Opportune Job Shredding: An Effective Approach for Scheduling Parameter Sweep Applications

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Abstract

*A number of applications comprise of several small independent and homogeneous tasks that need to be executed. However, most supercomputer centers enforce a restriction on the number of jobs a single user can submit to the cluster at any time in order to ensure fairness to the other submitted jobs. This forces the users to combine these independent homogeneous tasks into a single parallel Parameter Sweep Application (PSA). In this paper we propose a new and efficient scheme, termed as **Opportune Job Shredding**, which allows Supercomputer Centers to take advantage of the sequentializing capabilities of Parameter Sweep Applications without affecting the other submitted jobs significantly. Our simulation results show that this scheme significantly improves both the turnaround time and the slow down of Parameter Sweep Applications together with considerable improvement in the system metrics such as the loss of capacity of the system. Further, our results also show that the degradation in the performance of the non Parameter Sweep Applications is minimal ($< 4\%$). Infact, in most cases the better packing of the schedule results in improvement in the performance of the Non-Parameter Sweep Applications as well. We also propose an extension of the previously proposed "Multiple Simultaneous Requests" scheme combining it with the Opportune Job Shredding scheme allowing Parameter Sweep Applications to be executed in parts on remote clusters.*

Keywords: *Parameter Sweep Applications, Multiple Simultaneous Requests, Meta Scheduling*

1 Introduction

Parameter Sweep Applications (PSA's) represent an important class of computationally intense applications that require significant compute resources. Many users of shared computational facilities like supercomputer centers generate PSA's. PSA's generally consist of a large number of independent tasks that may share some common files for input and output. All tasks of a PSA must complete before the job is complete, but the various tasks can be executed independently and in any order. Parallel Tomography [30] and MCell [20] are examples of PSA's. The Parallel Tomography Application (also known as GTOMO) is being used in production at the National Center For Microscopy and Imaging Research. The MCell application is used as a simulator for Cellular Micro-Physiology. Other such applications include those used for modelling photochemical pollution, fluid flows, etc. We will go over some applications in more detail in section 3.

Due to the importance of PSA's, scheduling/resource-management systems have been built to facilitate their execution. These include APST (AppLeS Parameter Sweep Template) [5, 26] and Nimrod/G [2]. APST, Nimrod/G and SETIHome [28] are primarily targeted at utilizing distributed computational resources over the web/grid for PSA's. Without such systems, users of PSA's would have to manually create and submit a large number of independent jobs on different available machines. Middleware like APST greatly eases the burden of PSA users, by automatically spawning multiple tasks for a PSA job at suitable sites. It uses dynamic load information on processors and network links to determine the "best" sites to submit the tasks of a PSA , i.e. the sites that will result in the fastest completion.

It is of great interest to look at effective ways of supporting the use of parallel systems at supercomputer centers in exe-

cuting PSA's. Besides the tedium of manually creating hundreds of separate jobs to submit to a supercomputer center, users of PSAs have to face fair-share constraints imposed by most centers on the maximum number of simultaneously executable jobs from any user. These fair-share limits are imposed to ensure that the resources of the center are not monopolized by a single user.

While PSA scheduling systems like APST could be set up to work in conjuncion with schedulers at supercomputer centers, there is a problem that has to be addressed in this regard. Clearly, the usual fair-share limits of a supercomputer center's policy need to be relaxed for, if the individual jobs created by APST for a PSA are to execute without delay. But if this were done, it could result in significant delays of other non-PSA jobs in the system - the avoidance of this problem is the reason why fair-share limits are imposed at supercomputer centers.

In this paper we first use trace-driven simulations to characterize the impact of introducing PSA job "fragments" (i.e. the large number of individual independent small jobs spawned for a single PSA job submitted to a system like APST) into a mix of non-PSA jobs in a supercomputer center environment. We show that non-PSA jobs are indeed adversely affected. We then propose a new approach, termed as *Opportune Job Shredding*, to significantly overcome the degradation of non-PSA jobs, while still allowing for considerable improvement of PSA jobs. We demonstrate that the proposed scheme improves the slowdown of PSA's by up to 70% and the overall loss of capacity of the system by up to 21%. Not only does the scheme avoid significant degradation of the average turnaround time of non-PSA jobs in all cases, but it even improves their performance in some cases.

Meta Schedulers and Grid Computing have become an area of increasing interest in the past couple of years. A number of researchers have been studying various schemes to harness the capabilities of multiple clusters. Different schemes have been proposed to efficiently allow jobs to be executed on remote and potentially heterogeneous clusters. Most of these schemes rely on a centralized administrative authority which handles the scheduling on all clusters. Recently, a "Multiple Simultaneous Requests" scheme had been proposed in order to efficiently schedule jobs on clusters which do not belong to a single administrative domain. However, both the existing variations of this scheme[32, 27] make certain inherent assumptions which do not allow them to be used in a generic environment consisting of clusters of heterogeneous processing speeds and using different scheduling strategies. In this paper, we combine our scheme with the existing "Multiple Simultaneous Requests" scheme to allow Parameter Sweep Applications to be executed in parts on remote clusters.

The remaining part of the paper is organized as follows:

In Section 2 we provide a brief background of the work and some other related work. In Section 3 we discuss the nature of the Parameter Sweep Applications in more detail. In Section 4 we describe the new scheme developed in this paper. We discuss the simulations we carried out and the results comparing the various schemes in Section 5 and present some concluding remarks and possible future work in Section 6.

2   Background and Related Work

Parallel job scheduling strategies have been widely studied [13, 22, 10, 24, 21, 3, 23, 7, 25, 32, 1]. Scheduling of parallel jobs is usually viewed in terms of a 2D chart with time along one axis and the number of processors along the other axis. Each job can be thought of as a rectangle whose length is the user estimated run time and width is the number of processors required. The simplest way to schedule jobs is to use the First-Come-First-Served (FCFS) policy. This approach suffers from low system utilization [19]. Backfilling [22, 9] was proposed to improve system utilization and has been implemented is several production schedulers [8]. Backfilling works by identifying "holes" in the 2D chart and moving forward smaller jobs that fit those holes. There are two common variations to backfilling - conservative and aggressive (EASY) [22, 29]. In conservative backfill, every job is given a reservation when it enters the system. A smaller job is moved forward in the queue as long as it does not delay any previously queued job. In aggressive backfilling, only the job at the head of the queue has a reservation. A small job is allowed to leap forward as long as it does not delay the job at the head of the queue. Fig. 1 shows an example of a schedule with EASY backfilling.
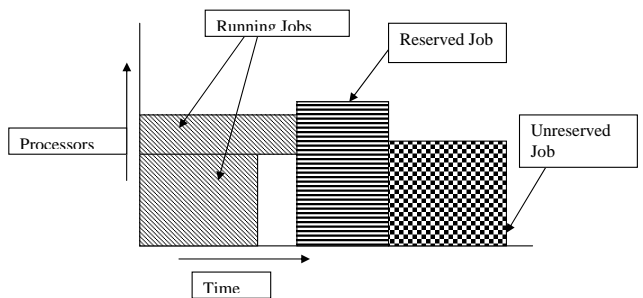

Figure 1. A job schedule with EASY backfilling

2.1   Multi-Site Scheduling

While much of the research on job scheduling has focused on the homogeneous single-site case, there has been con-

siderable recent interest in distributed and multi-site job scheduling [4, 6, 11, 14, 15, 16, 17, 18, 31, 33]. Cooperative multi-site scheduling enables jobs from heavily loaded sites to be executed at remote sites that have a lighter load. Analysis of job log traces [12] shows that the load at supercomputer centers follows a "sinusoidal" pattern of load variation, with the load increasing during the day, peaking somewhere in the evening and then decreasing to a low in the very early hours of the morning. By performing multi-site scheduling over geographically distributed sites, better load balancing can be facilitated.

We recently evaluated the impact of using multiple simultaneous reservations in a multi-site environment [32]. Each job was simultaneously placed in the queue at more than one site, and when a job was ready to actually start at any of the sites, the other requests were cancelled. It was found that this resulted in improved average job response times compared to a scheme where each job is placed on the site that had the least load. The primary reason for the effectiveness of the multiple-simultaneous-request scheme is that backfilling dynamics are very complex and unpredictable, especially when user estimates of job runtime are inaccurate. Therefore, it is very possible that a job may be able to backfill and start earlier at a more heavily loaded site than a lightly loaded site. Further, allowing more jobs in each site's queue enhances the chances of backfilling, thereby reducing the loss of capacity of the system.

When the multiple-simultaneous-requests scheme was evaluated in a heterogeneous environment [27], it was found that it needed some adaptation in order to be effective - primarily, it was important to choose the execution site for a job on the basis of expected completion time rather than expected start time. In order to accurately estimate a job's completion time at multiple sites, it was necessary to use conservative backfilling instead of aggressive backfilling. Thus, some constraints must be imposed on the local scheduling strategy at the sites in order for the multiple-simultaneous-requests strategy to be effective. We show later that in the context of PSA jobs, we can apply the multiple-simultaneous-requests strategy effectively without imposing any constraints on the local job scheduling strategy at the different sites.

3 Parameter Sweep Applications

Parameter Sweep Applications (PSA) are naturally parallel applications that can be structured as a large set of independent tasks that may share common files. The name derives from applications that may be structured as sets of experiments, each of which is executed with a distinct set of parameters. Each experiment (task) may be independently carried out, but the entire set must be completed before results can be generated. There are no tasks precedence constraints and therefore the total work may be packaged into a number of independent chunks.

Due to the independent nature of the chunks of a PSA, the user of a supercomputer center has many options in creating jobs for submission to the system. At one extreme, each chunk could be submitted as an independent job. At the other extreme, all chunks could be combined and submitted as a very wide parallel job, requesting as many processors as the number of chunks. In between, a range of possibilities exist - the total number of jobs submitted can vary from one to the number of chunks; further, each jobs can be shaped to be short and very wide (requesting many processors) or narrow and long (requesting few processors). A significant consideration is that most supercomputer centers impose "fair-share" constraints, that limit the total number of simultaneous jobs or the number of processors requested by the collection of simultaneously queued/active jobs of a user. If the center imposes limits on the number of simultaneously active jobs of a user, users submit one or a few parallel jobs that include the chunks of the PSA. Since the scheduling system does not identify such jobs as PSA jobs, they can only be started when the requested number of processors is available - opportunities to start off independent chunks of a PSA job on available idle processors cannot be utilized.
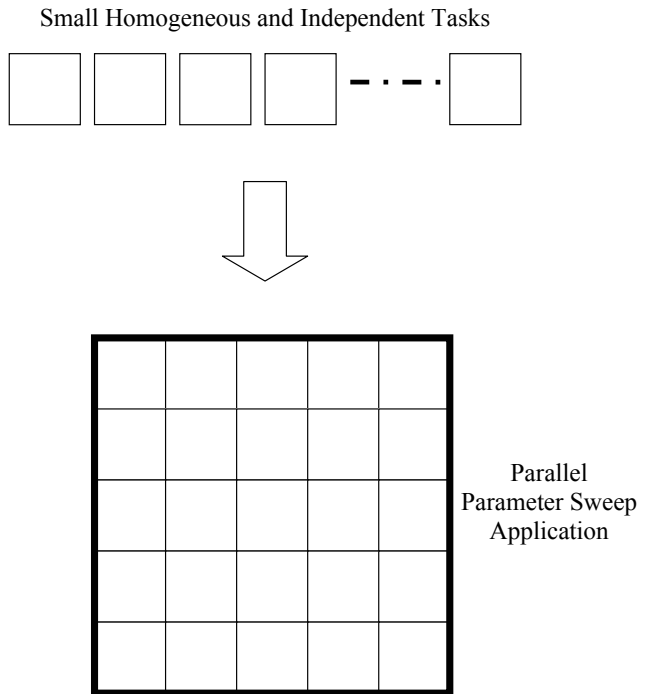
Small Homogeneous and Independent Tasks

Figure 2. Parameter Sweep Application Formation

Systems like Nimrod/G and APST, that support the execu-

tion of PSA's, have primarily targeted a grid environment. Nimrod/G proposed the use of an economic model in determining where the chunks of a PSA job are to be executed - a cost is associated with execution on each of the potential execution sites, and chunks are dispatched to sites based on cost considerations. APST too primarily targets a grid environment, and uses a load monitoring service such as Network Weather Service (NWS) to determine dynamic processor and network load information. The scheduling of the chunks of a PSA job is done using estimates of response time at various sites. Thus the scheduling strategy may be categorized as a greedy approach that attempts to minimize the response time of the PSA job, without any global considerations regarding other jobs. Although a system like APST could be configured to interact with job schedulers at supercomputer centers, its greedy strategy of disributing chunks of a PSA job can be expected to have an adverse effect on the regular non-PSA jobs submitted to the supercomputer centers. The problem we address in this paper is the development of a scheduling strategy that can exploit the independence characteristic of the chunks of a PSA job to improve its performance and and that of the system, without much degradation of non-PSA jobs.

4 Proposed Scheme

A naive and simple approach to take advantage of the benefits of the PSA jobs is a flooding based scheme where the PSA jobs are shred into a number of small tasks. These tasks are then submitted to the supercomputer center as independent sequential jobs. We'll refer to this approach as the **"Flooding-based approach"**. As we'll see in the later sections, this approach not only improves the average turnaround time and slow down, in general, for the PSA jobs but also benefits the overall system metrics such as the Loss of Capacity (LOC) due to better back-filling. However, this scheme gives an unfair advantage to the PSA jobs by allowing them to flood the schedule and does little to ensure fairness for the other Non-PSA jobs.

To remedy this we propose a simple and novel scheme. The basic idea of the scheme is to allow the PSA jobs to shred and back-fill as long as they don't hamper the back-fill opportunities for the Non-PSA jobs. The focus of the scheme is to take benefit of the inherent characteristics of the PSA jobs without affecting the Non-PSA jobs significantly. We term this new scheme as **"Opportune Job Shredding"**. In this model, we use an application-level scheduler similar to APST or NIMROD/G which continuously monitors the current state of the schedule looking for opportunities for the tasks in the PSA jobs to back-fill. If at the current time, the application-level scheduler finds a hole to fit in one or more of the PSA tasks, these tasks are shred from their parent PSA job and allowed to back-fill and fill up the hole.

