.38	0.937	0.22	874.5	2356.5	**3231.0**

In order to reinforce these inferences about the relation of threshold level and workload of machines, another experimentation is conducted. The results of this experimentation is depicted below (Tables 5.24, 5.25, 5.26). Layout and job mix definitions of this experimentation is given in secondary subsections of Section A.2, A.3, A.4 in Appendix A.

Table 5.24. Inputs and outputs for SD, when target is 6000 (Exp. II).

	Mean Input Values			**Output Values**		
	I. Buffer Length	**Utilization**	**O. Buffer Length**	**Direct Load**	**Indirect Load**	**Total Load**
M1	36.74	0.923	0.12	4249.2	27.8	4277.0
M2	0.20	0.923	0.18	22.9	4245.8	4268.6
M3	8.47	0.843	0.15	960.4	4460.4	5420.8
M4	0.21	0.920	0.10	23.9	5643.0	5666.9
M5	0.13	0.919	0.12	14.4	5671.9	**5686.2**
M6	0.09	0.841	0.08	9.0	5287.1	5296.2

The identified parameters in this approach are route usage ratios, machine utilizations, mean input and output buffer lengths in the system.From the results and experiences gained through experimentations show that route usage ratios are not significant. So it has been aforementioned as taking the usage ratios of job sequences uniformly distributed over the its job's mix ratio. On the other hand machine utilizations are also not so much significant, since it contributes a small portion indirect load calculation. These two parameters can be derived from LMM, by giving the tool allocation to the model as parameter (not decision variable in this case). Besides, the big portion affecting the result is the mean buffer lengths of the system. When material handling system (i.e. AGVs) does not evaluated to possess any bottleneck, the output buffers tends to null. So the critical parameter remains as mean input buffer lengths in the system. These values are gathered by preliminary runs, as aforementioned. However, it seems that a healthy offline estimation of these parameters requires some sophisticated approaches (i.e. queuing network models); which is mentioned in future remarks section in this study.

Table 5.25. Inputs and outputs for GD, when target is 800 (Exp. II).

	Mean Input Values			**Output Values**		
	I. Buffer Length	**Utilization**	**O. Buffer Length**	**Direct Load**	**Indirect Load**	**Total Load**
M1	3.12	0.926	0.19	360.8	36.4	397.2
M2	3.34	0.927	0.22	386.6	36.4	423.0
M3	1.17	0.900	0.23	134.7	538.4	673.0
M4	1.19	0.894	0.16	136.4	538.4	674.8
M5	0.39	0.837	0.18	45.1	722.3	**767.4**
M6	0.34	0.830	0.21	34.8	718.1	752.9

Table 5.26. Inputs and outputs for UD, when target is 3000 (Exp. II).

	Mean Input Values			**Output Values**		
	I. Buffer Length	**Utilization**	**O. Buffer Length**	**Direct Load**	**Indirect Load**	**Total Load**
M1	5.69	0.934	12.68	508.4	2077.7	2586.1
M2	12.94	0.936	0.16	1237.4	1252.8	2490.1
M3	3.91	0.922	10.87	364.7	1237.2	1602.0
M4	12.52	0.943	0.09	1215.6	554.9	1770.5
M5	10.21	0.933	0.13	956.6	1859.5	2816.1
M6	12.47	0.930	0.08	1171.6	2146.8	**3318.4**

6. CONCLUSION

The basic aim of this thesis is to grasp the notion of order release in terms of system performance. Besides the classical shop environments used in the literature, releases of orders are achieved in a flexible manufacturing environment as a novel approach. Flexible process plans of jobs are fixed at the release phase, and part routing execution is avoided on the floor.

ORR mechanism used has a two level, load-oriented structure for release of jobs into shop floor. Incidentally, two fundamental manipulation methods are applied in order release phase. In the first level, machine routes of jobs are sorted regarding workload balancing of machines and in the second level, workload bounding method is applied.

Some modifications in the approach are proposed and investigated regarding the limiting timing convention and internal structure such as workload determination method, update of desirability listing method.

In terms of time convention, both periodic and continuous forms are utilized. In periodic ORR usage, the effect of period length is investigated and a critical level is found such that up to a certain period length, effort for execution of the algorithm contributes an insignificant amount to performance measure and instead leads to computational burden. In addition to periodic case, a pull-type system regarding the processing updates in the shop floor is implemented. The major drawback in this form is found to be the computation burden by high frequency ORR checks. However, for cases of where the arrival rates are more variable over time; pull-type system can be more effective by utilizing internal dynamics of the system, despite the burden.

On comparing the results of proposed methods and do-nothing cases (IMM or IR), the results showed that WLC methods do improve performance measures and is an effective tool when used with an appropriate parameter set. It is evident that by decomposing the overall scheduling problem by introducing order release stage, the weaknesses resulting from the online scheduling rules used on the shop floor can effectively be reduced. Threshold level and period length parameters are the critical ones in this set. A proper threshold level is tried to be estimated by inducement of some desired mean queue sizes and predetermined layout and job mix definitions. On the other hand, periodic structure of ORR mechanism is tried to be eliminated by implementing a pull-type and self-triggered structure.

As the primitive form of WLC, effect of finite I/O. Buffer queue sizes are examined for IMM and IR methods. Some parallel behaviors are observed with respect to period length parameter resembling a thorough WLC strategy.

Studying the ORR policies under different job flow patterns has been an important aspect of the study that reinforces the conclusions drawn, especially on th effect of introducing process plan flexibility. Strictly directed (SD) flow pattern acts as a base case in this respect. Under SD, where routes are fixed, it has been observed that workload determination method is of little importance and load-based ORR policies perform significantly better than IMM or IR. On the other hand; under UD, where there is full routing flexibility, workload determination method gains importance; and more interestingly, although the sophisticated ORR policies are still far more better than IMM or IR the relative gap among them is reduced. This is a result of the inherent flexibility. IMM (or IR) policy by making use of the processing flexibility in a dynamic fashion can compensate can compensate its weakness at least to a degree. This observation highlights the importance of flexibility during execution and leads to some new research directions.

6.1. Future Studies and Final Remarks

Appreciating Da Vinci's famous quote "Tell me if anything was ever done", studies will never be absolutely completed. There can be many extensions and, new methods can be developed and tested within the context of WLC based on the experience gained in. Here are some points that need further investigation:

- The major disadvantage can be eliminated in the structure of process-triggered pull type mechanism by modifying to decrease its frequency of ORR checks. By this way, the advantages of this idea would come into prominence.
- The analytical approach introduced in this thesis highlighted the relation between system parameters and threshold value. This could be considered as a first step towards a method for estimation of the threshold. Threshold estimation seems to be a promising and interesting direction for the further research (i.e. by queuing network models) and requires the estimation of significant input parameters that were identified in this study.
- In practical cases, due date restrictions of jobs are becoming of paramount importance than capacity restrictions. In this study, the investigation of ORR policies is restricted to the load-oriented approaches. A similar study can be conducted on due date-based policies (e.g. hybrid policies), considering also due date-based performance measures.
- On fixing the flexible routes of jobs two methods have been discussed: dynamic routing on the shop floor versus routing decision at order release. As a third one, these two approaches can be hybridized. In such a hybrid method, job release should still consider the possible routes, but not eliminate (some of) them, by postponing the final routing decision (with all and some of the flexibility) to until actual dispatching. In such a case, the workload determination method would be far more complex, since the routes of the jobs on the floor are still not known. The findings in this study show that research in this section could be interesting.

APPENDIX A: LAYOUT AND JOB MIX DEFINITIONS

A.1. Layout Definition

Abstraction of physical properties of layout such as locations of cells, nodes, lanes, etc. are depicted in Figure 5.1 of Section 5.3. The distance matrix is provided below (Table A.1) and the remainder include job mix definitions for each shop model type.

Table A.1. Distance matrix.

	Receival	Cell1	Cell2	Cell3	Cell4	Cell5	Cell6	Shipment
Receival		1600	200	1900	600	1000	500	1500
Cell1			700	200	700	1100	600	1600
Cell2		1200		1500	200	600	100	1100
Cell3		1900	500		900	1300	800	1800
Cell4		800	1600	1100		200	1500	700
Cell5		500	1300	800	1300		1200	400
Cell6		1100	1900	1400	1900	500		1000
Shipment								

A.2. Strictly Directed (SD) Flow Pattern - Job Definition

A.2.1. Experimentation I

Table A.2. SD - part type process routes

Product	Name	Operations
JobA	Alternate1	Receival-JAO1-JAO2-JAO3-JAO4-JAO5-JAO6-Shipment
JobB	Alternate1	Receival-JBO1-JBO2-JBO3-JBO4-JBO5-JBO6-Shipment
JobC	Alternate1	Receival-JCO1-JCO2-JCO3-JCO4-JCO5-JCO6-Shipment

Table A.3. SD - part type arrival summary

Product	Interarrival Time	Mix Ratio	Submitted
A	150	0.43	504
B	250	0.26	302
C	200	0.32	378
	Total Demand	1184	
	Inter Arrival	1 part / 63.8 time unit	

Table A.4. SD - cell-tool allocation by LMM

Cell	Loaded Tool Type
Cell1	Tool1
Cell2	Tool2
Cell3	Tool3
Cell4	Tool4
Cell5	Tool5
Cell6	Tool6

Table A.5. SD - operation, tool, mean processing time relations

Operation Name	**Mean Processing Time**	**Tool Name**
JAO1	80	Tool1
JAO2	70	Tool2
JAO3	90	Tool3
JAO4	70	Tool4
JAO5	80	Tool5
JAO6	80	Tool6
JBO1	60	Tool1
JBO2	40	Tool2
JBO3	70	Tool3
JBO4	50	Tool4
JBO5	60	Tool5
JBO6	70	Tool6
JCO1	50	Tool1
JCO2	60	Tool2
JCO3	60	Tool3
JCO4	30	Tool4
JCO5	50	Tool5
JCO6	50	Tool6