To demonstrate the functionality of the Application-level scheduler, let us consider a PSA job using 'p' processors and running for 'nT' time units. Lets assume that this can be broken into 'pn' number of independent sequential tasks, each running for 'T' time units. When this PSA job is submitted, the supercomputer center follows its own mechanism to schedule this "parallel" job together with the other submitted jobs. During the scheduling event, a copy of the PSA job is also given to the Application-level scheduler which continuously monitors the state of the schedule. Whenever a hole big enough to contain one or more of the tasks in the PSA job is available at the current execution time, the tasks are shred from the PSA job are allowed to back-fill to be executed. When the PSA job reaches its actual execution time, it coordinates with the Application-level scheduler and executes only the tasks which have not already been executed by the Application-level scheduler. This might result in the PSA job terminating before its estimated execution time, depending on the number of tasks that were able to back-fill.

For the multi-cluster scenario, we extend this model to have a two-stage hierarchy of Application-level schedulers (Figure 3). Each supercomputer center is associated with a local application-level scheduler. Together with this, there's also a higher level meta-application-level scheduler. When a PSA job is submitted to one cluster, multiple copies of the job are created and submitted simultaneously to all the participating clusters. The local application-level schedulers try to schedule this PSA job on the cluster as described in the single-site scenario. However, the distribution of the tasks of a single PSA job over different clusters is taken care by the meta-scheduler.

Consider a PSA job using 'p' processors and running for 'nT' time units. Lets again assume that this can be broken into 'pn' number of independent sequential tasks, each running for 'T' time units. As explained earlier, when the job is submitted to the supercomputer center, and is scheduled with the other jobs, a copy of the job is also given to the local application-level scheduler. However, now the local application-level scheduler forwards a copy of the job to the local application-level schedulers on the other participating clusters and informs the meta-scheduler about this. Each local application-level scheduler tries to schedule the PSA job in it's cluster and informs the meta-scheduler every time it completes a task in the PSA job. The meta-scheduler explicitly exchanges information with each local application-level scheduler to make sure that the tasks executed on one cluster are not re-executed on the others. Once all the tasks of the PSA job are executed (potentially in parts on the different clusters), all the local application-level schedulers are notified.

It is to be noted that, this scheme does not modify the ex-
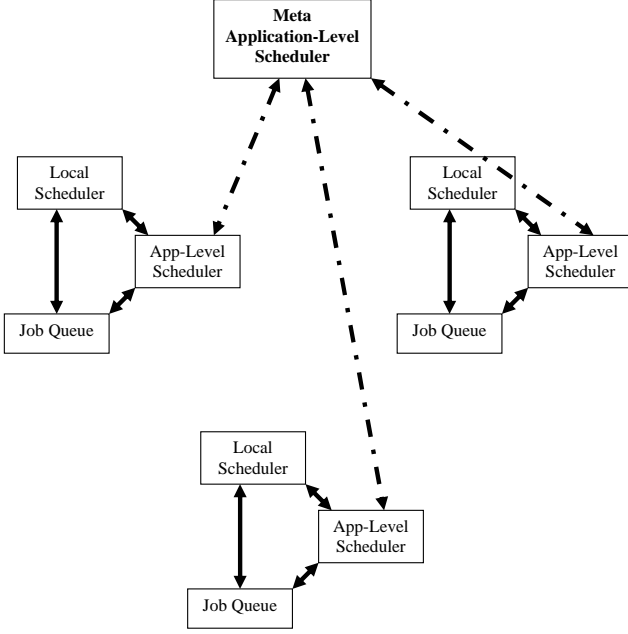
Figure 3. Hierarchical Application-Level Schedulers for Multi-Site Scheduling

isting scheduling mechanisms at the clusters. It relies on an external application-level scheduler which keeps track of the current schedule of the cluster to support the "Opportune Job Shredding" model for PSA jobs. Further, in the multi-cluster scenario, it allows each of the clusters to have a different processing power, both in terms of the number of nodes available and also the processing speed of the nodes.

An interesting scenario is when a PSA job is submitted to a cluster and one of the participating clusters does not have enough processors to support this job. For example, lets consider that the LANL cluster, the San Diego Supercomputing Center (SDSC) and the Cornell Theory Center (CTC) are the participating clusters. The LANL cluster has 1024 processors. It is possible that a PSA job requesting 800 processors is submitted to this cluster. However, the Cornell Theory Center only has 512 processors and would not be able to support this job as it is. In such a scenario, we take advantage of the moldability of the PSA jobs to reassemble the tasks in the PSA job to form a 512 processor parallel job and submit a copy to CTC.

An issue worth noting is the scheduling algorithm used by the Application-level scheduler for scheduling the PSA jobs. In most cases this decision depends on the workload characteristics of the supercomputer center in which it's used. However, in this paper, we demonstrate three different scheduling algorithms for the Application-level scheduler: First Come First Served (FCFS), Round-Robin (RR) and Shortest Job First (SJF). For clusters where short PSA

jobs being greatly delayed due to a larger PSA job being ahead of it in the queue is a common case, RR or SJF might help improve the average Slowdown and Turn-around times of the jobs.

5 Experimental Results

In this section we use a simulation based approach to evaluate the impacts of the two schemes, "Flooding-based Job Shredding" and "Opportune Job Shredding", on both the PSA jobs and the Non-PSA jobs. We also study the impact of the schemes on the different categories of the jobs within the PSA and Non-PSA jobs, such as short-narrow, short-wide, long-narrow and long-wide. The simulations for Sections 5.1 and 5.2 were carried out on a 5000-job subset of the CTC trace from Feitelson's archive. For Section 5.3, we used three 1-month subsets of the CTC trace. Throughout this section, a number of jobs using more than 8 processors are picked randomly and treated as PSA jobs. In general, the breakdown for the time taken by each task in the PSA job is specified by the PSA job. For example, a breakdown factor of 'b' means that the total runtime of the PSA jobs is 'b' times the runtime of each task. In other words, the PSA job can be broken down into 'b' tasks along the time axis. We chose a value of 10 for 'b' in all our experiments.

We have concentrated mainly on three metrics for evaluating the two schemes. The first two are user-metrics: the turn-around time and the slowdown of the job. The turn-around time of the job is the difference between the time when the job is submitted to the cluster and the time when it completes its execution. The slowdown of the job is defined as the ratio of the turn-around time and the runtime.

The third metric is the Loss of Capacity (LOC) of the system. This metric is defined as zero if the number of queued jobs is zero. Otherwise, it's calculated as follows: If at the current time, there are a number of jobs queued which totally require 'p' processors and there are 'q' idle processors in the cluster, then

$\Delta LOC = \min\{p, q\}$ x ΔT, where ΔT is the time for which this state lasts.

The Loss of Capacity of the system is the summation of ΔLOC over the time of interest. The reason we have chosen this metric instead of the Utilization metric is the nature of the submissions of the jobs to the cluster. As described earlier, studies have shown that the submission pattern of jobs by users to the cluster tends to be bursty. In particular, the number of jobs submitted tends to be high during the day, peak somewhere in the evenings and decrease to a low during the night [12]. Assuming that the cluster is not in a state of super-saturation (where the number of jobs submitted is far greater than the resources available, resulting in a continuous and non-terminating increase in the job queue length), the jobs piled during the day time can be expected

to be completed during the nights. This results in roughly a 50% Utilization for a number of clusters and is relatively invariant with most alternate schemes.

5.1 Flooding-based Approach

This section shows the impact of the "flooding-based scheme" on the user-metrics for both the PSA jobs as well as the non-PSA jobs and the overall system metrics.

Figure 4 shows the average turn-around time and the average slow-down of the PSA and the Non-PSA jobs when 5% of the jobs are PSA jobs. It can be easily noted that though this scheme significantly improves both the user-metrics for the PSA jobs as well as the overall system metrics such as Loss of Capacity (Figure 7), it significantly hampers the performance of the Non-PSA jobs.

Figures 5 and 6 show similar trends for the cases when 10% and 20% of the jobs are PSA jobs respectively. Further, it can also be seen that as the percentage of the PSA jobs increases, the benefit the PSA jobs are able to achieve also decreases significantly. We can also notice a drop in the improvement of the turn-around time for the PSA jobs as load increases. These observations show that this scheme might not be scalable to more constraining situations.
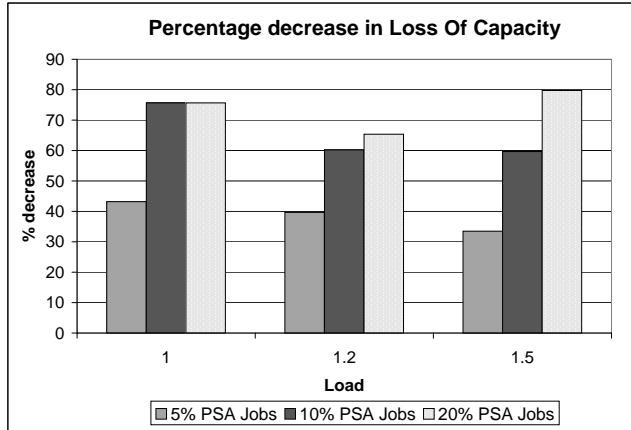
Figure 7. Flooding-based Job Shredding (Exact User Estimate): Loss of Capacity

Though both the turn-around time and the slow-down metrics suffer for the Non-PSA jobs, it is to be noted that the degradation in the slow-down is considerably higher compared to that of the turn-around time. For a clearer understanding of the reason for this, we look at the effect of the flooding-based approach on the various categories of the Non-PSA jobs such as the short-wide, short-narrow, long-wide and the long-narrow jobs.

The jobs are categorized along two dimensions: the number of processors they use and their execution time. Jobs

using lesser than 32 processors are categorized as "narrow" and the others as "wide". Similarly, jobs having execution times lesser than one hour are categorized as "short" and the others as "long". Figure 8 shows the average turn-around time and the average slow-down for the different categories of the jobs. It can be seen that the "short-narrow" jobs suffer much more than the other categories. The reason for this is the reduction in the number of back-fill opportunities available for the "short-narrow" jobs. This category of jobs typically have the most opportunities to back-fill due to their small structure. However, with the advent of the PSA jobs, the multiple segments forming the PSA job are flooded into the network. These segments use up the holes present in the schedule, denying the "short-narrow" Non-PSA jobs present in the schedule of their opportunities to back-fill.

Figures 9 and 10 the category wise breakup for the Non-PSA jobs for the cases with 10% and 20% PSA jobs respectively. These results again point to the conclusion that though a naive approach such as this can improve the performance of the PSA jobs and that of the overall system (in the form of system metrics such as the Loss of Capacity), it adversely affects the performance of the Non-PSA jobs, especially when the percentage of the PSA jobs is high.

5.2 Opportune Job Shredding

As mentioned earlier, the basic idea of the Opportune Job Shredding scheme is to allow the PSA jobs to shred and back-fill as long as they don't hamper the back-fill opportunities for the Non-PSA jobs. This section shows the impact of the "Opportune Job-Shredding scheme" on the user-metrics for both the PSA jobs and the non-PSA jobs and the overall Loss of Capacity of the system.

Figure 11 shows the average turn-around time and the average slow-down of the PSA and the Non-PSA jobs when 5% of the jobs are PSA jobs. It can be seen that while this scheme continues to improve the performance of the PSA jobs significantly, it does not adversely affect that of the Non-PSA jobs. The degradation of the performance of the Non-PSA jobs is less than 4% in all cases. In fact, in most cases the better back-filling the scheme allows, results in an improvement in performance for the Non-PSA jobs as well.

Figures 12 and 13 show the impact of the Opportune Job Shredding scheme for the cases when 10% and 20% of the jobs are PSA jobs respectively. It can be seen that the trend continues even for these cases.

To fully understand the impact of the Opportune Job Shredding scheme on the Non-PSA jobs, we'll now look at the impact of the scheme on the various categories of the Non-PSA jobs such as "short-narrow", "short-wide", etc. Figure 15 shows the impact of the scheme on the various categories of the Non-PSA jobs in the case when there are 5% PSA jobs. It can be seen that neither of the categories
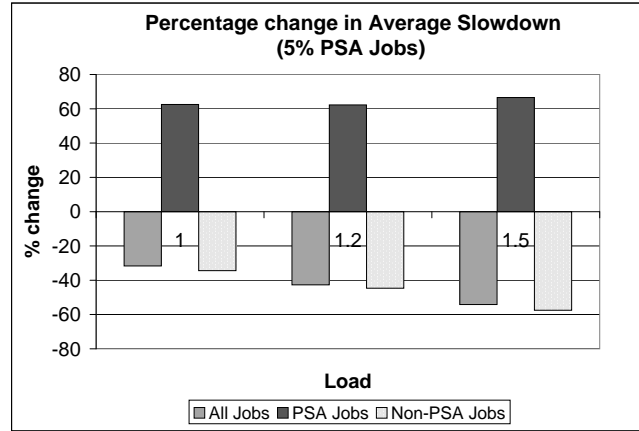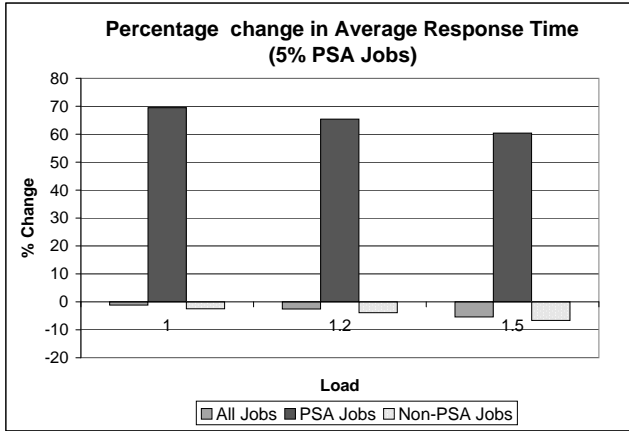
Figure 4. Flooding-based Job Shredding (5% PSA Jobs, Exact User Estimate): (a) Average Response Time; (b) Average Slow Down
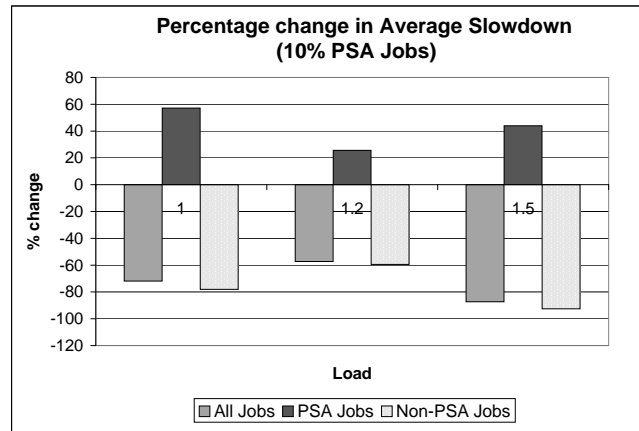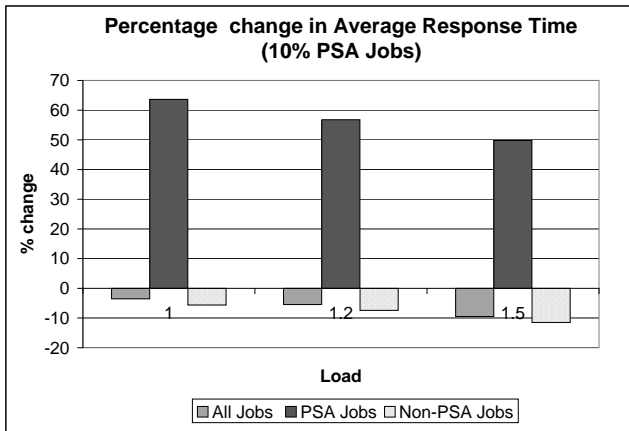
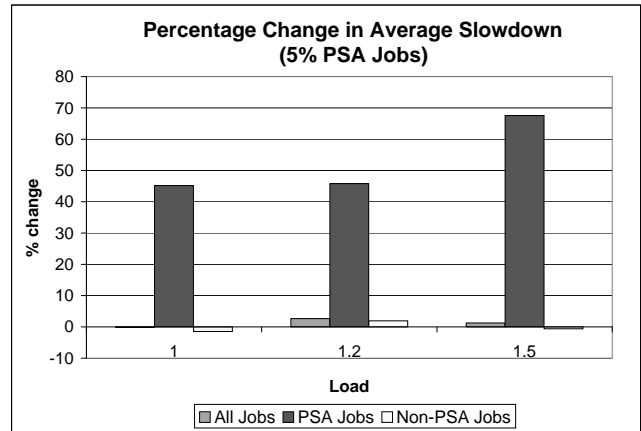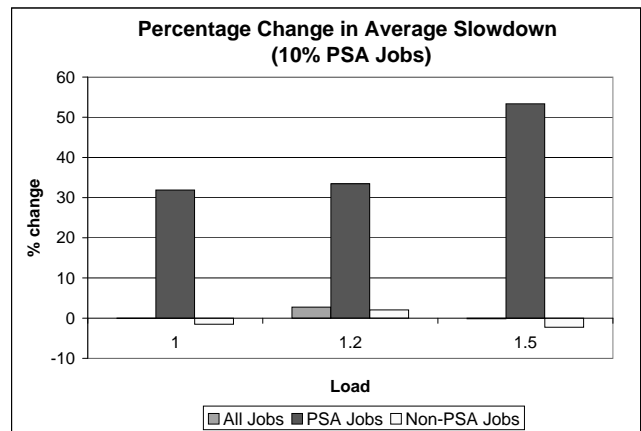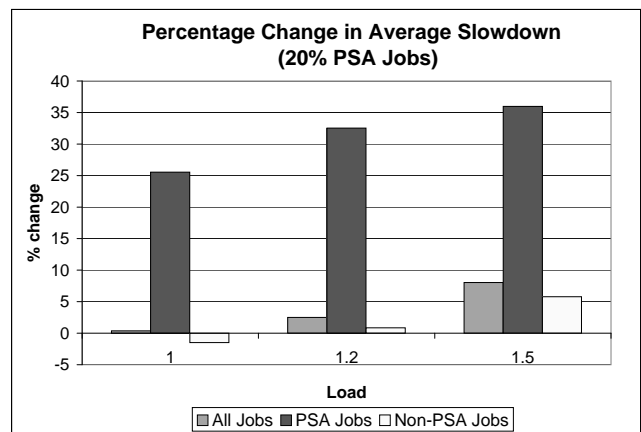**Figure 5. Flooding-based Job Shredding (10% PSA Jobs, Exact User Estimate): (a) Average Response Time; (b) Average Slow Down**
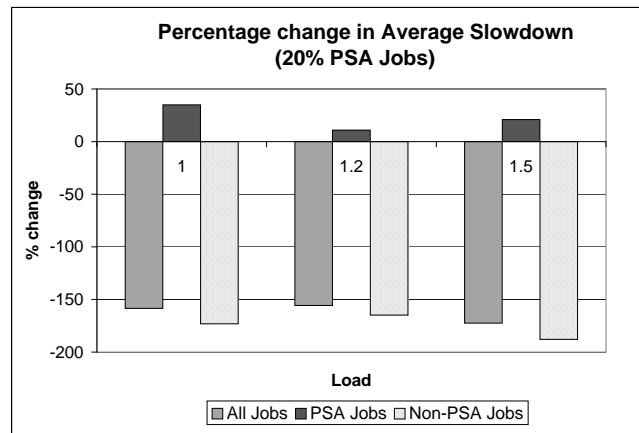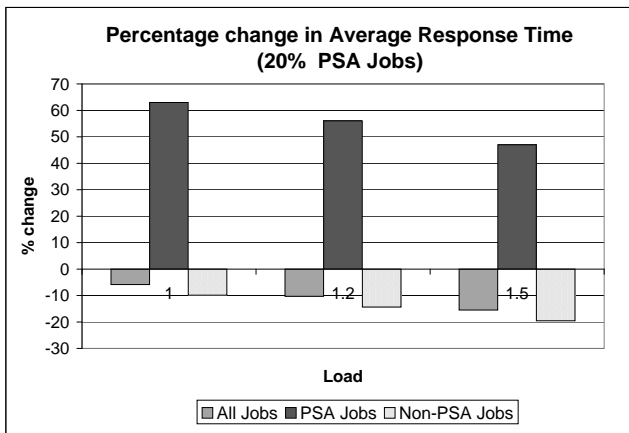
Figure 6. Flooding-based Job Shredding (20% PSA Jobs, Exact User Estimate): (a) Average Response Time; (b) Average Slow Down
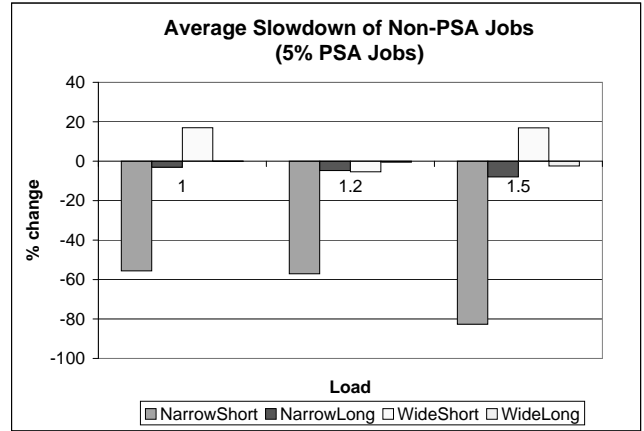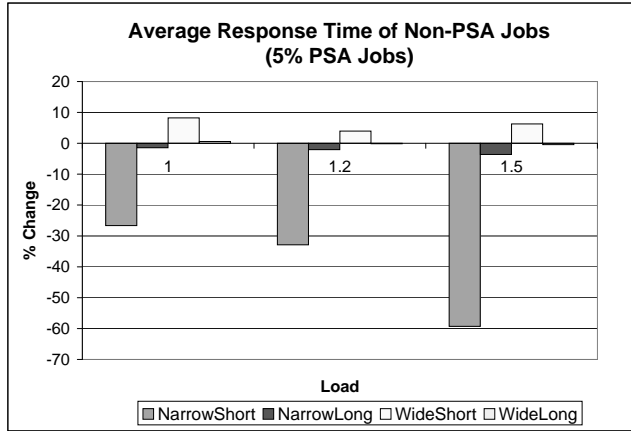
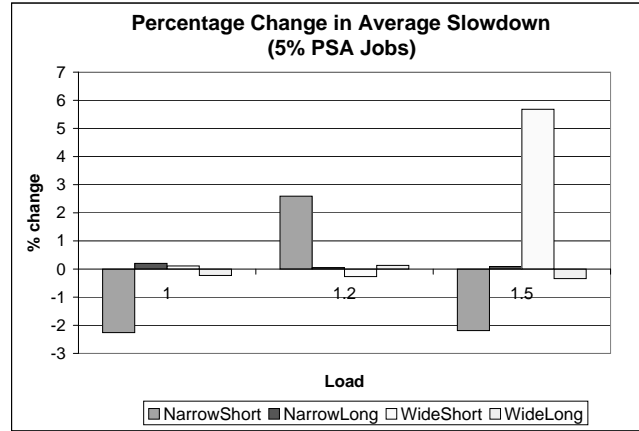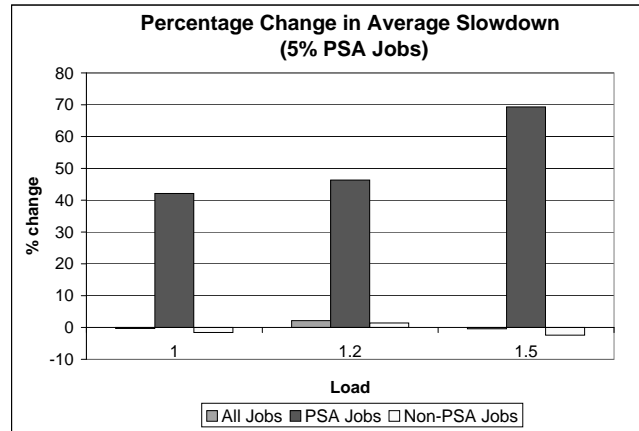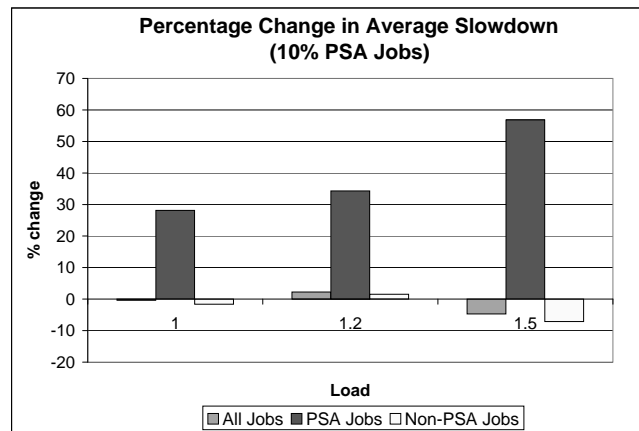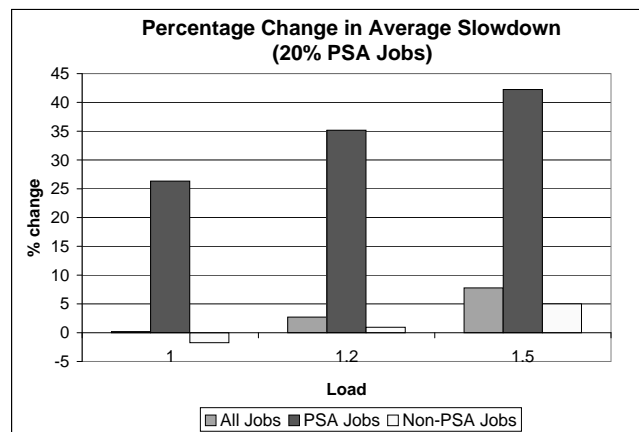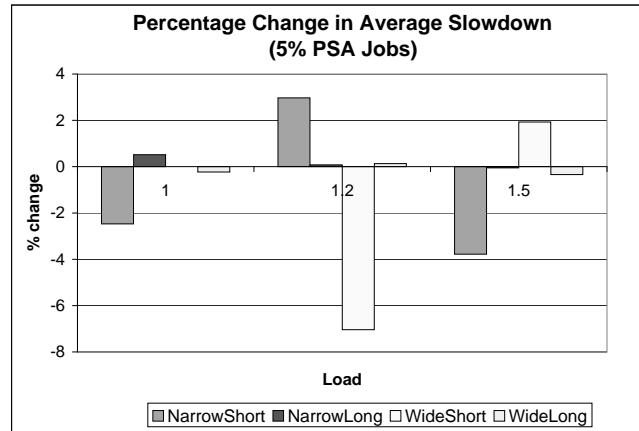**Figure 8. Flooding-based Job Shredding (5% PSA Jobs, Exact User Estimate), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down**
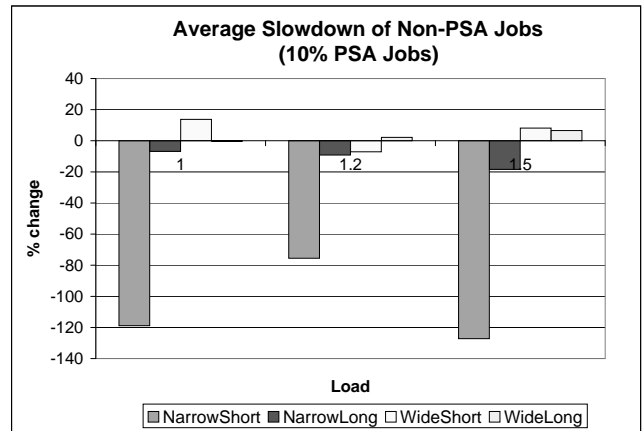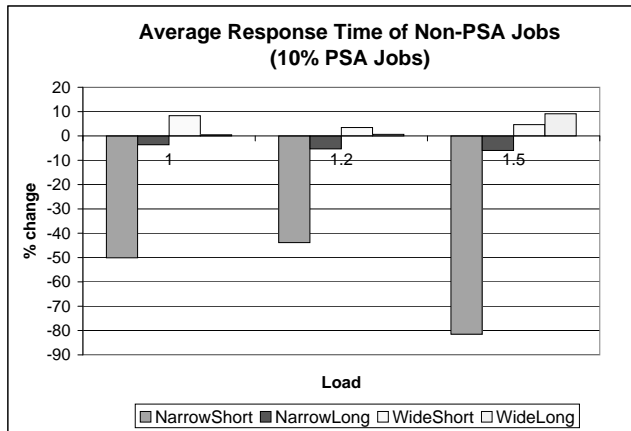