A.2.2. Experimentation II

Table A.6. SD - part type process routes

Product Name		Operations
JobA	Alternate1	Receival-JAO1-JAO2-JAO3-JAO4-JAO5-JAO6-Shipment
JobB	Alternate2	Receival-JBO1-JBO2-JBO3-JBO4-JBO5-JBO6-Shipment
JobC	Alternate3	Receival-JCO1-JCO2-JCO3-JCO4-JCO5-JCO6-Shipment

Table A.7. SD - part type arrival summary

Product	Interarrival Time	Mix Ratio	Submitted
JobA	175	0.377	432
JobB	225	0.293	336
JobC	200	0.330	378
	Total Demand	1146	
	Inter Arrival	65.97	

Table A.8. SD - cell-tool allocation by LMM

Cell	Loaded Tool Type
Cell1	Tool1
Cell2	Tool2
Cell3	Tool3
Cell4	Tool4
Cell5	Tool5
Cell6	Tool6

Table A.9. SD - operation, tool, mean processing time relations

Operation Name	**Mean Processing Time**	**Tool Name**
JAO1	120	Tool1
JAO2	110	Tool2
JAO3	120	Tool3
JAO4	120	Tool4
JAO5	110	Tool5
JAO6	120	Tool6
JBO1	105	Tool1
JBO2	110	Tool2
JBO3	120	Tool3
JBO4	105	Tool4
JBO5	110	Tool5
JBO6	120	Tool6
JCO1	120	Tool1
JCO2	115	Tool2
JCO3	100	Tool3
JCO4	120	Tool4
JCO5	115	Tool5
JCO6	100	Tool6

A.3. General Directed (GD) Flow Pattern Model - Job Definition

A.3.1. Experimentation I

Table A.10. GD - part type process routes

Product Name	**Process Route Name**	**Operations**
JobA	Alternate1	Receival-JAO1-JAO2-JAO3-Shipment
JobB	Alternate1	Receival-JBO1-JBO2-JBO3-Shipment
JobC	Alternate1	Receival-JCO1-JCO2-JCO3-Shipment
JobC	Alternate2	Receival-JCO4-JCO5-Shipment
JobD	Alternate1	Receival-JDO1-JDO2-Shipment

Table A.11. GD - part type arrival summary

Product	**Interarrival Time**	**Mix Ratio**	**Submitted**
A	150	0.31	504
B	250	0.19	302
C	200	0.23	378
D	175	0.27	432

Total Demand	1616
Inter Arrival	1 part / 46.8 time unit

Table A.12. GD - cell-tool allocation by LMM

Cell	**Loaded Tool Type**
Cell1	Tool1
Cell2	Tool1
Cell2	Tool6
Cell3	Tool2
Cell3	Tool4
Cell4	Tool2
Cell4	Tool7
Cell5	Tool5
Cell5	Tool3
Cell6	Tool3

Table A.13. GD - operation, tool, mean processing time relations

Operation Name	**Mean Processing Time**	**Tool Name**
JAO1	160	Tool1
JAO2	120	Tool2
JAO3	100	Tool3
JBO1	100	Tool1
JBO2	60	Tool2
JBO3	80	Tool3
JCO1	180	Tool1
JCO2	120	Tool2
JCO3	160	Tool3
JCO4	120	Tool6
JCO5	160	Tool7
JDO1	140	Tool4
JDO2	120	Tool5

A.3.2. Experimentation II

Table A.14. GD - part type process routes

Product Name	Process Route Name	Operations
JobA	Alternate1	Receival-JAO1-JAO2-JAO3-Shipment
JobB	Alternate2	Receival-JBO1-JBO2-JBO3-Shipment
JobC	Alternate3	Receival-JCO1-JCO2-JCO3-Shipment

Table A.15. GD - part type arrival summary

Product	Interarrival Time	Mix Ratio	Submitted
JobA	175	0.38	432
JobB	225	0.29	336
JobC	200	0.33	378
	Total Demand	1146.00	
	Inter Arrival	65.96859	

Table A.16. GD - cell-tool allocation by LMM

Cell	Loaded Tool Type
Cell1	Tool1
Cell2	Tool1
Cell3	Tool2
Cell4	Tool2
Cell5	Tool3
Cell6	Tool3

Table A.17. GD - operation, tool, mean processing time relations

Operation Name	**Mean Processing Time**	**Tool Name**
JAO1	120	Tool1
JAO2	110	Tool2
JAO3	120	Tool3
JBO1	105	Tool1
JBO2	110	Tool2
JBO3	120	Tool3
JCO1	120	Tool1
JCO2	115	Tool2
JCO3	105	Tool3

A.4. Undirected (UD) Flow Pattern Model- Job Definition

A.4.1. Experimentation I

Table A.18. UD - part type process routes

Product Name		Operations
JobA	Alternate1	ReceivalA-JAO1-JAO2-JAO3-ShipmentA
JobA	Alternate2	ReceivalA-JAO4-JAO5-JAO6-JAO3-ShipmentA
JobA	Alternate3	ReceivalA-JAO1-JAO7-JAO8-JAO9-JAO10-ShipmentA
JobB	Alternate1	ReceivalB-JBO1-JBO2-JBO3-ShipmentB
JobB	Alternate2	ReceivalB-JBO4-JBO2-JBO3-ShipmentB
JobB	Alternate3	ReceivalB-JBO1-JBO2-JBO5-JBO6-JBO7-ShipmentB
JobC	Alternate1	ReceivalC-JCO1-JCO2-JCO3-JCO4-ShipmentC
JobC	Alternate2	ReceivalC-JCO5-JCO6-JCO7-JCO3-JCO4-ShipmentC
JobD	Alternate1	ReceivalD-JDO1-JDO2-JDO3-ShipmentD
JobD	Alternate2	ReceivalD-JDO4-JDO5-JDO2-JDO3-ShipmentD
JobD	Alternate3	ReceivalD-JDO1-JDO6-JDO7-JDO3-ShipmentD
JobE	Alternate1	ReceivalE-JEO1-JEO2-JEO3-ShipmentE
JobF	Alternate1	ReceivalF-JFO1-JFO2-JFO3-JFO4-ShipmentF
JobF	Alternate2	ReceivalF-JFO1-JFO2-JFO3-JFO5-ShipmentF
JobG	Alternate1	ReceivalG-JGO1-JGO2-JGO3-JGO4-ShipmentG
JobH	Alternate1	ReceivalH-JHO1-JHO2-JHO3-ShipmentH
JobH	Alternate2	ReceivalH-JHO1-JHO2-JHO4-JHO5-ShipmentH
JobH	Alternate3	ReceivalH-JHO1-JHO2-JHO6-JHO7-JHO8-ShipmentH

Table A.19. UD - part type arrival summary

Product	Inter Arrival Time	Total Demand	Product Mix Ratio
A	400	189	14.5%
B	520	145	11.2%
C	420	180	13.9%
D	500	151	11.6%
E	440	172	13.2%
F	480	158	12.1%
G	460	164	12.6%
H	540	140	10.8%

Total Demand	1299
Inter Arrival	1 part / 58.2 time unit

Table A.20. UD - cell-tool allocation by LMM

Cell	Loaded Tool Type	Cell	Loaded Tool Type
Cell1	Tool3	Cell4	Tool1
Cell1	Tool9	Cell4	Tool5
Cell2	Tool2	Cell5	Tool2
Cell2	Tool4	Cell5	Tool3
Cell3	Tool6	Cell6	Tool7
		Cell6	Tool8

Table A.21. UD - operation, tool, mean processing time relations

Operation Name	**Mean Processing Time**	**Tool Name**
JAO1	90	Tool1
JAO2	140	Tool2
JAO3	50	Tool3
JAO4	110	Tool4
JAO5	80	Tool4
JAO6	120	Tool5
JAO7	140	Tool6
JAO8	100	Tool5
JAO9	120	Tool6
JAO10	80	Tool6
JBO1	110	Tool6
JBO2	140	Tool2
JBO3	50	Tool1
JBO4	110	Tool7
JBO5	90	Tool1
JBO6	50	Tool5
JBO7	140	Tool8
JCO1	70	Tool5
JCO2	50	Tool1
JCO3	50	Tool2
JCO4	140	Tool6
JCO5	80	Tool4
JCO6	80	Tool7
JCO7	60	Tool8

Table A.22. UD - operation, tool, mean processing time relations (cont.)