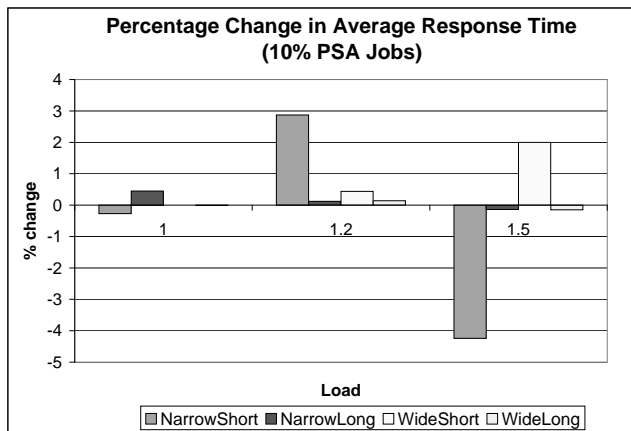**Figure 9. Flooding-based Job Shredding (10% PSA Jobs, Exact User Estimate), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down**
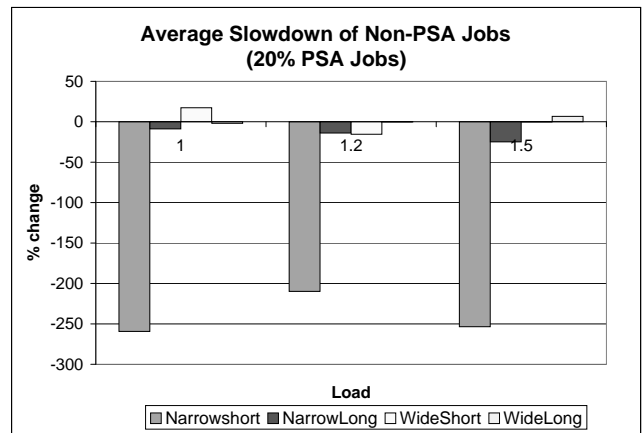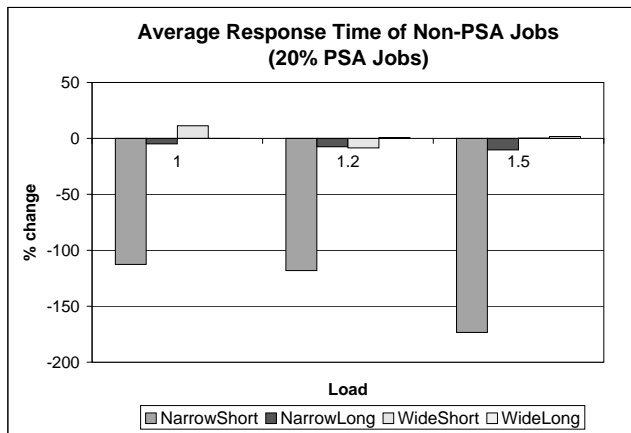
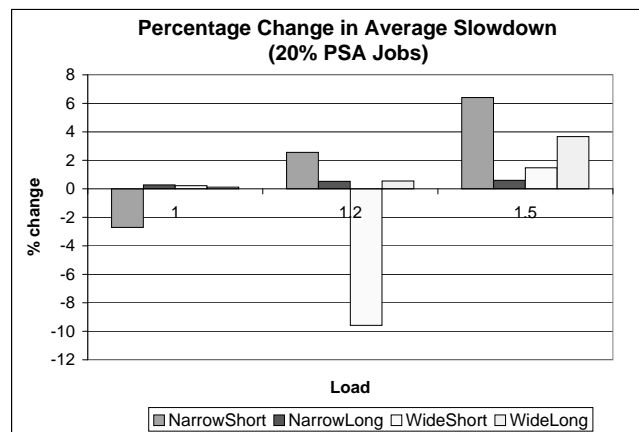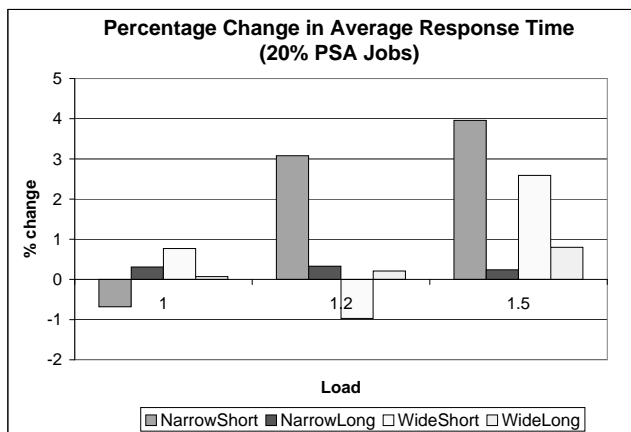**Figure 10. Flooding-based Job Shredding (20% PSA Jobs, Exact User Estimate), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down**
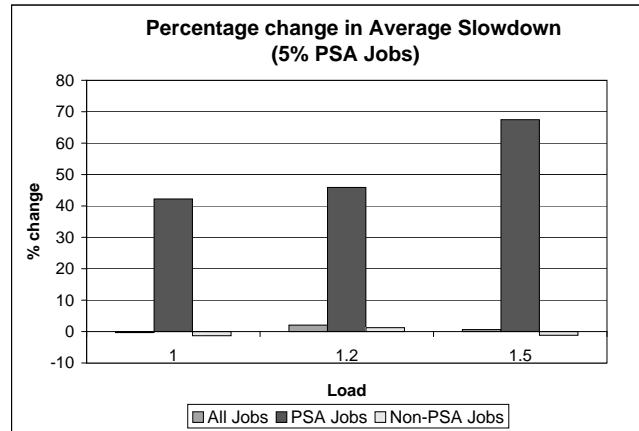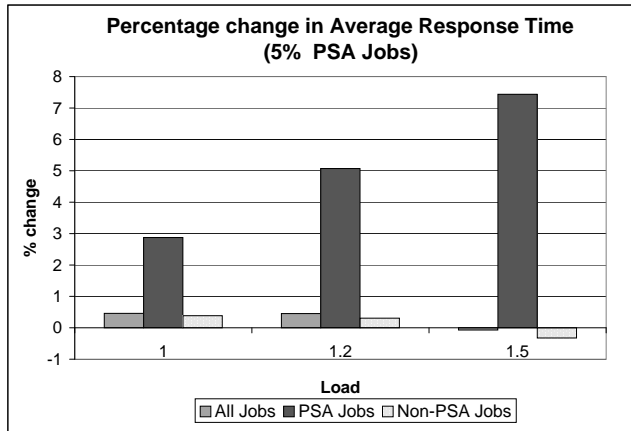
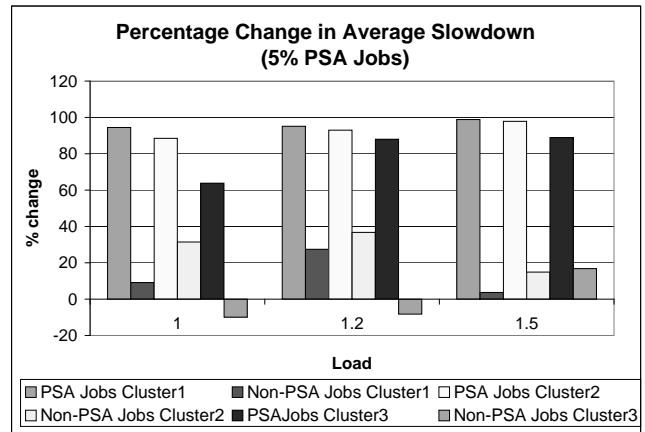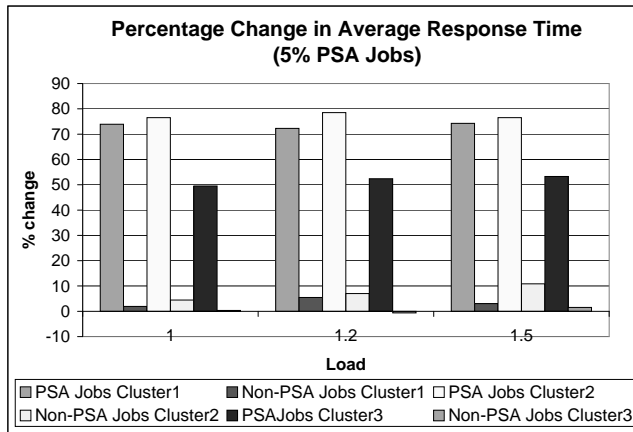**Figure 11. Opportune Job Shredding (5% PSA Jobs, Exact User Estimate, FCFS priority scheme): (a) Average Response Time; (b) Average Slow Down**
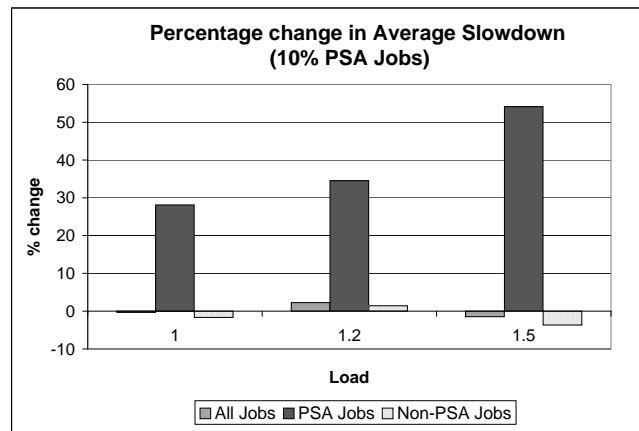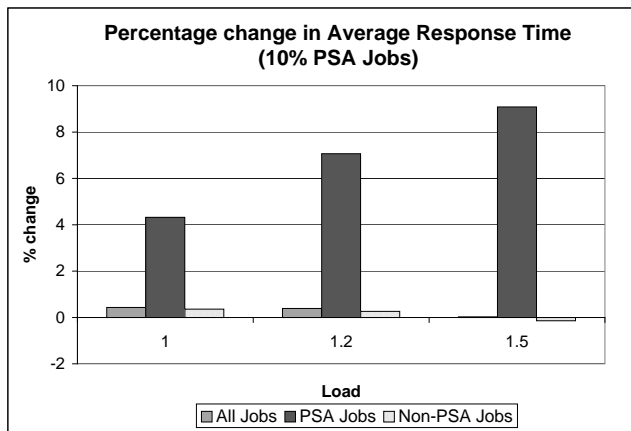
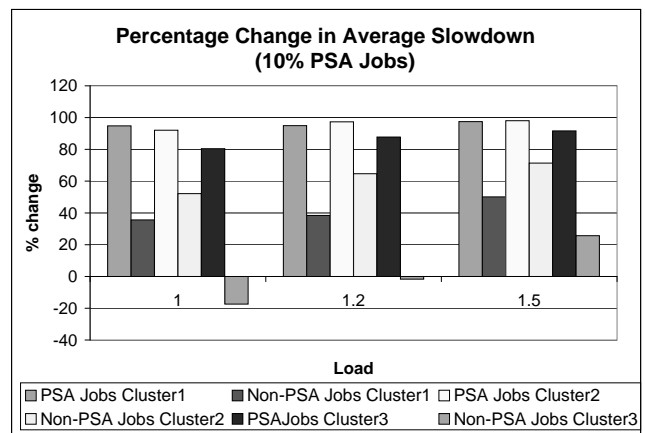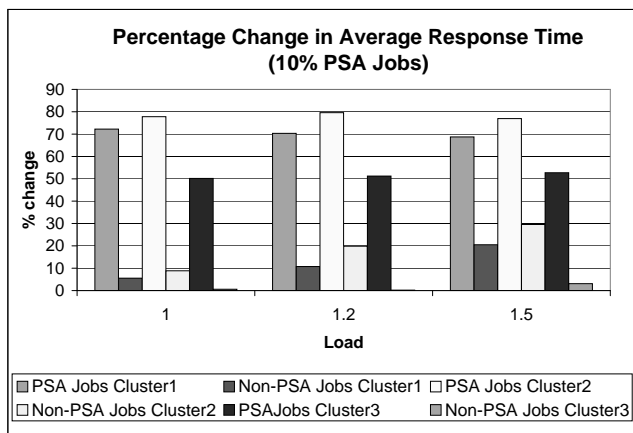**Figure 12. Opportune Job Shredding (10% PSA Jobs, Exact User Estimate, FCFS priority scheme): (a) Average Response Time; (b) Average Slow Down**
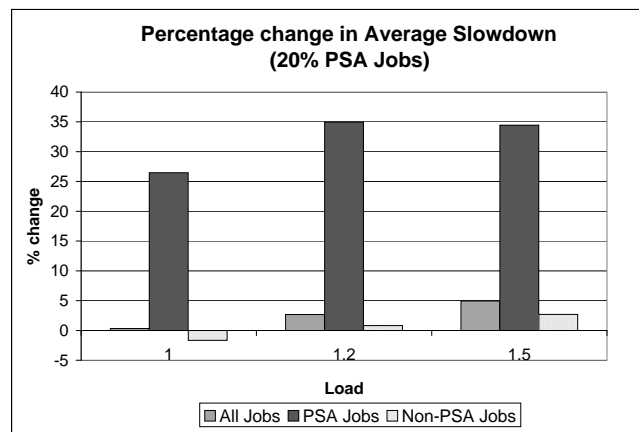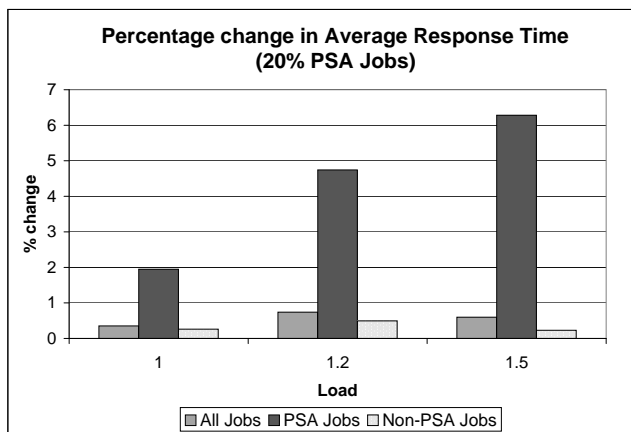
Figure 13. Opportune Job Shredding (20% PSA Jobs, Exact User Estimate, FCFS priority scheme): (a) Average Response Time; (b) Average Slow Down
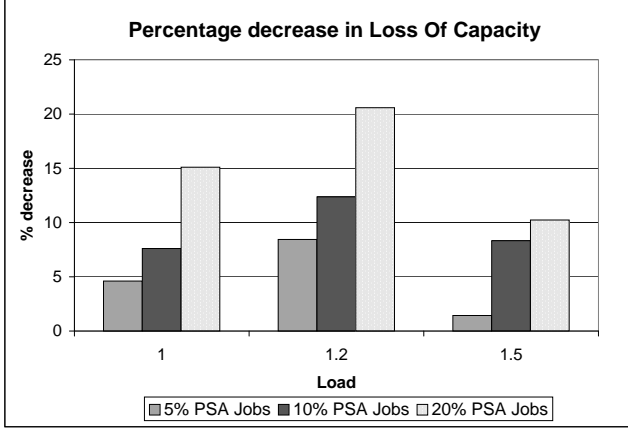
Figure 14. Opportune Job Shredding (Exact User Estimate, FCFS priority scheme): Loss of Capacity
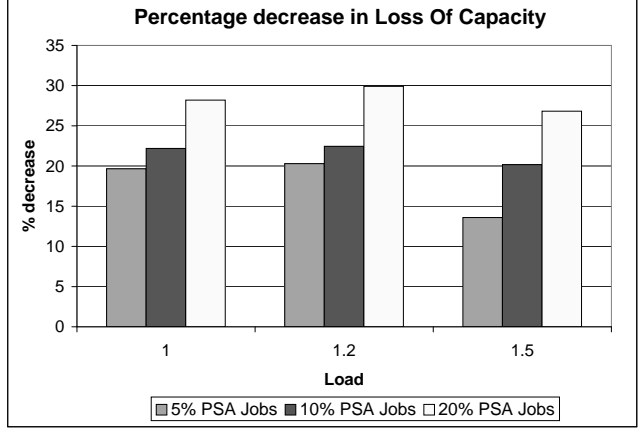
Figure 28. Opportune Job Shredding (Exact User Estimate, SJF priority scheme): Loss of Capacity

suffer more than 2.5% for the turn-around time and more than 10% for the slowdown.

Figures 16 and 17 show similar results for the cases when there are 10% and 20% PSA jobs respectively. Even as the percentage of the PSA jobs increases, the Non-PSA jobs do not suffer greatly.

Figures 18 through 31 show the data for these cases when the priority scheme used between the PSA jobs is Round Robin (RR) and Shortest Job First (SJF) respectively.

**Figure 21. Opportune Job Shredding (Exact User Estimate, RR priority scheme): Loss of Capacity**

5.3 Multi-Site Evaluation

This section evaluates the Opportune Job Shredding scheme in a multi-cluster (or multi-site) environment. As described earlier, in a multi-cluster environment, whenever a PSA job is submitted, a copy of it is sent to the local Application-Level Scheduler of each of the clusters. These Application-Level Schedulers coordinate with the meta-scheduler to execute the different tasks of the application over the clusters. It is to be noted that this scheme is independent of the scheduling mechanism of the individual clusters and takes into consideration the different speeds at which the clusters might operate. Throughout this section, the simulated results correspond to that of three clusters formed by taking three 1-month subsets from the CTC trace. Also, to demonstrate the adaptability of the scheme to heterogeneity in processing speeds for the different clusters, we have considered the processing speeds of the three clusters to be in the ratio 2:1:3.

Figure 32 shows the Average Response Time and the Average Slow-Down of the PSA and Non-PSA jobs in the three clusters for the case when each cluster has 5% PSA jobs. It can be seen that while the performance of the PSA jobs has improved significantly, that of the Non-PSA jobs has hardly been affected. Figures 33 and 34 show similar results for the cases when each cluster has 10% and 20% PSA jobs respectively. The Loss of Capacity of the system is given in Figures 35 through 37.
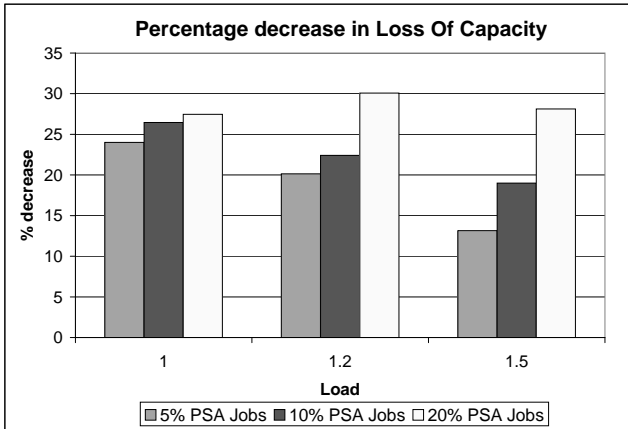
Percentage Change in Average Response Time (5% PSA Jobs)

NarrowShort ▪Narrow Long □WideShort □WideLong

Percentage Change in Average Slowdown (5% PSAJobs)

NarrowShort ▪NarrowLong □WideShort □WideLong

Figure 15. Opportune Job Shredding (5% PSA Jobs, Exact User Estimate, FCFS priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down

Percentage Change in Average Response Time (10% PSA Jobs)

NarrowShort ▪NarrowLong □WideShort □WideLong

Percentage Change in Average Slowdown (10% PSAJobs)

NarrowShort ▪NarrowLong □WideShort □WideLong
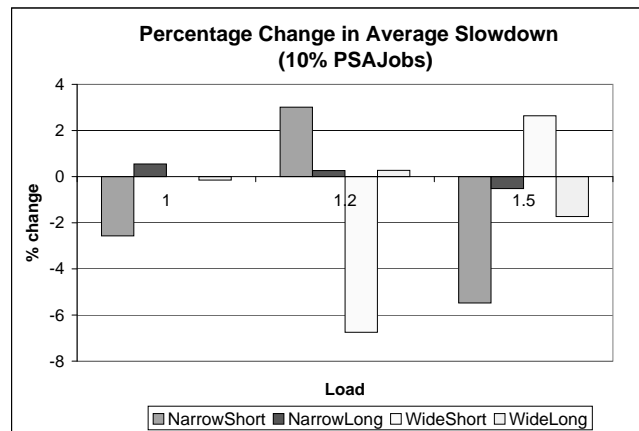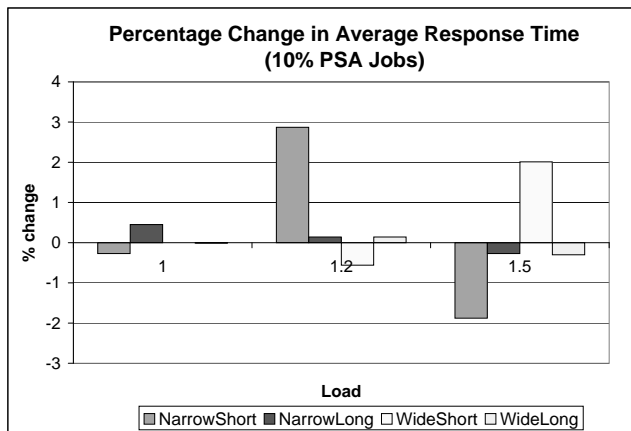
Figure 16. Opportune Job Shredding (10% PSA Jobs, Exact User Estimate, FCFS priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down

Percentage Change in Average Response Time (20% PSA Jobs)

NarrowShort ▪NarrowLong □WideShort □WideLong

Percentage Change in Average Slowdown (20% PSAJobs)