Operation Name	Mean Processing Time	Tool Name
JDO1	120	Tool3
JDO2	110	Tool6
JDO3	110	Tool3
JDO4	50	Tool3
JDO5	140	Tool7
JDO6	120	Tool8
JDO7	70	Tool1
JEO1	130	Tool2
JEO2	70	Tool9
JEO3	120	Tool7
JFO1	140	Tool8
JFO2	60	Tool1
JFO3	70	Tool9
JFO4	80	Tool9
JFO5	110	Tool9
JGO1	110	Tool9
JGO2	110	Tool6
JGO3	140	Tool4
JGO4	120	Tool4
JHO1	120	Tool5
JHO2	70	Tool3
JHO3	100	Tool9
JHO4	110	Tool8
JHO5	50	Tool2
JHO6	100	Tool8
JHO7	130	Tool8
JHO8	70	Tool6

A.4.2. Experimentation II

Table A.23. UD - part type process routes

Product Name		Operations
JobA	Alternate1	ReceivalA-JAO1-JAO2-JAO3-ShipmentA
JobB	Alternate1	ReceivalB-JBO1-JBO2-JBO3-ShipmentB
JobB	Alternate2	ReceivalB-JBO1-JBO4-JBO5-JBO3-ShipmentB
JobB	Alternate3	ReceivalB-JBO1-JBO6-JBO7-JBO3-ShipmentB
JobC	Alternate1	ReceivalC-JCO1-JCO2-JCO3-ShipmentC
JobC	Alternate2	ReceivalC-JCO1-JCO2-JCO4-JCO5-ShipmentC
JobD	Alternate1	ReceivalD-JDO1-JDO2-JDO3-ShipmentD
JobD	Alternate2	ReceivalD-JDO1-JDO4-JDO5-JDO6-ShipmentD
JobE	Alternate1	ReceivalE-JEO1-JEO2-JEO3-ShipmentE
JobE	Alternate2	ReceivalE-JEO1-JEO4-JEO5-JEO6-ShipmentE
JobE	Alternate3	ReceivalE-JEO1-JEO7-JEO8-JEO3-ShipmentE
JobF	Alternate1	ReceivalF-JFO1-JFO2-JFO3-ShipmentF
JobF	Alternate2	ReceivalF-JFO1-JFO2-JFO4-JFO5-ShipmentF
JobG	Alternate1	ReceivalG-JGO1-JGO2-JGO3-ShipmentG
JobG	Alternate2	ReceivalG-JGO1-JGO2-JGO4-JGO5-ShipmentG
JobG	Alternate3	ReceivalG-JGO1-JGO6-JGO7-JGO8-ShipmentG
JobH	Alternate1	ReceivalH-JHO1-JHO2-JHO3-JHO4-ShipmentH

Table A.24. UD - part type arrival summary

Product	Interarrival Time	Release	Mix Ratio
A	500	151	10.4%
B	350	216	14.9%
C	470	161	11.1%
D	410	184	12.7%
E	450	168	11.6%
F	430	176	12.1%
G	370	204	14.1%
H	400	189	13.0%

Total Demand	1450
Inter Arrival	52.15305

Table A.25. UD - cell-tool allocation by LMM

Cell	Loaded Tool Type	Cell	Loaded Tool Type
Cell1	Tool2	Cell4	Tool11
Cell1	Tool3	Cell4	Tool4
Cell1	Tool4	Cell4	Tool5
Cell2	Tool1	Cell5	Tool3
Cell2	Tool3	Cell5	Tool5
Cell2	Tool7	Cell5	Tool6
Cell3	Tool11	Cell5	Tool8
Cell3	Tool6	Cell6	Tool1
Cell3	Tool9	Cell6	Tool12
		Cell6	Tool5

Table A.26. UD - operation, tool, mean processing time relations

Operation Name	**Mean Processing Time**	**Tool Name**
JAO1	100	Tool1
JAO2	80	Tool2
JAO3	80	Tool3
JBO1	90	Tool4
JBO2	90	Tool4
JBO3	90	Tool2
JBO4	90	Tool4
JBO5	100	Tool4
JBO6	80	Tool5
JBO7	80	Tool6
JCO1	100	Tool7
JCO2	100	Tool8
JCO3	80	Tool4
JCO4	100	Tool1
JCO5	100	Tool3
JCO6	90	Tool9
JCO8	90	Tool6
JDO1	110	Tool5
JDO2	100	Tool7
JDO3	100	Tool3
JDO4	90	Tool9
JDO5	90	Tool2
JDO6	80	Tool2

Table A.27. UD - operation, tool, mean processing time relations (cont.)

Operation Name	**Mean Processing Time**	**Tool Name**
JEO1	90	Tool1
JEO2	110	Tool11
JEO3	110	Tool7
JEO4	90	Tool3
JEO5	80	Tool6
JEO6	80	Tool9
JEO7	90	Tool3
JEO8	90	Tool2
JFO1	90	Tool6
JFO2	110	Tool11
JFO3	90	Tool5
JFO4	100	Tool9
JFO5	100	Tool8
JGO1	90	Tool3
JGO2	80	Tool1
JGO3	90	Tool9
JGO4	110	Tool1
JGO5	110	Tool9
JGO6	90	Tool3
JGO7	90	Tool3
JGO8	90	Tool12
JHO1	90	Tool4
JHO2	110	Tool5
JHO3	100	Tool3
JHO4	90	Tool12

APPENDIX B: FIGURES AND TABLES FOR WORKLOAD DETERMINATION METHODS OF PERIODIC ORR

B.1. Strictly Directed (SD) Flow Pattern - Figures and Tables

Table B.1. Best total flow time points for figure B.1

	Best Average Total Flow Time	Total Throughput	Total Mean. Q. Lengths	Best Threshold
PP 50	30,501	731.5	4.04	400
PP 100	30,587	731.3	3.98	500
PP 500	31,369	714.4	3.19	650
PP 1000	32,363	393.1	1.86	750

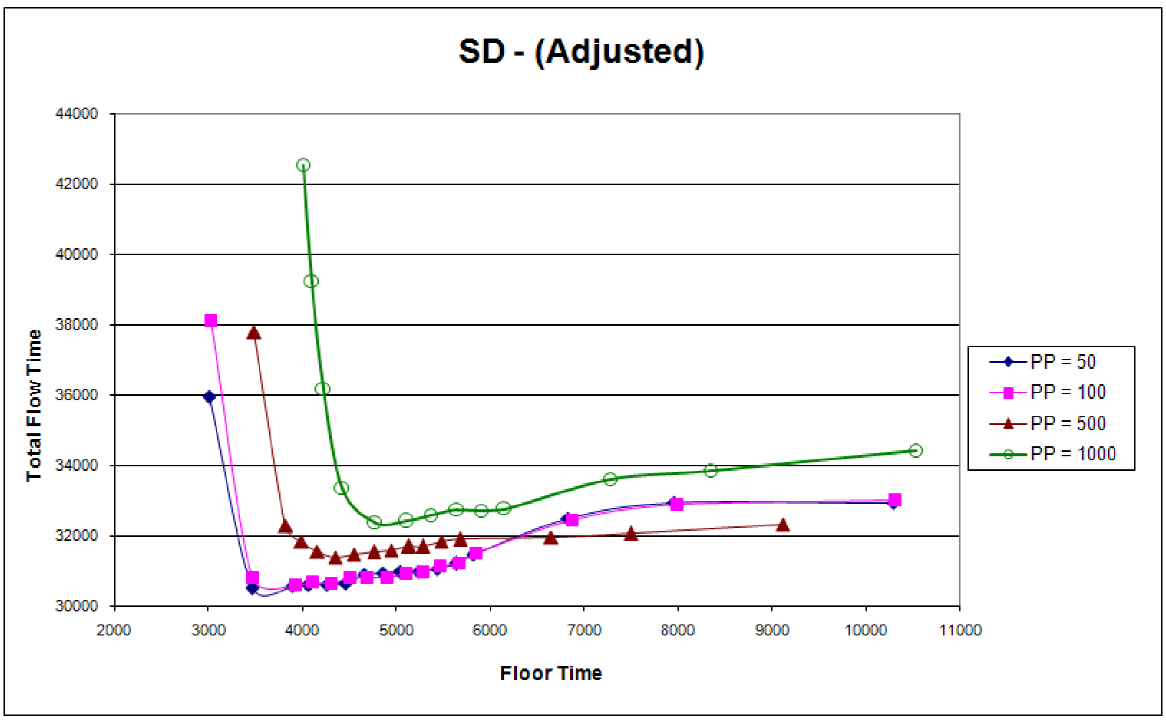

Figure B.1. SD with adjusted method for four levels of ORR period length

Table B.2. Best total flow time points for figure B.2

	Best Average Total Flow Time	Total Throughput	Total Mean. Q. Lengths	Best Threshold
PP 50	30,383	731.7	11.69	225
PP 100	30,584	731.9	11.38	300
PP 500	31,838	730.8	9.27	550
PP 1000	32,675	393.1	1.86	750

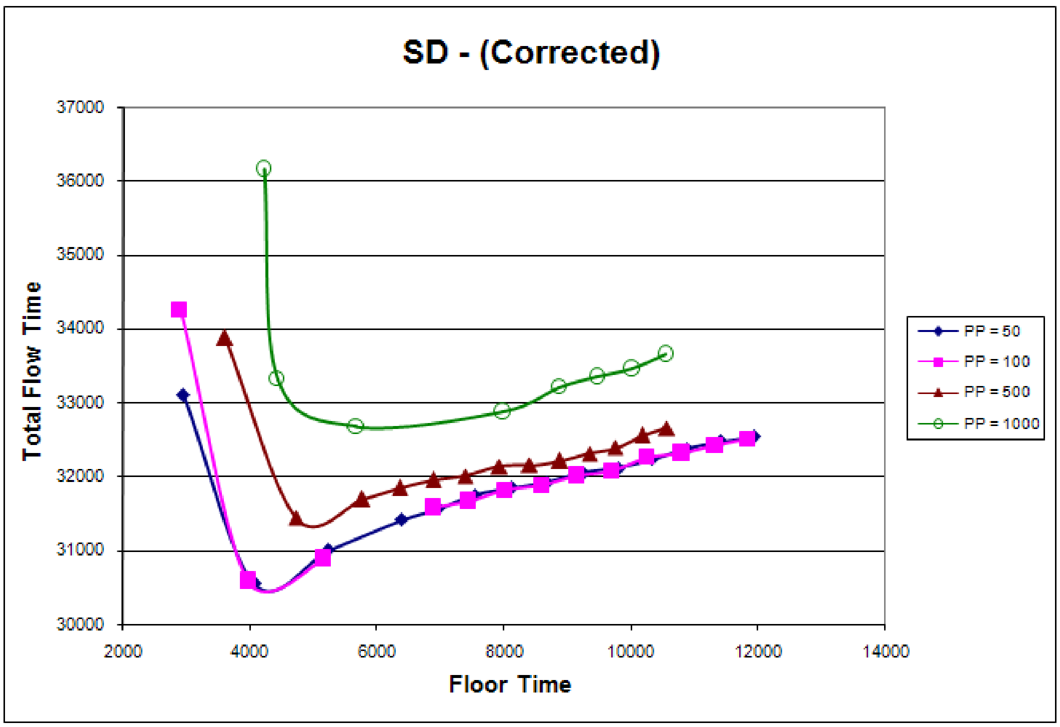

Figure B.2. SD flow pattern with corrected method for four levels of ORR period length