NarrowShort ▪NarrowLong □WideShort □WideLong
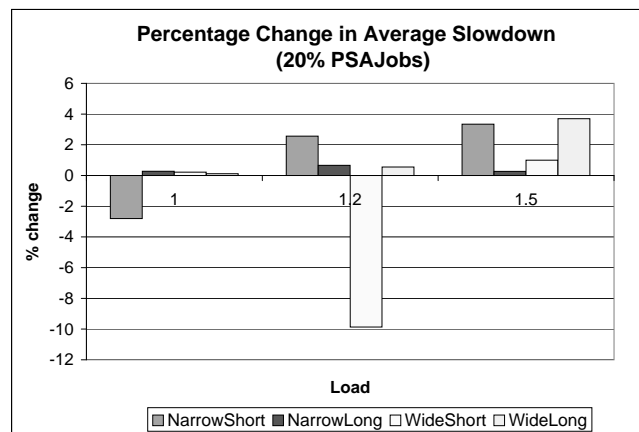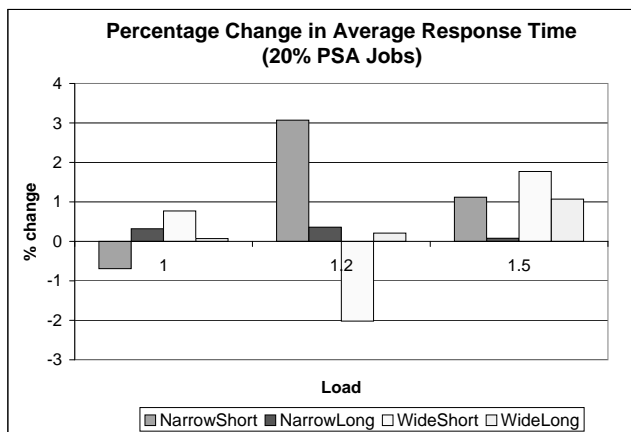
Figure 17. Opportune Job Shredding (20% PSA Jobs, Exact User Estimate, FCFS priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down
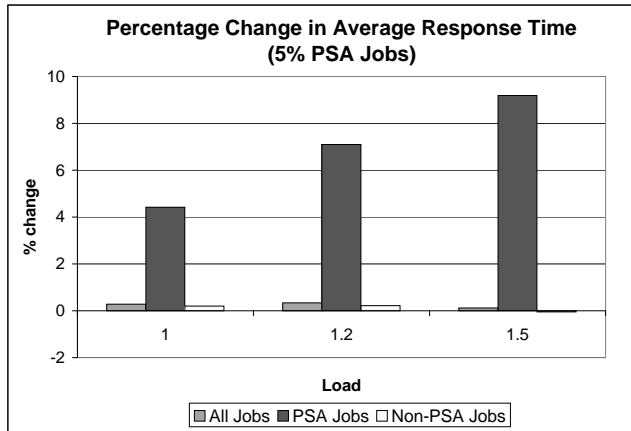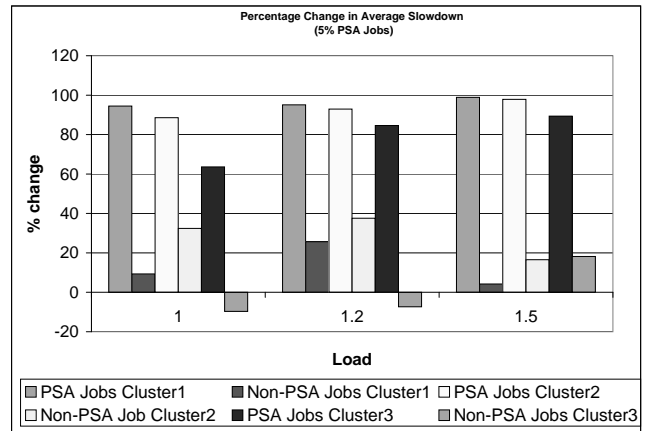
Figure 18. Opportune Job Shredding (5% PSA Jobs, Exact User Estimate, RR priority scheme): (a) Average Response Time; (b) Average Slow Down
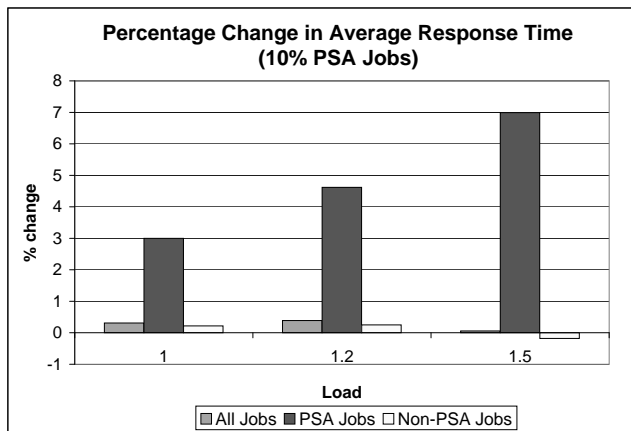
Figure 19. Opportune Job Shredding (10% PSA Jobs, Exact User Estimate, RR priority scheme): (a) Average Response Time; (b) Average Slow Down
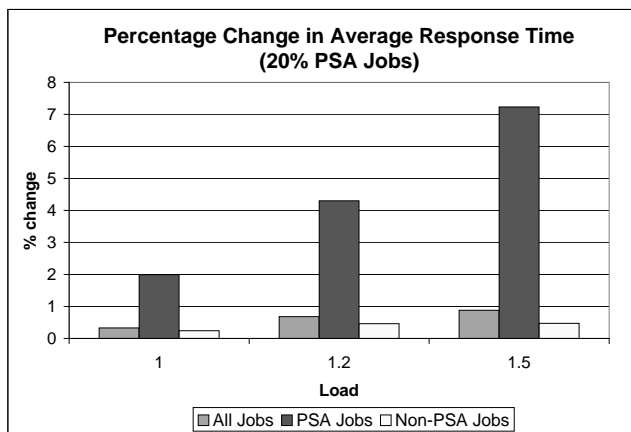
Figure 20. Opportune Job Shredding (20% PSA Jobs, Exact User Estimate, RR priority scheme): (a) Average Response Time; (b) Average Slow Down
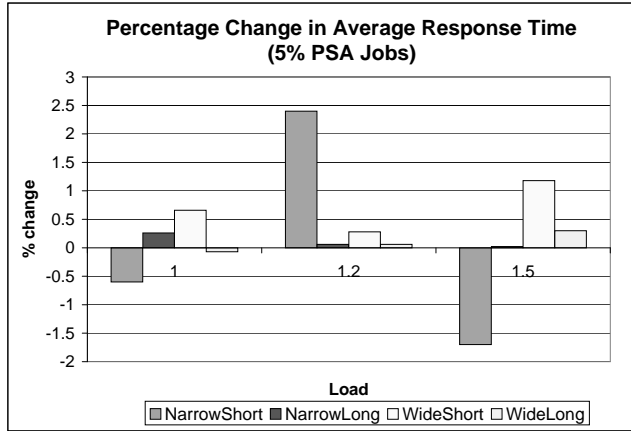
Figure 22. Opportune Job Shredding (5% PSA Jobs, Exact User Estimate, RR priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down
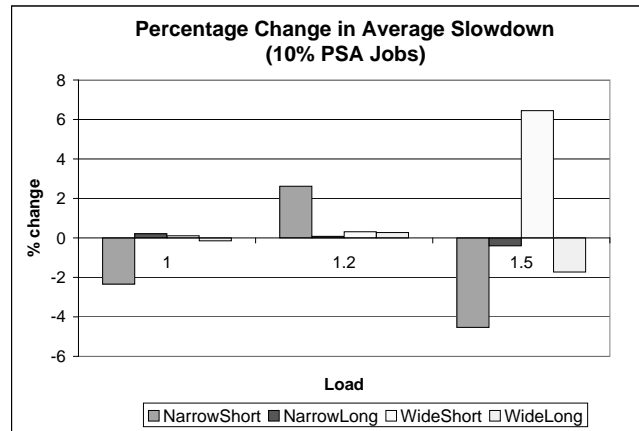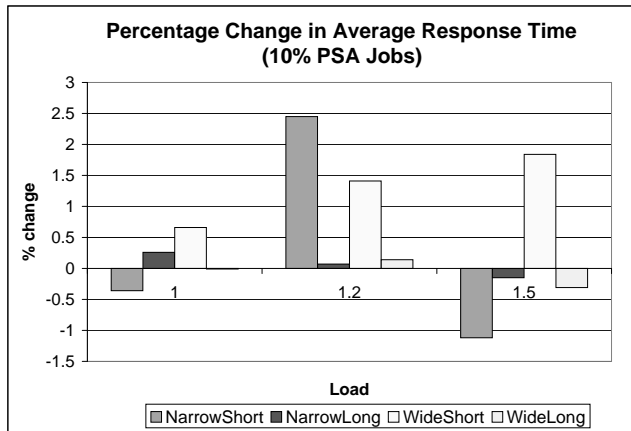
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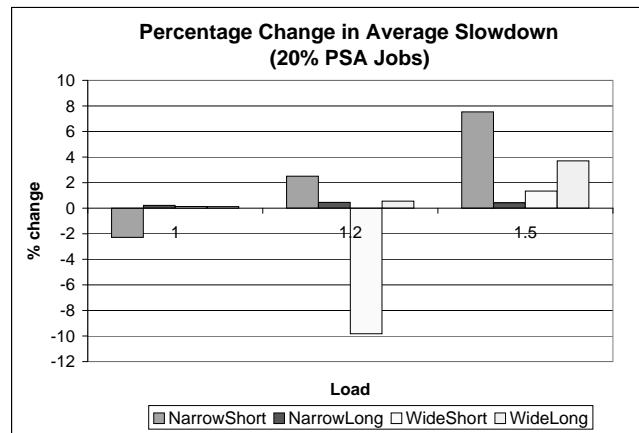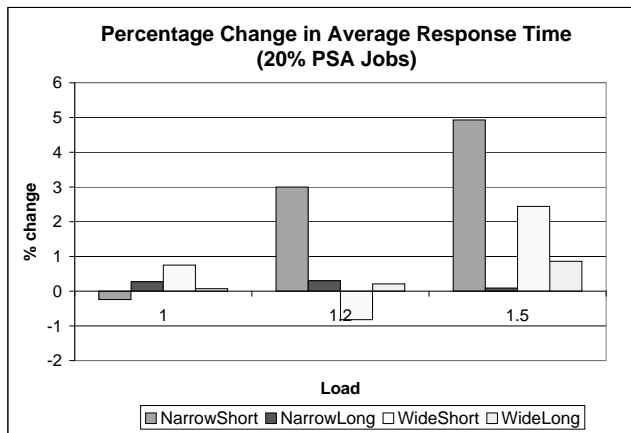
Figure 24. Opportune Job Shredding (20% PSA Jobs, Exact User Estimate, RR priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down
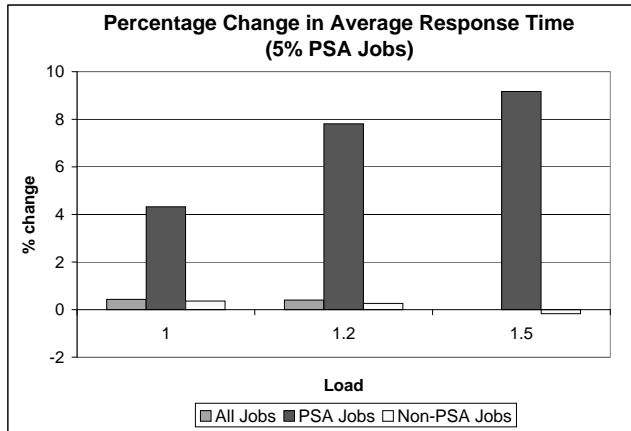
Figure 25. Opportune Job Shredding (5% PSA Jobs, Exact User Estimate, SJF priority scheme): (a) Average Response Time; (b) Average Slow Down
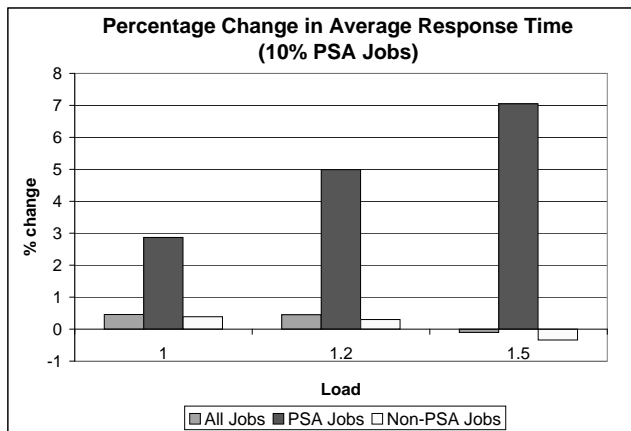
Figure 26. Opportune Job Shredding (10% PSA Jobs, Exact User Estimate, SJF priority scheme): (a) Average Response Time; (b) Average Slow Down
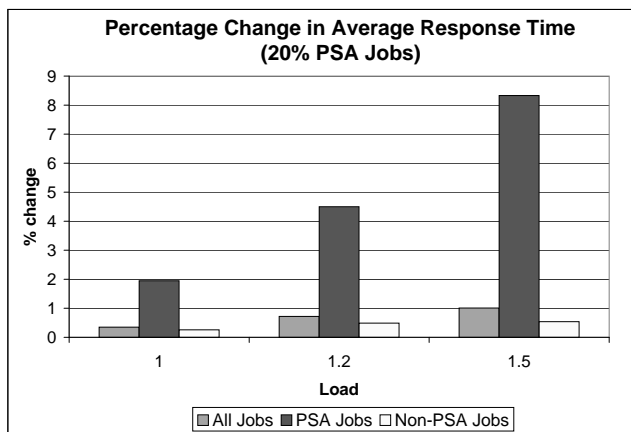
Figure 27. Opportune Job Shredding (20% PSA Jobs, Exact User Estimate, SJF priority scheme): (a) Average Response Time; (b) Average Slow Down
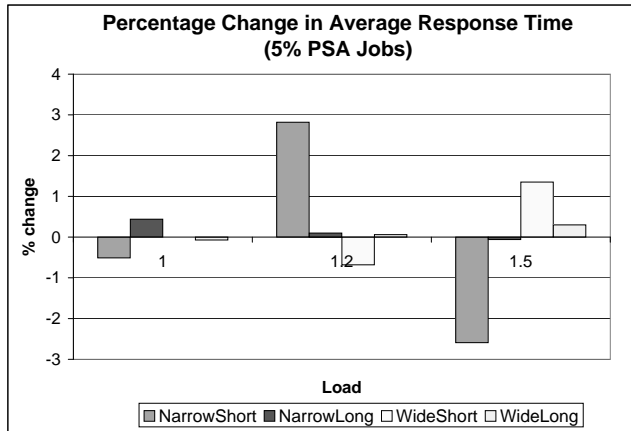
Figure 29. Opportune Job Shredding (5% PSA Jobs, Exact User Estimate, SJF priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down
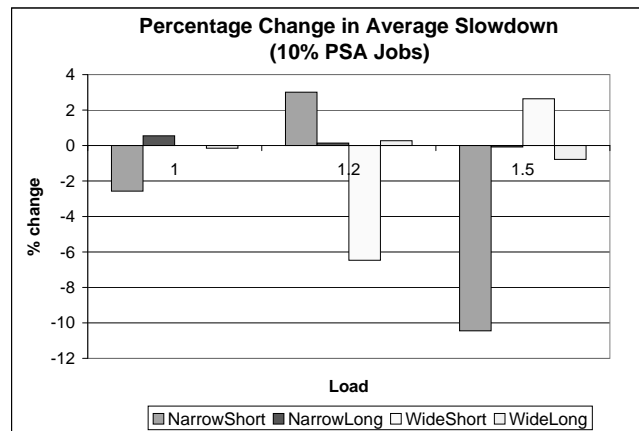
Figure 30. Opportune Job Shredding (10% PSA Jobs, Exact User Estimate, SJF priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down

Figure 31. Opportune Job Shredding (20% PSA Jobs, Exact User Estimate, SJF priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down

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Figure 32. Multi-Site Evaluation (5% PSA Jobs, Exact User Estimate, FCFS priority scheme): (a) Average Response Time; (b) Average Slow Down

Figure 33. Multi-Site Evaluation (10% PSA Jobs, Exact User Estimate, FCFS priority scheme): (a) Average Response Time; (b) Average Slow Down
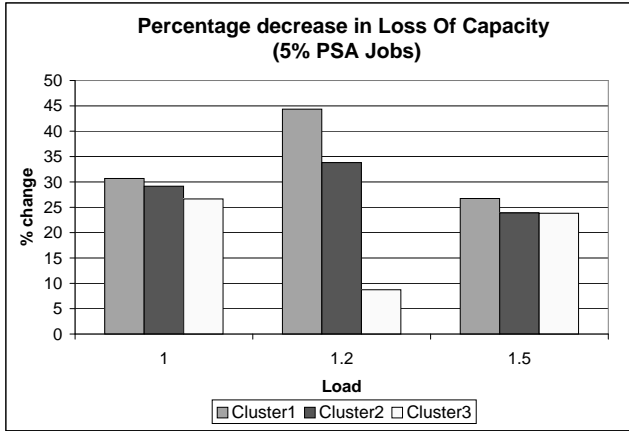
Figure 35. Multi-Site Evaluation (5% PSA Jobs, Exact User Estimate, FCFS priority scheme): Loss of Capacity
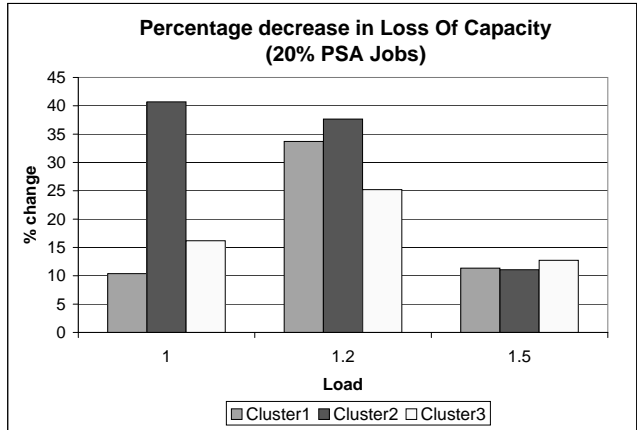
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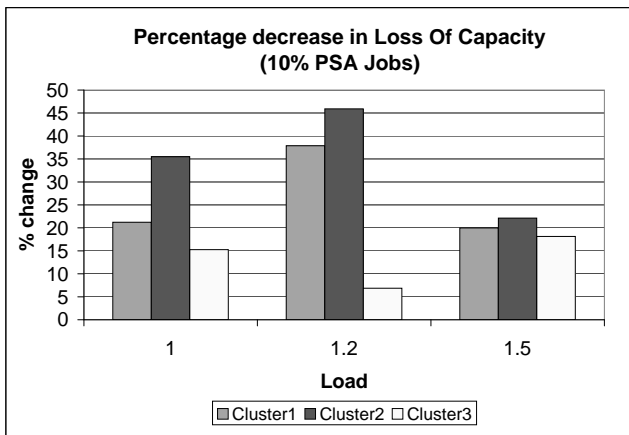
Figure 36. Multi-Site Evaluation (10% PSA Jobs, Exact User Estimate, FCFS priority scheme): Loss of Capacity

Figures 38 through 49 show the data for these cases when the priority scheme used between the PSA jobs is Round Robin (RR) and Shortest Job First (SJF) respectively.