Table B.3. Best total flow time points for figure B.3

	Best Average Total Flow Time	Total Throughput	Total Mean. Q. Lengths	Best Threshold
PP 50	30,690	731.9	5.74	550
PP 100	30,767	731.5	5.66	500
PP 500	31,386	730.0	4.7	700
PP 1000	32,308	393.1	1.86	1000

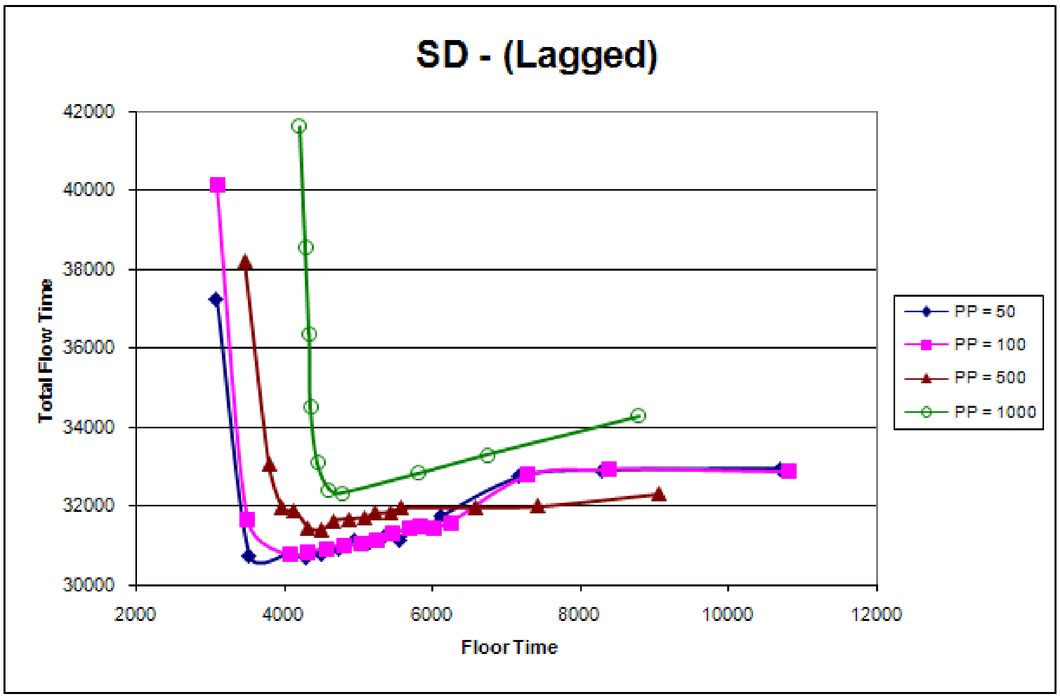

Figure B.3. SD flow pattern with adjusted method for four levels of ORR period length

B.2. General Directed (GD) Flow Pattern Model - Figures and Tables

Table B.4. Best total flow time points for figure B.4

ORR Period Length	Best Average Total Flow Time	Total Throughput	Total Mean Q. Lengths	Best Threshold
PP50	54,043	994.78	83.86	5000
PP100	54,042	996.22	83.62	5000
PP500	82,838	575.33	1.82	8000
PP1000	86,447	290.33	0.96	8000

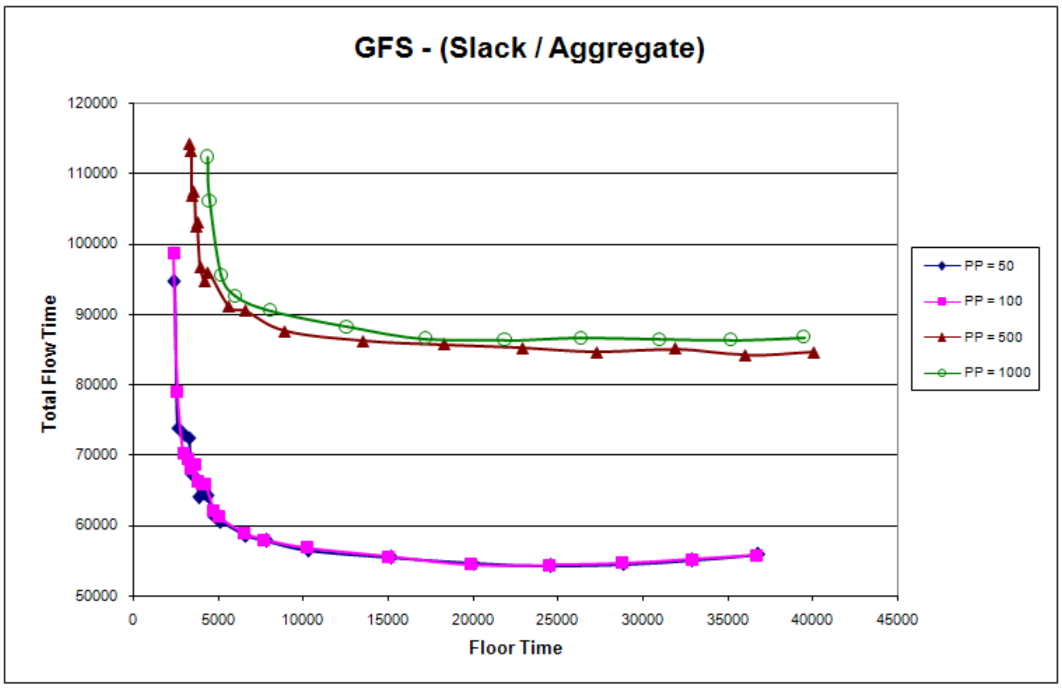

Figure B.4. GD flow pattern with aggregate and slack-based listing methods for four levels of ORR period length

Table B.5. Best total flow time points for figure B.5

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Length	Best Threshold
PP50	55,335	982.78	29.08	1250
PP100	55,300	981.78	28.52	1500
PP500	84,030	575.11	1.80	2000
PP1000	76,891	290.11	0.96	8000

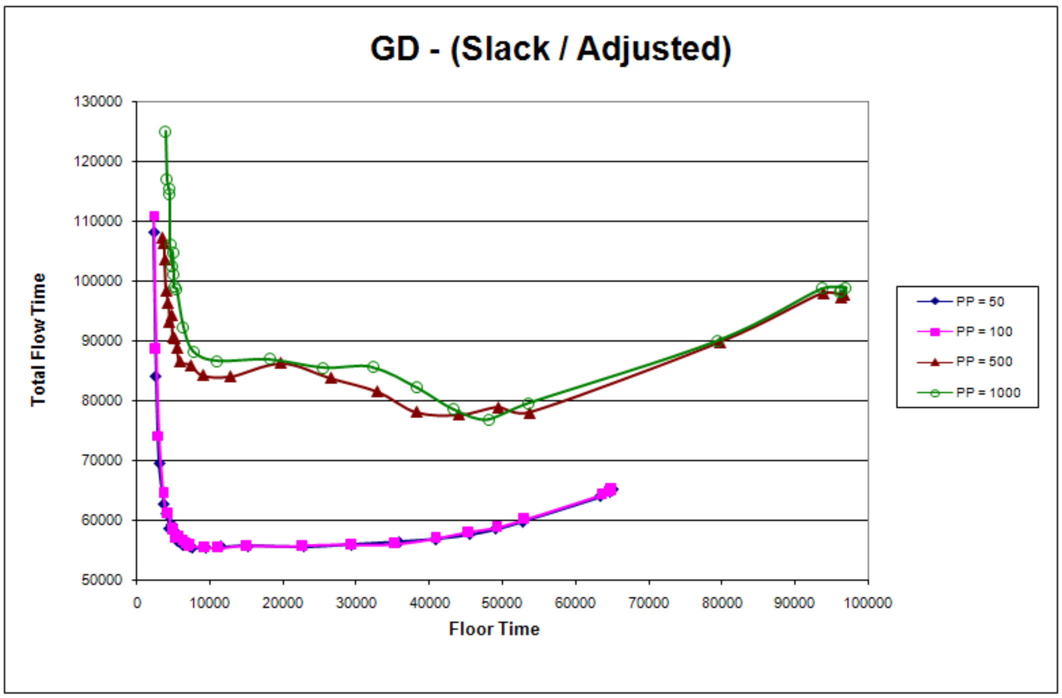

Figure B.5. GD flow pattern with adjusted and slack-based listing methods for four levels of ORR period length

Table B.6. Best total flow time points for figure B.6

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Length	Best Threshold
PP50	54,105	994.78	83.86	4000
PP100	54,042	996.22	83.62	4000
PP500	82,838	575.33	1.82	9000
PP1000	86,447	290.33	0.96	5000

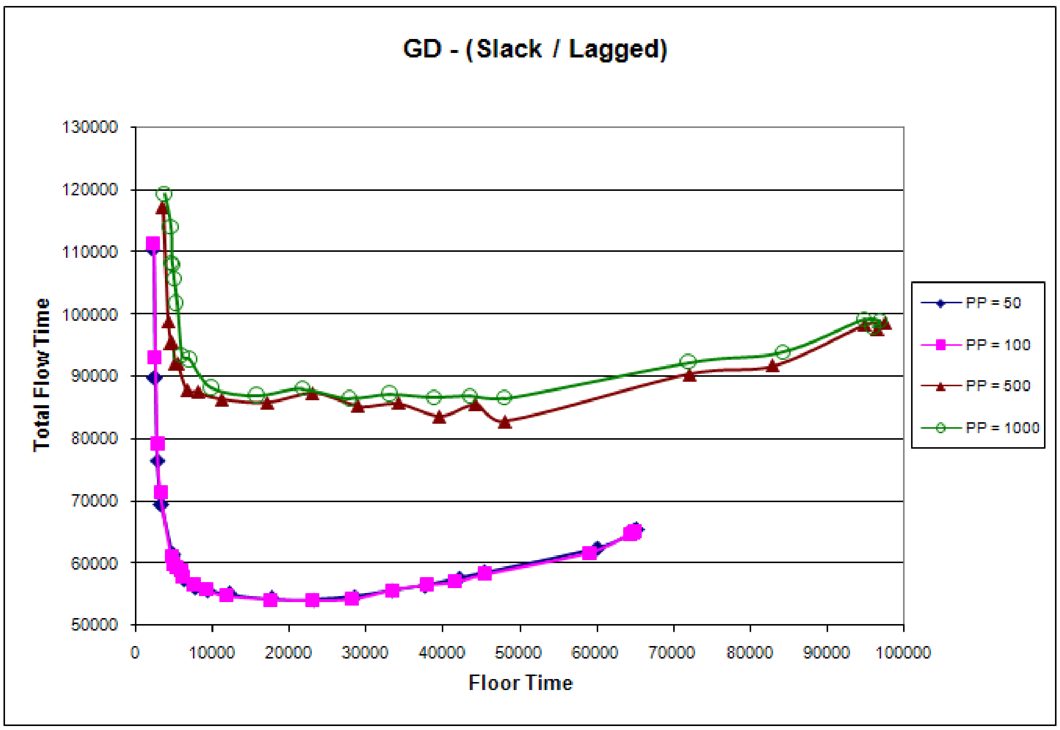

Figure B.6. GD flow pattern with lagged and slack-based listing methods for four levels of ORR period length

Table B.7. Best total flow time points for figure B.7

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Length	Best Threshold
PP50	55,139	973	71.76	4000
PP100	55,351	956.00	71.41	4000
PP500	80,300	521.78	1.98	9000
PP1000	84,021	261.00	0.96	9000

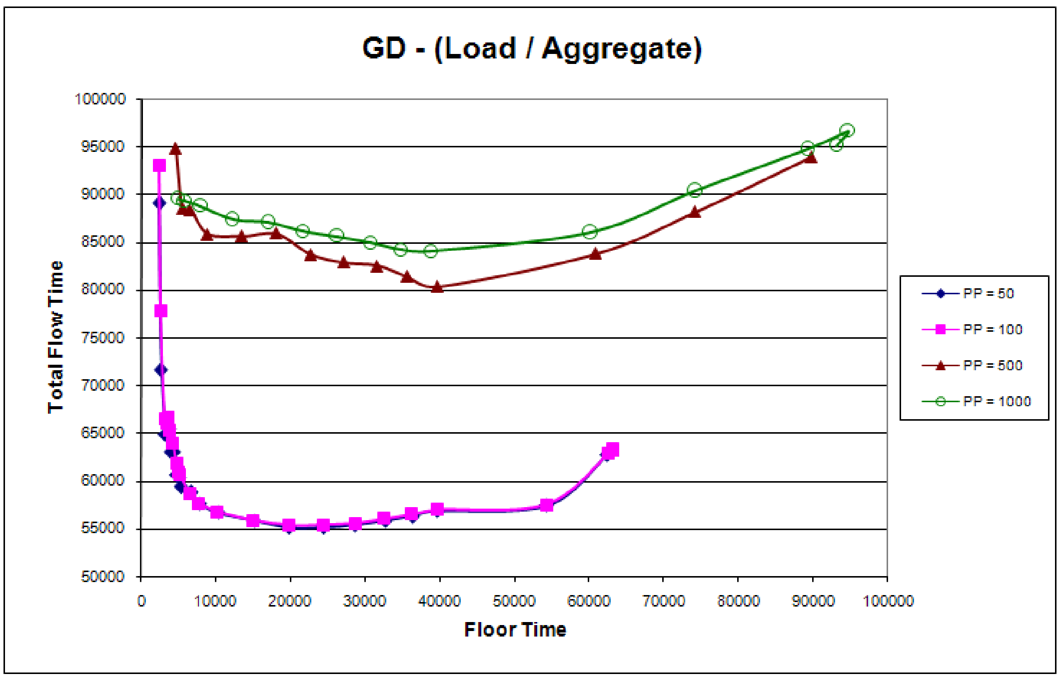

Figure B.7. GD flow pattern with aggregate and load-based listing methods for four levels of ORR period length

Table B.8. Best total flow time points for figure B.8

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Length	Best Threshold
PP50	54,799	976.67	36.61	1500
PP100	55,400	978.89	36.2	1500
PP500	72,140	573.11	2.24	8000
PP1000	71,155	291.33	1.3	7000

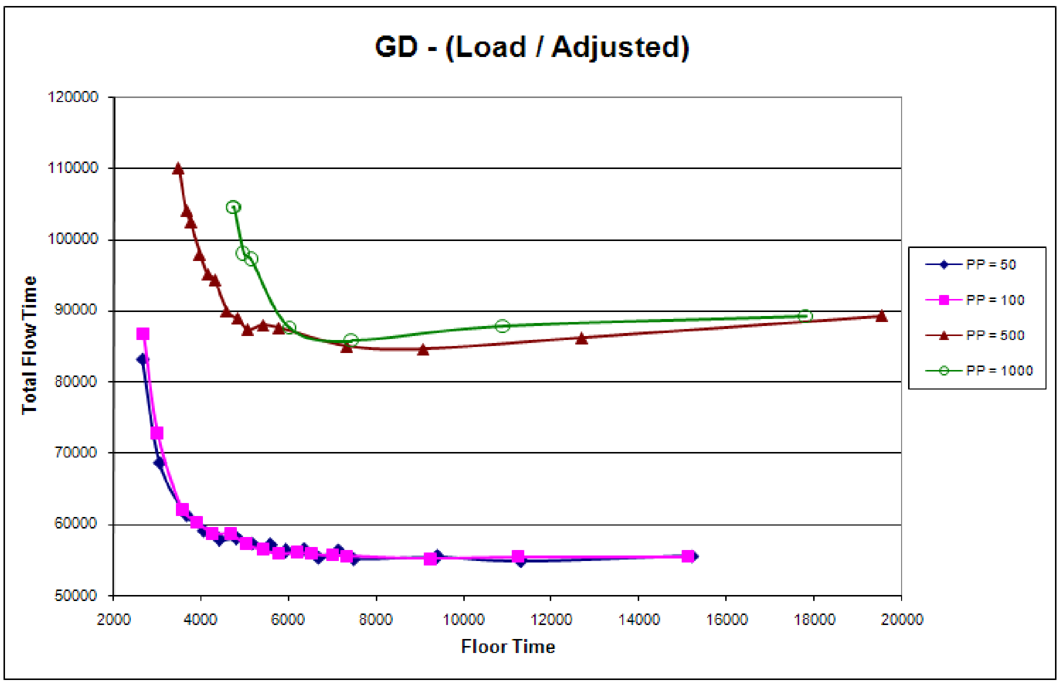

Figure B.8. GD flow pattern with adjusted and load-based listing methods for four levels of ORR period length

Table B.9. Best total flow time points for figure B.9

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Length	Best Threshold
PP50	53,921	990.89	17.02	700
PP100	53,950	992.44	16.16	700
PP500	55,222	749.33	2.20	4000
PP1000	62,465	750.33	1.07	5000

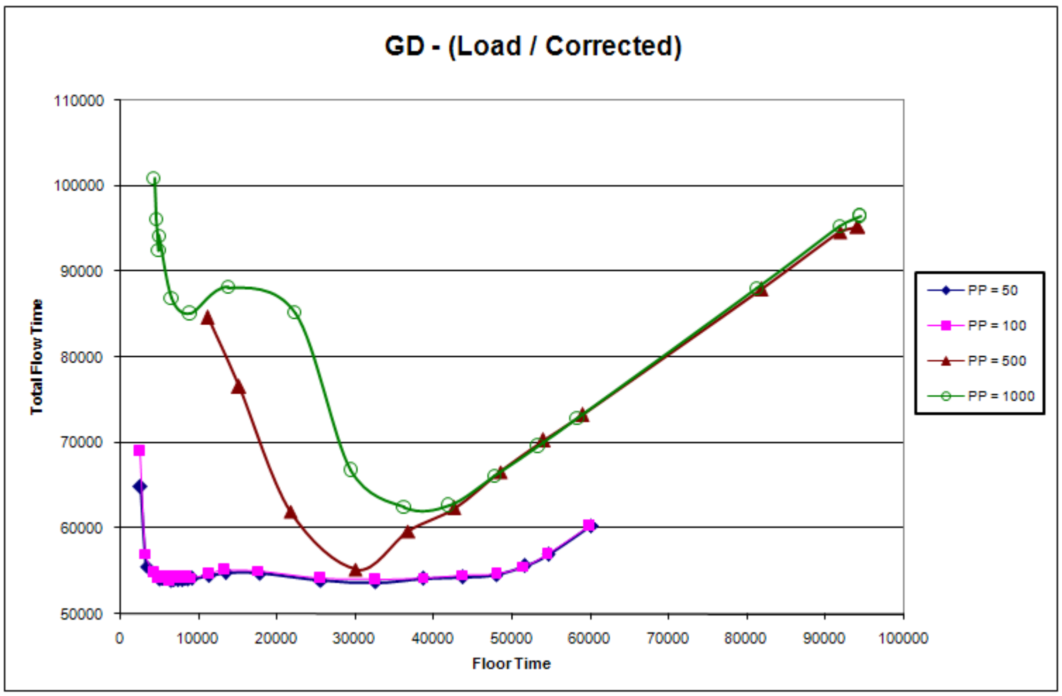

Figure B.9. GD flow pattern with corrected and load-based listing methods for four levels of ORR period length