6   Conclusions and Future Work

A number of applications comprise of several small independent and homogeneous tasks that need to be executed. However, most supercomputer centers enforce a restriction on the number of jobs a single user can submit to the cluster at any time in order to ensure that the resources of the center are not monopolized by a single user. Even if this constraint were relaxed, while PSA scheduling systems like
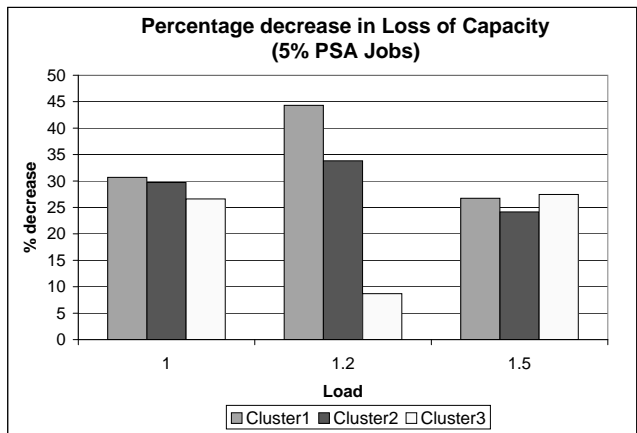
Figure 41. Multi-Site Evaluation (5% PSA Jobs, Exact User Estimate, RR priority scheme): Loss of Capacity

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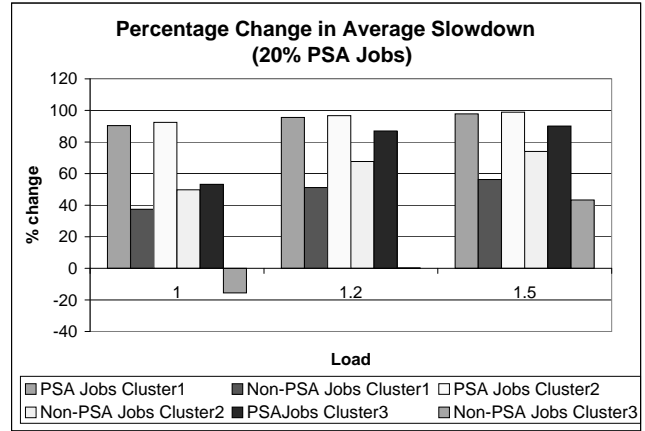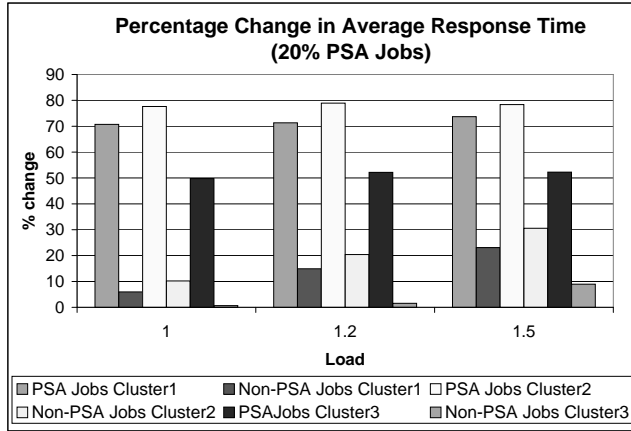
Figure 34. Multi-Site Evaluation (20% PSA Jobs, Exact User Estimate, FCFS priority scheme): (a) Average Response Time; (b) Average Slow Down
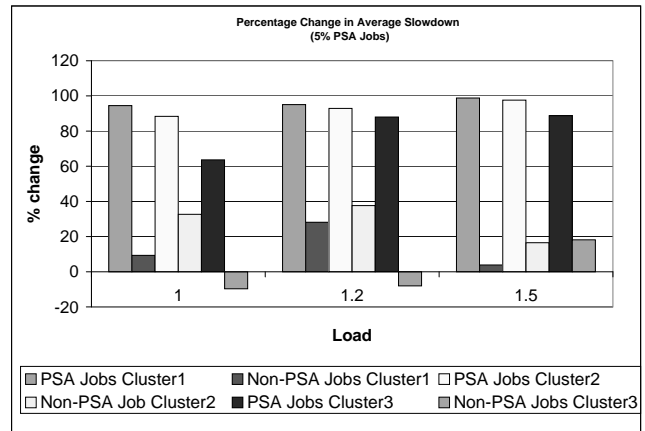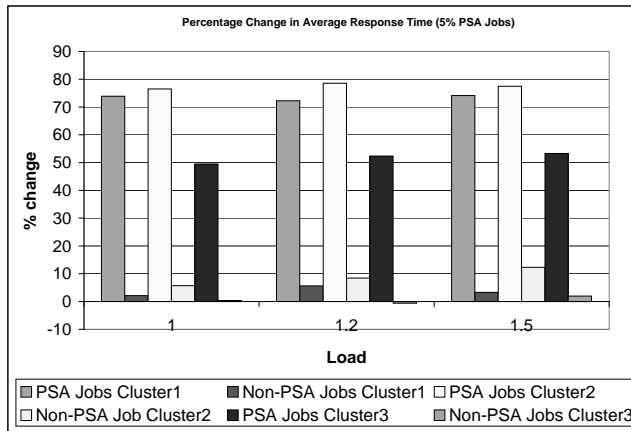
Figure 38. Multi-Site Evaluation (5% PSA Jobs, Exact User Estimate, RR priority scheme): (a) Average Response Time; (b) Average Slow Down
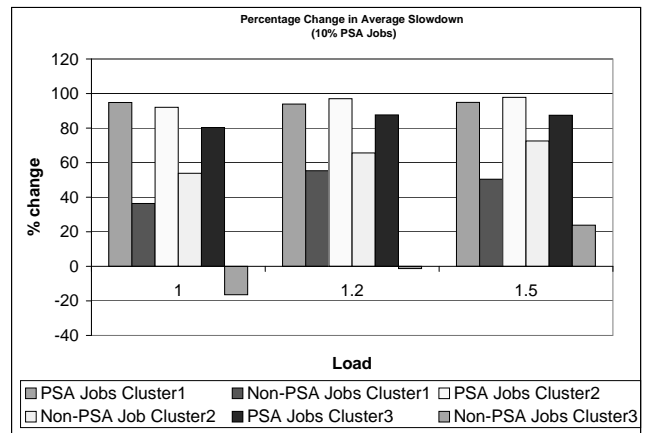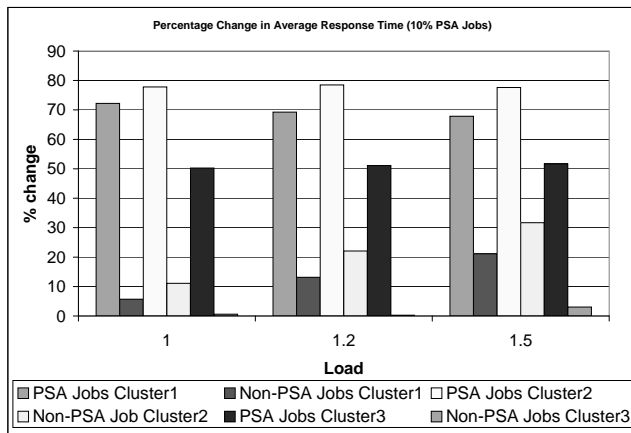
Figure 39. Multi-Site Evaluation (10% PSA Jobs, Exact User Estimate, RR priority scheme): (a) Average Response Time; (b) Average Slow Down
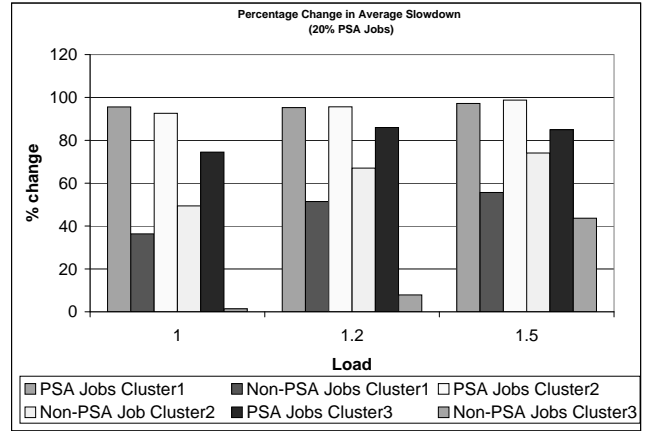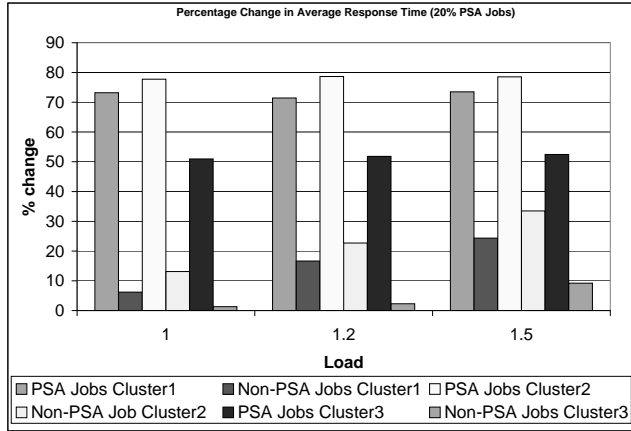
Figure 40. Multi-Site Evaluation (20% PSA Jobs, Exact User Estimate, RR priority scheme): (a) Average Response Time; (b) Average Slow Down
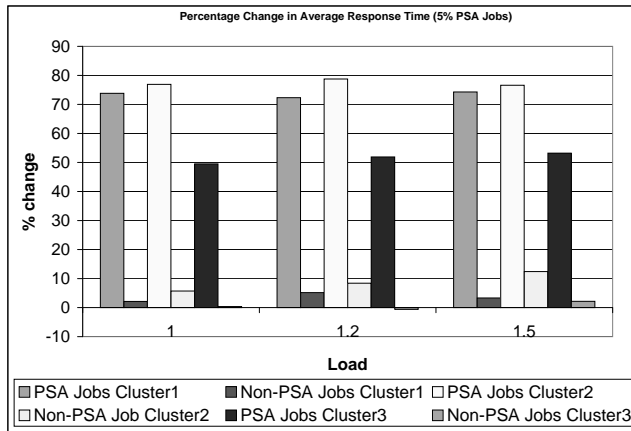
Figure 44. Multi-Site Evaluation (5% PSA Jobs, Exact User Estimate, SJF priority scheme): (a) Average Response Time; (b) Average Slow Down
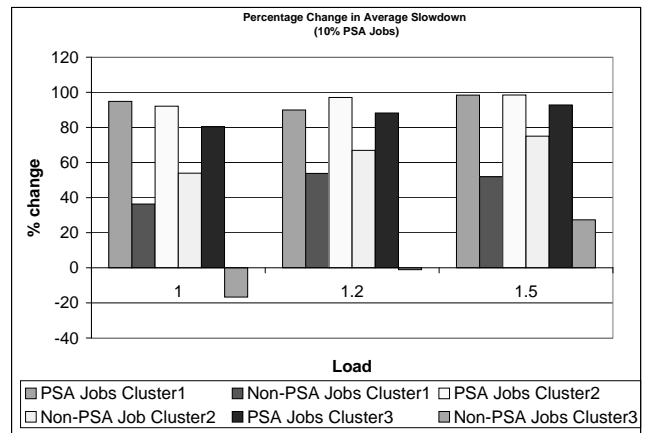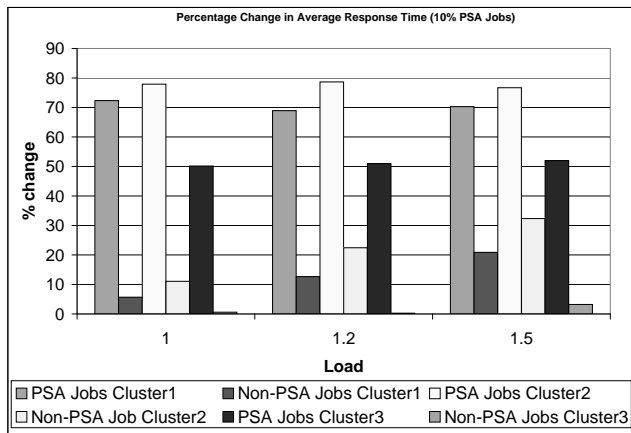
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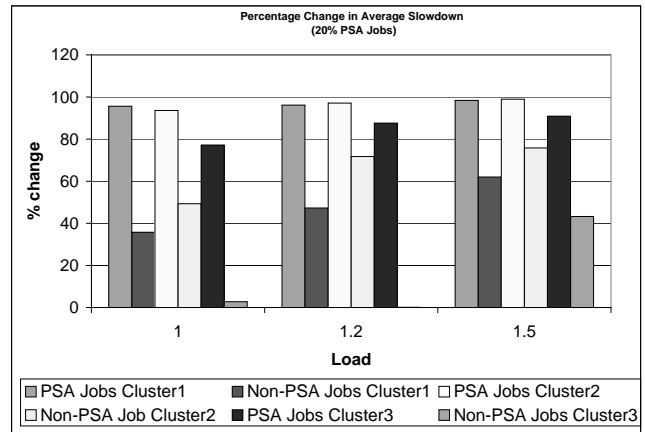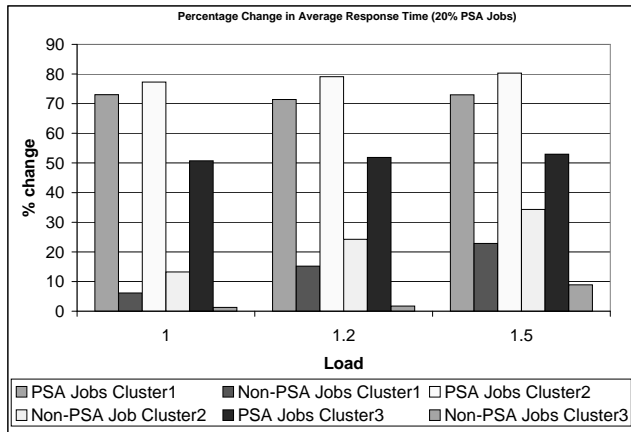
Figure 46. Multi-Site Evaluation (20% PSA Jobs, Exact User Estimate, SJF priority scheme): (a) Average Response Time; (b) Average Slow Down
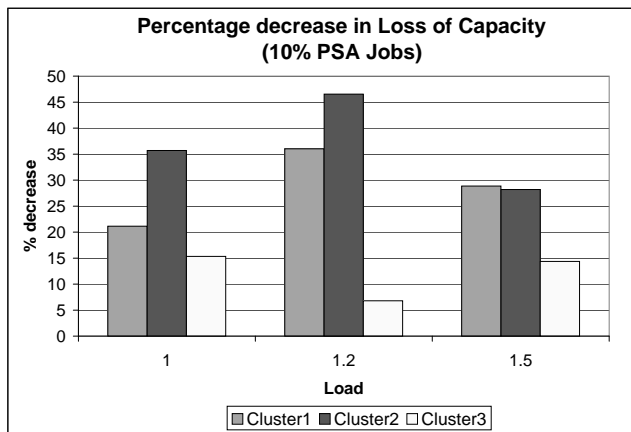
Figure 42. Multi-Site Evaluation (10% PSA Jobs, Exact User Estimate, RR priority scheme): Loss of Capacity
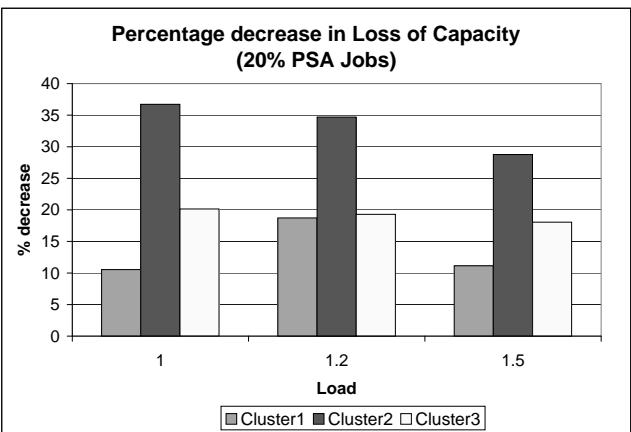
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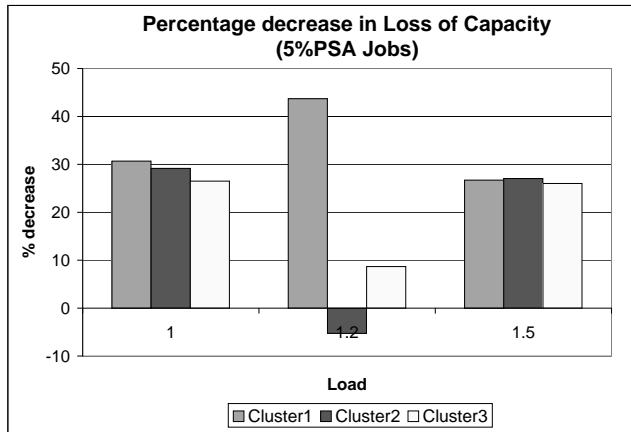
Figure 47. Multi-Site Evaluation (5% PSA Jobs, Exact User Estimate, SJF priority scheme): Loss of Capacity
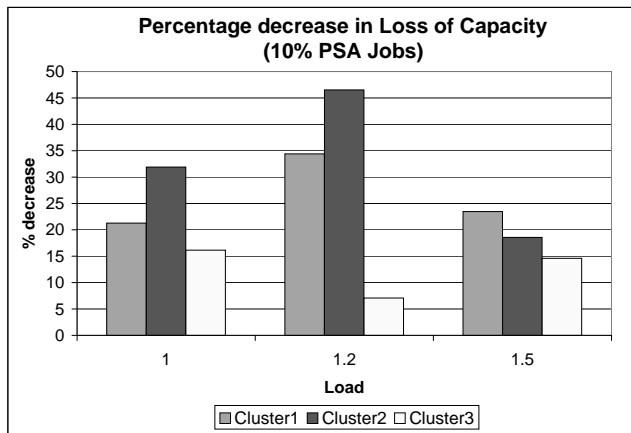
Figure 48. Multi-Site Evaluation (10% PSA Jobs, Exact User Estimate, SJF priority scheme): Loss of Capacity
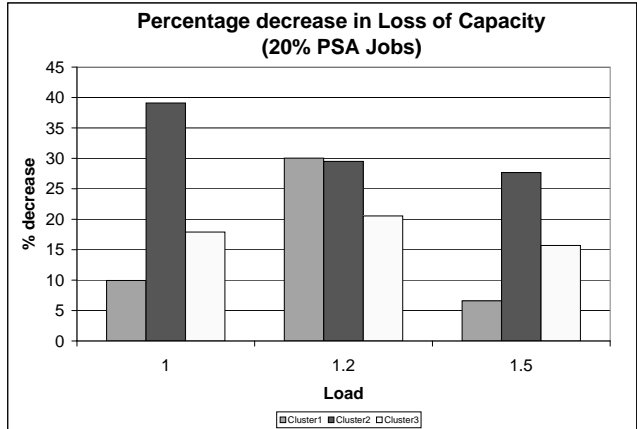
Figure 49. Multi-Site Evaluation (20% PSA Jobs, Exact User Estimate, SJF priority scheme): Loss of Capacity