Table B.10. Best total flow time points for figure B.10

	Best Average Total Flow Time	**Total Throughput**	**Total Mean Q. Length**	**Best Threshold**
PP50	55,947	981.00	67.62	3000
PP100	56,024	981.78	67.42	3000
PP500	71,878	571.11	2.2	5000
PP1000	71,326	290.44	1.05	6000

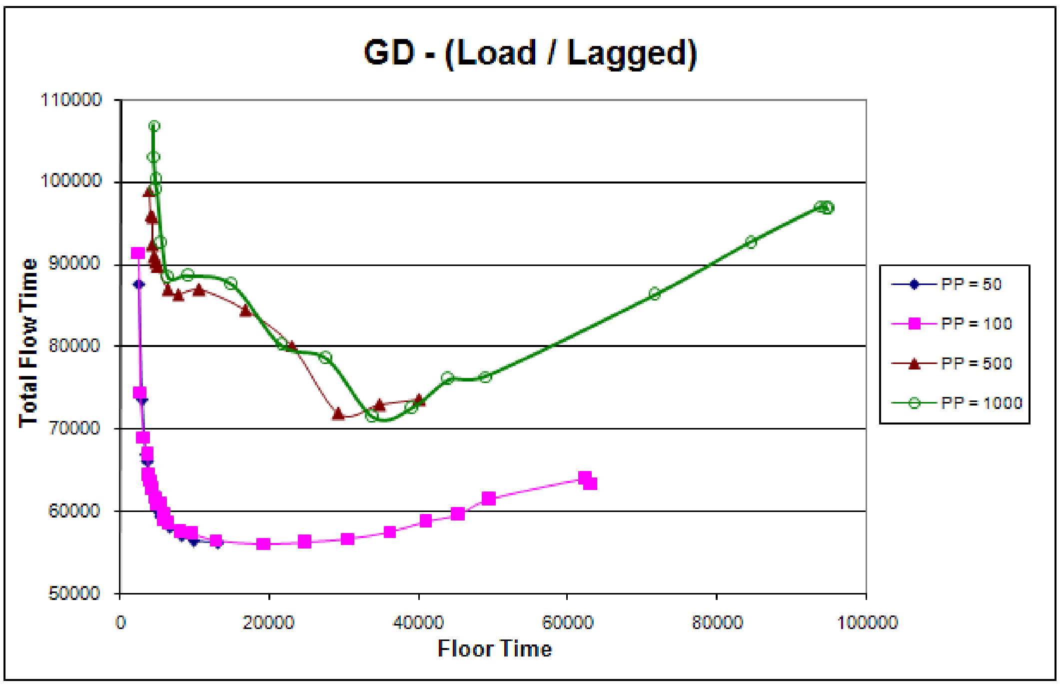

Figure B.10. GD flow pattern with lagged and load-based listing methods for four levels of ORR period length

B.3. Undirected (UD) Flow Pattern Model - Figures and Tables

Table B.11. Best total flow time points for figure B.11

	Best Average Total Flow Time	**Total Throughput**	**Total Mean Q. Length**	**Best Threshold**
PP50	71,606	930.00	29.09	1500
PP100	73,411	923.82	28.27	2000
PP500	79,439	555.36	59.49	3000
PP1000	81,034	285.81	52.77	3000

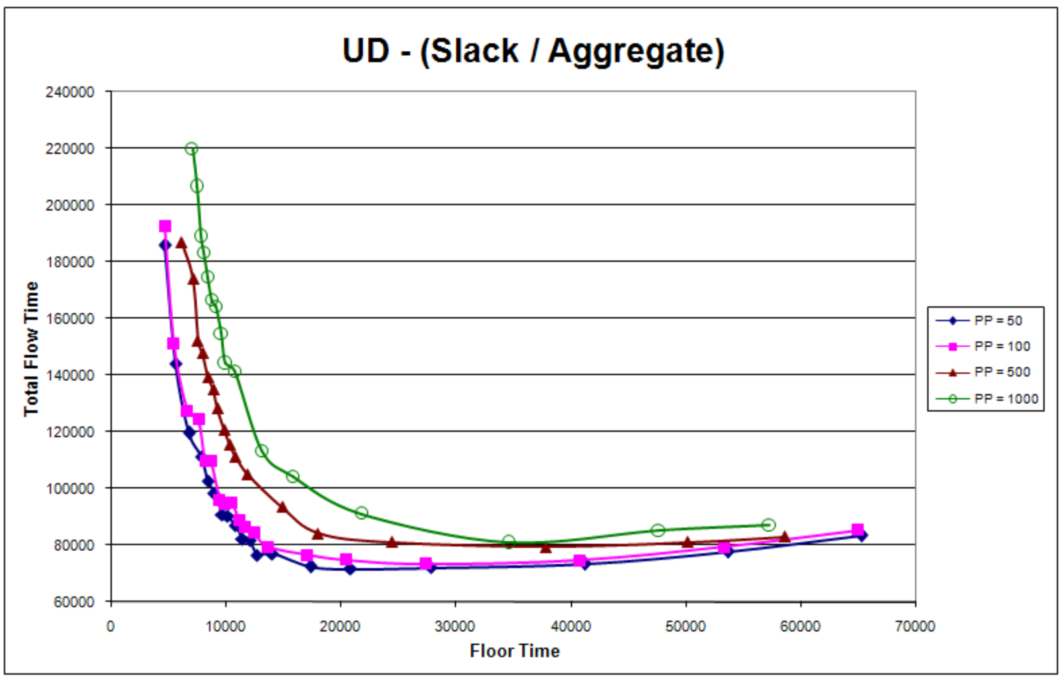

Figure B.11. UD flow pattern with aggregate and slack-based listing methods for four levels of ORR period length

Table B.12. Best total flow time points for figure B.12

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Length	Best Threshold
PP50	70,359	940.00	24.79	950
PP100	71,447	923.82	28.27	1000
PP500	77,423	555.36	59.49	1250
PP1000	83,296	285.82	52.77	2000

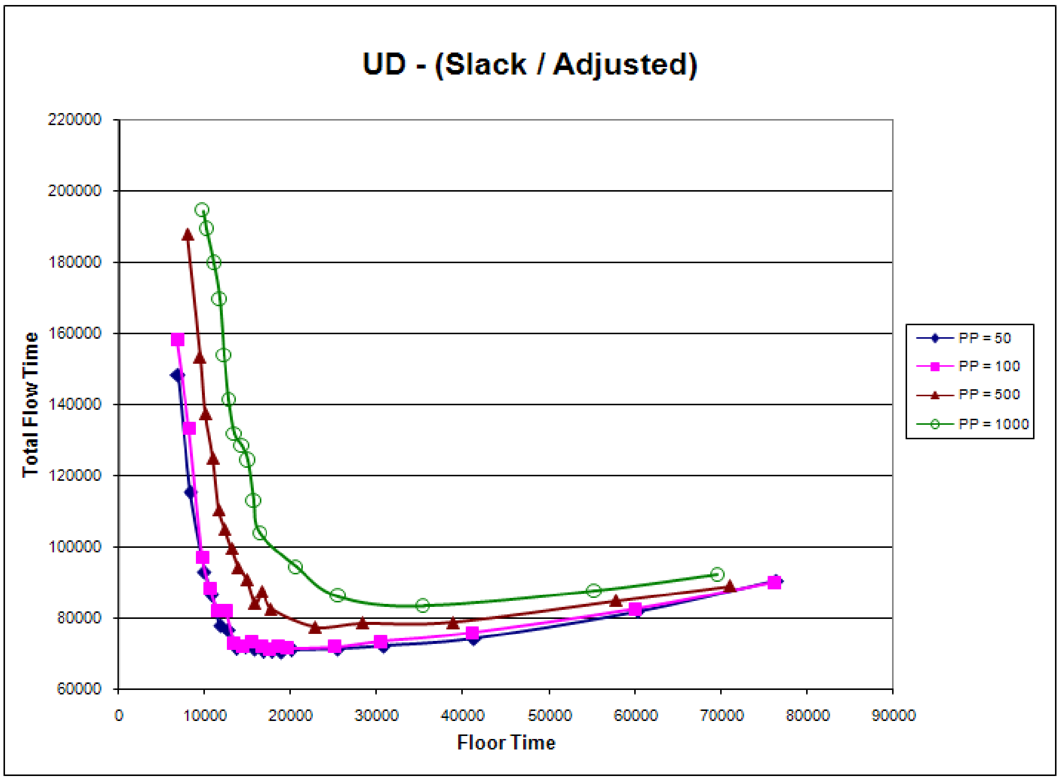

Figure B.12. UD flow pattern with adjusted and slack-based listing methods for four levels of ORR period length

Table B.13. Best total flow time points for figure B.13

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Length	Best Threshold
PP50	70,209	938.00	21.18	1000
PP100	70,971.95	935.30	20.54	1500
PP500	79,063.82	555.30	50.75	2000
PP1000	81,957.86	288.20	41.40	2000

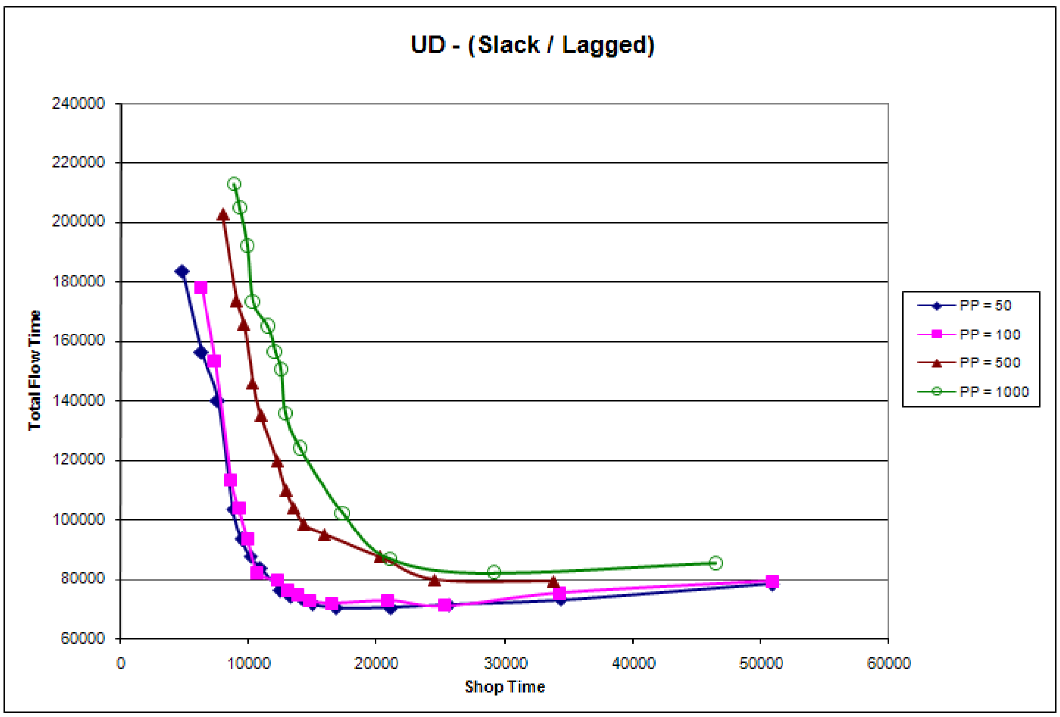

Figure B.13. UD flow pattern with lagged and slack-based listing methods for four levels of ORR period length

Table B.14. Best total flow time points for figure B.14

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Length	Best Threshold
PP50	72,482	925.00	66.81	3000
PP100	74,692.91	921.00	66.13	3000
PP500	80,945.10	558.70	35.08	2000
PP1000	84,558.31	288.30	53.19	3000

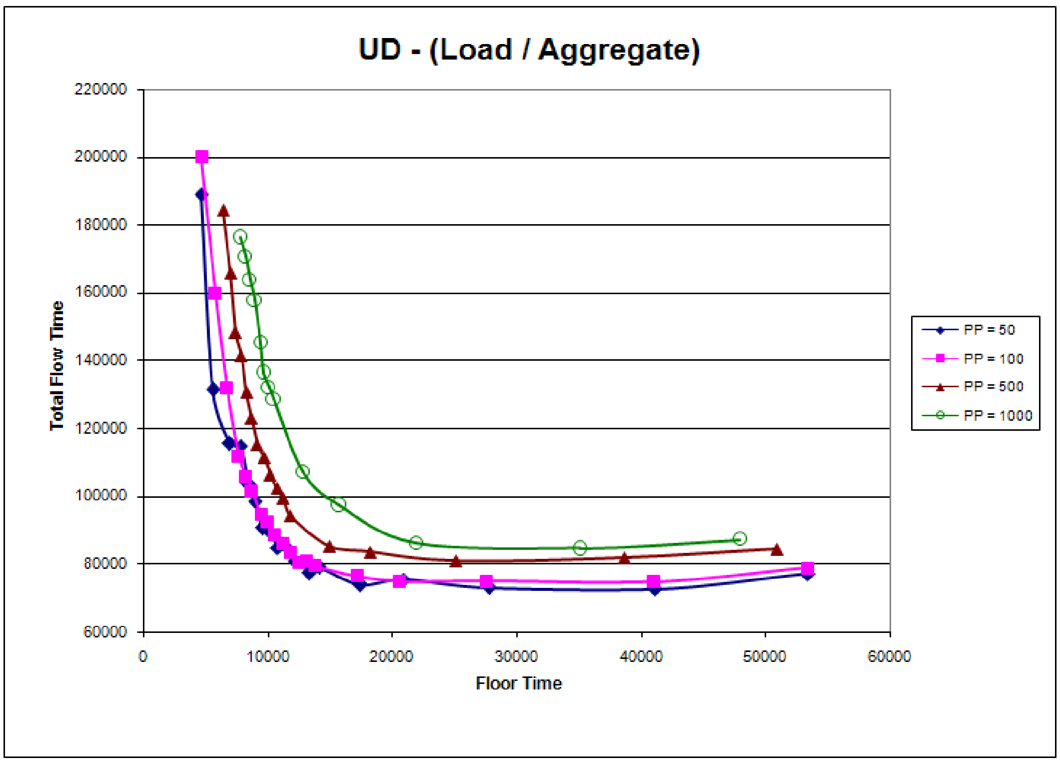

Figure B.14. UD flow pattern with aggregate and load-based listing methods for four levels of ORR period length

Table B.15. Best total flow time points for figure B.15

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Length	Best Threshold
PP50	70,523	933.40	20.81	950
PP100	72,071.47	930.60	19.9	1000
PP500	79,087.87	555.00	39.44	1500
PP1000	85,436.23	289.70	1.63	2000

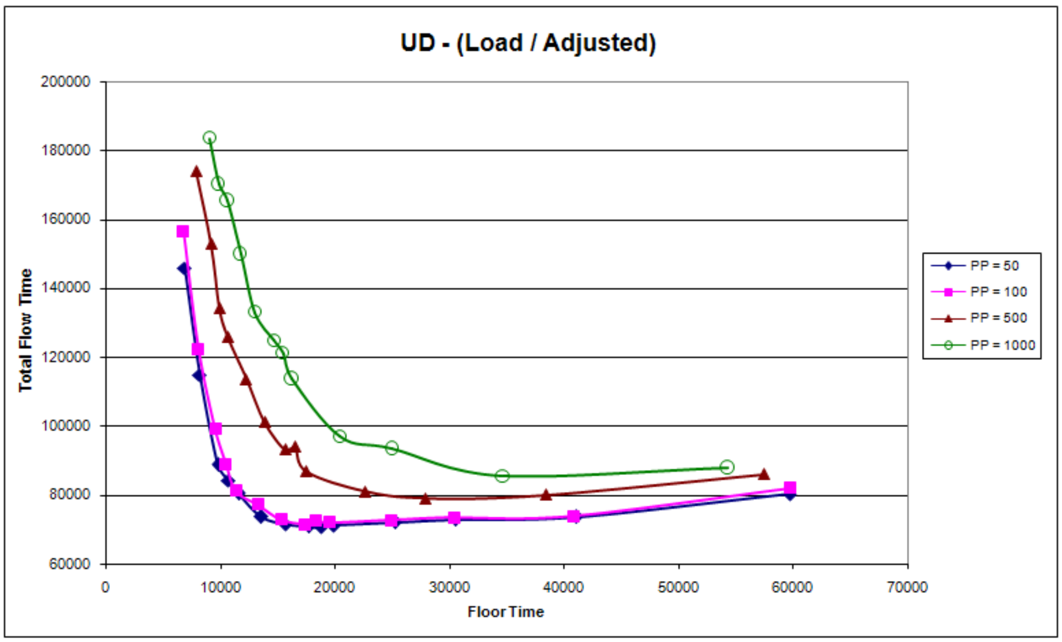

Figure B.15. UD flow pattern with adjusted and load-based listing methods for four levels of ORR period length

Table B.16. Best total flow time points for figure B.16

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Length	Best Threshold
PP50	69,141	941.30	19.75	600
PP100	69,284.97	938.80	19.35	600
PP500	76,228.62	555.60	27.24	850
PP1000	84,267.57	288.90	53.65	1500

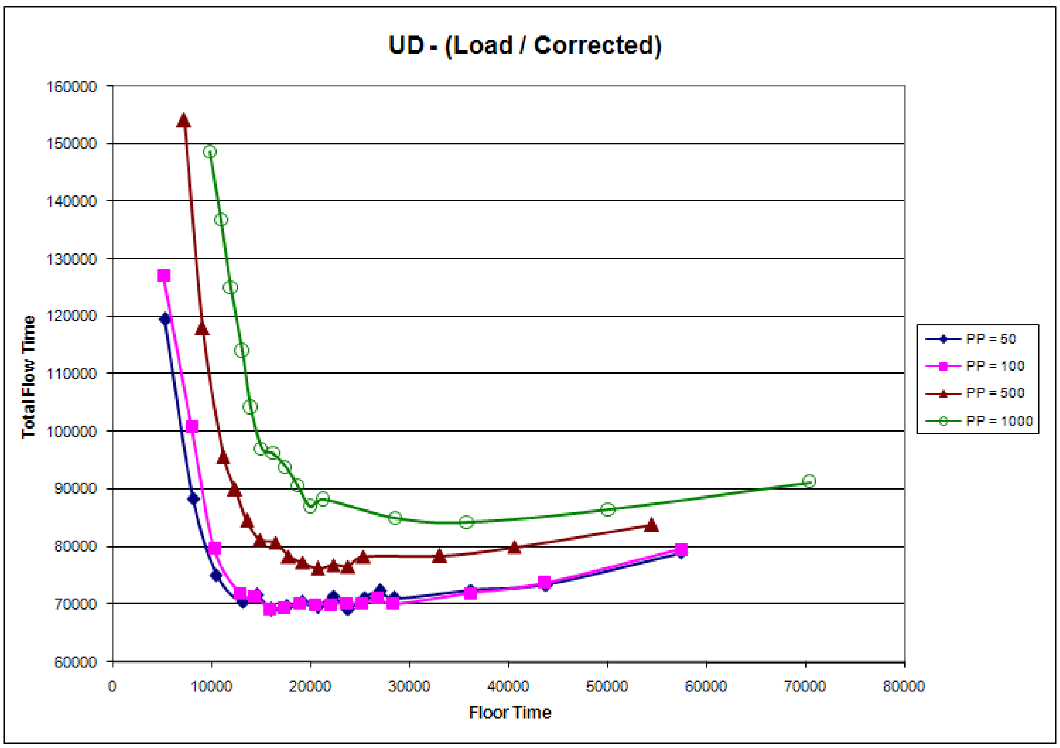

Figure B.16. UD flow pattern with corrected and load-based listing methods for four levels of ORR period length

Table B.17. Best total flow time points for figure B.17

	Best Average Total Flow Time	Total Throughput	Total Mean Q. Length	Best Threshold
PP50	69,590	935.33	48.7	1250
PP100	70,964	931.78	47.43	1000
PP500	78,246	558.44	46.82	2000
PP1000	85,672	292.44	70.60	3000

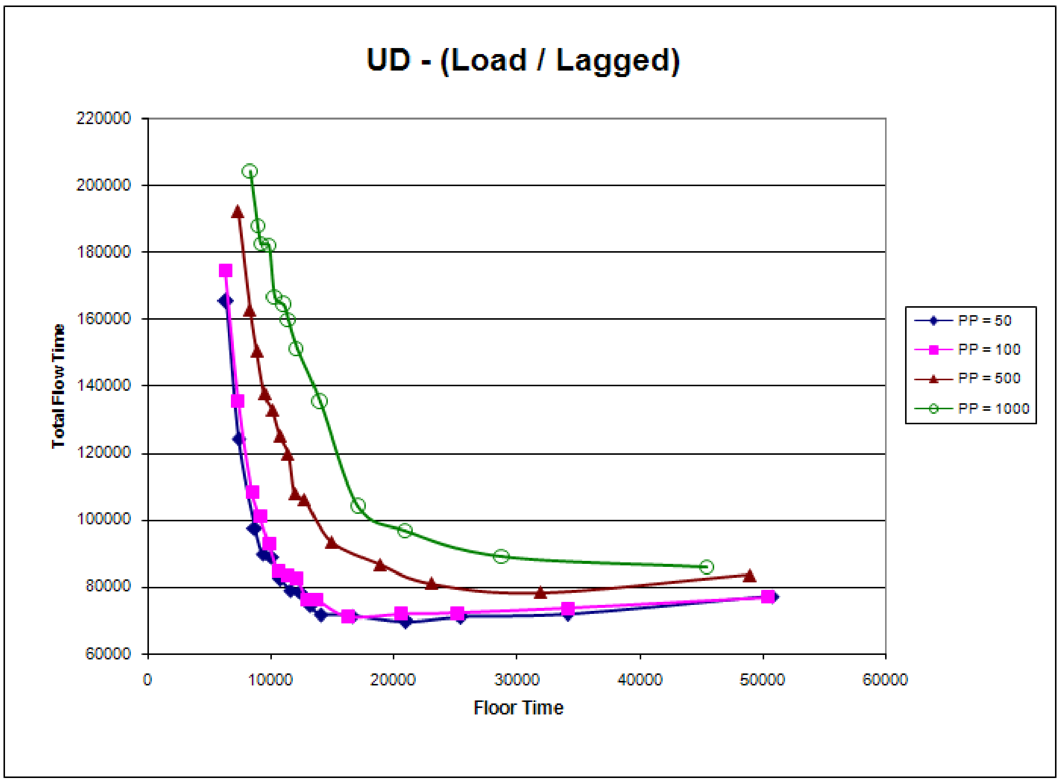

Figure B.17. UD flow pattern with lagged and load-based listing methods for four levels of ORR period length

APPENDIX C: TESTS OF HYPOTHESES FOR PERFORMANCES

The test of hypotheses are conducted for comparing means of any two methods with unknown and unequal variances assumption. Instead of assigning an α, P-values are presented for decision making. The statistic used is

$$t' = \frac{(\bar{X}_1 - \bar{X}_2) - d_0}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

and it has a n approximate t-distribution with approximate degrees of freedom

$$v = \frac{(s_1^2/n_1 + s_2^2/n_2)^2}{\frac{(s_1^2/n_1)^2}{n_1 - 1} + \frac{(s_2^2/n_2)^2}{n_2 - 1}}$$

As a result the procedure is to not reject H_0 when $-t_{\alpha/2,v} < t' < t_{\alpha/2,v}$

C.1. Hypothesis Testing for SD flow pattern

$$1: Adjusted, \quad 2: Aggregate, \quad 3: Corrected, \quad 4: Lagged$$

$$\begin{aligned} \bar{X}_1 &= 30498.8 & s_1 &= 1314.34 \\ \bar{X}_2 &= 30501.08 & s_2 &= 1204.125 \\ \bar{X}_3 &= 30383.11634 & s_3 &= 1184.691392 \\ \bar{X}_4 &= 30690.2254 & s_4 &= 1254.190339 \end{aligned}$$

Adjusted vs Aggregate **P-value = 0.99682** t' = -0.004044813, v = 17.86;

Adjusted vs Corrected **P-value = 0.83853** t' = 0.206743394 , v = 17.81;

Adjusted vs Lagged **P-value = 0.74283** t' = -0.333204464, v = 17.96;

Aggregate vs Corrected **P-value = 0.82771** t' = 0.220834079 , v = 18.00;

Aggregate vs Lagged **P-value = 0.73482** t' = -0.344019568, v = 17.97;

Corrected vs Lagged **P-value = 0.58044** t' = -0.562912155, v = 17.94;

C.2. Hypothesis Testing for GD flow pattern

Tests for differentiating Load and Slack based listings are depicted below:

Adjusted **P-value = 0.13631** t' = 1.55940153 v = 18.00

Aggregate **P-value = 0.58272** t' = -0.56010317 v = 17.38

Corrected **P-value = 0.96645** t' = 0.04264876 v = 17.99

Lagged **P-value = 0.01478** t' = 2.695828631 v = 17.71

Tests for differentiating Slack/Corr pair are depicted below:

Slack - Corrected vs Adjusted **P-value = 0.69948** t'= 0.394676053 V= 13.39

Slack - Corrected vs Aggregate **P-value = 0.19690** t'= 1.340064926 v= 17.88

Slack - Corrected vs Lagged **P-value = 0.81107** t'= -0.243292647 v= 15.30

Load - Corrected vs Adjusted **P-value = 0.19372** t'= 1.365226047 v= 13.63

Load - Corrected vs Aggregate **P-value = 0.39172** t'= 0.878881813 v= 16.94

Load - Corrected vs Lagged **P-value = 0.04275** t'= -2.228491067 v= 14.31

C.3. Hypothesis Testing for UD flow pattern

Tests for differentiating Slack/Corr pair are depicted below:

Slack - Corrected vs Adjusted **P-value 0.09291** T'= 1.77440026 V= 17.58

Slack - Corrected vs Aggregate **P-value 0.01834** T'= 2.593627587 V= 17.75

Slack - Corrected vs Lagged **P-value 0.06224** T'= -1.995721019 V= 17.37

Load - Corrected vs Adjusted **P-value = 0.53399** T'= 0.634830671 V= 16.85

Load - Corrected vs Aggregate **P-value = 0.04163** T'= 2.26002636 V= 13.20

Load - Corrected vs Lagged **P-value = 0.80332** T'= -0.2527537 V= 17.78

C.4. Hypothesis Testing for Summary of Results

Tests for differentiating compared results of GD are depicted below:

IMM vs IR **P-value 0.69035** T'=-0.40486 V= 17.97

IMM vs Slack/Corr Periodic **P-value 0.00000** T'= 7.499776 V= 13.35

IMM vs Slack/Agg Pull **P-value 0.00000** T'= 13.83143 V= 18.00

IR vs Slack/Corr Periodic **P-value 0.00000** T'= 7.694795 V= 13.68

IR vs Slack/Agg Pull **P-value 0.00000** T'= 13.93932 V= 17.98

Slack/Corr Periodic vs Slack/Agg Pull **P-value 0.18690** T'= 1.393291 V= 13.42

Tests for differentiating compared results of UD are depicted below:

IMM vs IR **P-value0.66434** T'= 0.441172 V= 17.99

IMM vs Slack/Corr Periodic **P-value 0.00000** T'= 13.83761 V= 18.00

IMM vs Slack/Adj Pull **P-value 0.00000** T'= 8.217055 V= 17.93

IR vs Slack/Corr Periodic **P-value 0.00000** T'= 13.53478 V= 17.99

IR vs Slack/Adj Pull **P-value 0.00000** T'= 7.849632 V= 17.97

Slack/Corr Periodic vs Slack/Adj Pull **P-value 0.00001** T'= -6.03374 V= 17.93

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