APST could be set up to work in conjunction with schedulers at supercomputer centers, it could result in significant delays of other non-PSA jobs in the system - the avoidance of this problem is the reason why fair-share limits are imposed at supercomputer centers. In this paper we first use trace-driven simulations to characterize the impact of introducing PSA job "fragments" into a mix of non-PSA jobs in a supercomputer center environment. We show that non-PSA jobs are indeed adversely affected. We then propose a new approach, termed as *Opportune Job Shredding*, to significantly overcome the degradation of non-PSA jobs, while still allowing for considerable improvement of PSA jobs. We demonstrate that the proposed scheme improves the slowdown time of PSA's by up to 70% and the overall loss of capacity of the system by up to 21%. Not only does the scheme avoid significant degradation of the performance of the non-PSA jobs in all cases, but it even improves their performance in some cases. We also propose an extension of the previously proposed "Multiple Simultaneous Requests" scheme combining it with the Opportune Job Shredding scheme allowing Parameter Sweep Applications to be executed in parts on remote clusters.

We plan next to incorporate and test the Opportune Job Shredding strategy using the Maui scheduler. After testing, we plan to evaluate it on one of the cluster systems at the Ohio Supercomputer Center, where PSA jobs represent a significant part of the system load.

References

[1] A. Streit. On Job Scheduling for HPC-Clusters and the dynP Scheduler. In *HiPC*, pages 58–67, 2001.

[2] D. Abramson, J. Giddy, and L. Kotler. High performance parametric modeling with nimrod/G: Killer application for the global grid? pages 520–528.

[3] O. Arndt, B. Freisleben, T. Kielmann, and F. Thilo. A comparative study of online scheduling algorithms for networks of workstations. *Cluster Computing*, 3(2):95–112, 2000.

[4] H. Casanova, T. Bartol, J. Stiles, and F. Berman. Distributing MCell Simulations on the Grid. *The International Journal of High Performance Computing and Supercomputing Applications*, 15(3), Fall 2001.

[5] H. Casanova, G. Obertelli, F. Berman, and R. Wolski. The AppLeS parameter sweep template: User-level middleware for the grid. pages 75–76, 2000.

[6] H. Casanova, G. Obertelli, F. Berman, and R. Wolski. The AppLeS Parameter Sweep Template: User-Level Middleware for the Grid. In *Supercomputing*, November 2000.

[7] S. H. Chiang and M. K. Vernon. Production job scheduling for parallel shared memory systems. In *Proceedings of International Parallel and Distributed Processing Symposium*, 2002.

[8] D. Jackson and Q. Snell and M. J. Clement. Core Algorithms of the Maui Scheduler. In *JSSPP*, pages 87–102, 2001.

[9] D. Lifka. The ANL/IBM SP Scheduling System. In *JSSPP*, pages 295–303, 1995.

[10] D. Talby and D. Feitelson. Supporting Priorities and Improving Utilization of the IBM SP Scheduler Using Slack-Based Backfilling. In *Proceedings of the 13th International Parallel Processing Symposium*, 1999.

[11] C. Ernemann, V.Hamscher, U. Schwiegelshohn, R. Yahyapour, and A. Streit. On advantages of grid computing for parallel job scheduling.

[12] D. G. Feitelson. Logs of real parallel workloads from production systems. URL: http://www.cs.huji. ac.il/labs/parallel/workload/.

[13] D. G. Feitelson, L. Rudolph, U. Schwiegelshohn, K. C. Sevcik, and P. Wong. Theory and Practice in Parallel Job Scheduling. In *Job Scheduling Strategies for Parallel Processing*. Springer Verlag, 1997.

[14] J. Frey, T. Tannenbaum, M. Livny, I. Foster, and S.Tuecke. Condor-g: A computation management agent for multi-institutional grids. In *Proc. Intl. Symp. On High Performance Distributed Computing*, 2001.

[15] J. Gehring and T. Preiss. Scheduling a metacomputer with uncooperative subschedulers. In *In Proc. JSSPP*, pages 179–201, 1999.

[16] J. Gehring and A. Streit. Robust resource management for metacomputers. In *High Performance Distributed Computing*, pages 105–111, 2000.

[17] V. Hamscher, U. Schwiegelshohn, A. Streit, and R. Yahyapour. Evaluation of job-scheduling strategies for grid computing. In *Proc. Grid '00*, pages 191–202, 2000.

[18] H. A. James, K. A. Hawick, , and P. D. Coddington. Scheduling independent tasks on metacomputing systems. In *Parallel and Distributed Systems*, 1999.

[19] J.P. Jones and B. Nitzberg. Scheduling for parallel supercomputing: A historical perspective of achievable utilization. In *5th Workshop on Job Scheduling Strategies for Parallel Processing*, 1999.

[20] J.R.Stiles, T.M. Bartol, E.E. Salpeter, and M.M. Salpeter. Monte carlo simulation of neuromuscular transmitter release using mcell,a general simulator of cellular physiological processes. In *Computational NeuroScience*, 1998.

[21] K. Aida. Effect of Job Size Characteristics on Job Scheduling Performance. In *JSSPP*, pages 1–17, 2000.

[22] A. W. Mu'alem and D. G. Feitelson. Utilization, predictability, workloads, and user runtime estimates in scheduling the ibm sp2 with backfilling. In *IEEE Transactions on Parallel and Distributed Systems*, volume 12, pages 529–543, 2001.

[23] P. J. Keleher and D. Zotkin and D. Perkovic. Attacking the Bottlenecks of Backfilling Schedulers. *Cluster Computing*, 3(4):245–254, 2000.

[24] D. Perkovic and P. J. Keleher. Randomization, speculation, and adaptation in batch schedulers. *Cluster Computing*, 3(4):245–254, 2000.

[25] R. Kettimuthu and V. Subramani and S. Srinivasan and T. B. Gopalsamy and P. Sadayappan. Selective Preemption Strategies for Parallel Job Scheduling. Proceedings of the International Conference on Parallel Processing, 2002.

[26] Grid Research and UCSD Innovation Laboratory. http:// grail.sdsc.edu.

[27] G. Sabin, R. Kettimuthu, A. Rajan, and P. Sadayappan. Scheduling of parallel jobs in a heterogeneous multisite environment. In *In Proc. JSSPP*, 2003.

[28] SETI@home. http:// setiathome.ssl.berkeley.edu.

[29] J. Skovira, W. Chan, H. Zhou, and D. Lifka. The EASY - LoadLeveler API Project. In *JSSPP*, pages 41–47, 1996.

[30] S. Smallen, W.Cirne, J.Frey, F.Berman, R.Wolski, M.Su, C.Kesselman, S.Young, and M.Ellisman. Combining workstations and supercomputers to support grid applications.

[31] Q. Snell, M. Clement, D. Jackson, , and C. Gregory. The performance impact of advance reservation meta-scheduling. In D. G. Feitelson and L. Rudolph, editors, *Workshop on Job Scheduling Strategies for Parallel Processing*, volume 1911 of *Lecture Notes in Computer Science*. Springer-Verlag, 2000.

[32] V. Subramani, R. Kettimuthu, S. Srinivasan, and P. Sadayappan. Distributed job scheduling on computational grids using multiple simultaneous requests. In *Proceedings of the 11th High Performance Distributed Computing Conference*, 2002.

[33] S. S. Vadhiyar and J. J. Dongarra. A metascheduler for the grid. In *11-th IEEE Symposium on High Performance Distributed Computing*, July 2002.

Appendix

Appendix A: Inaccurate User Estimates
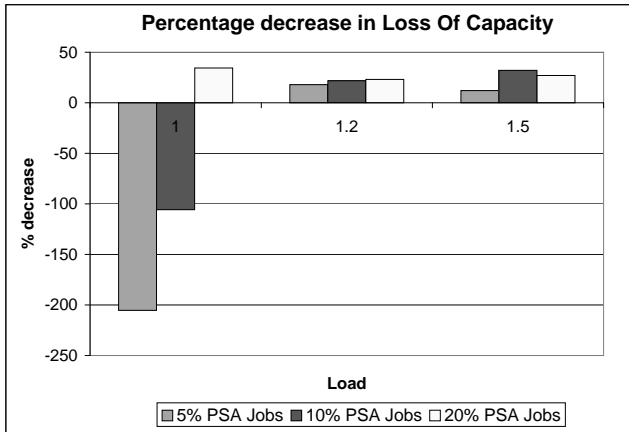
Figure 53. Flooding-based Job Shredding (Inaccurate User Estimate): Loss of Capacity
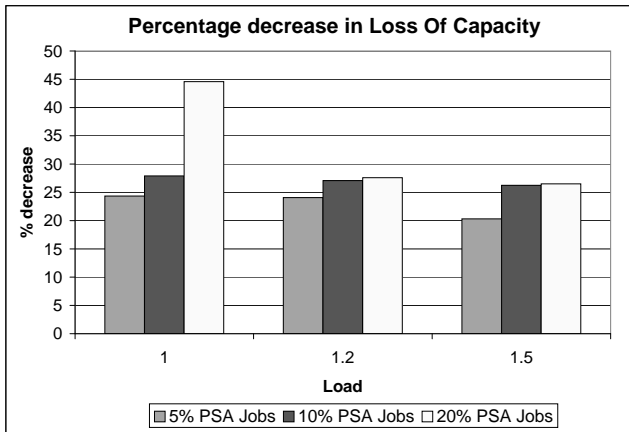
Figure 60. Opportune Job Shredding (Inaccurate User Estimate, FCFS priority scheme): Loss of Capacity
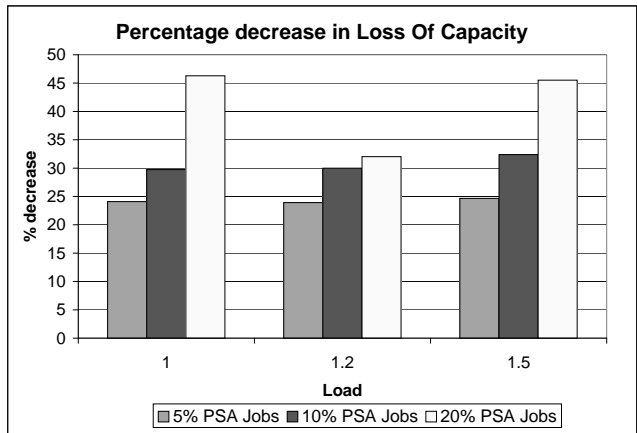
Figure 67. Opportune Job Shredding (Inaccurate User Estimate, RR priority scheme): Loss of Capacity
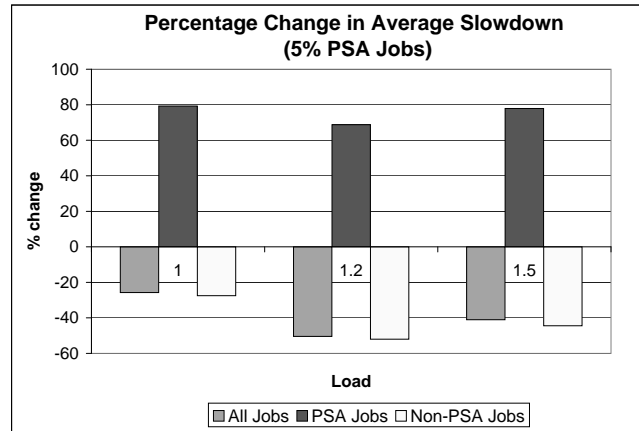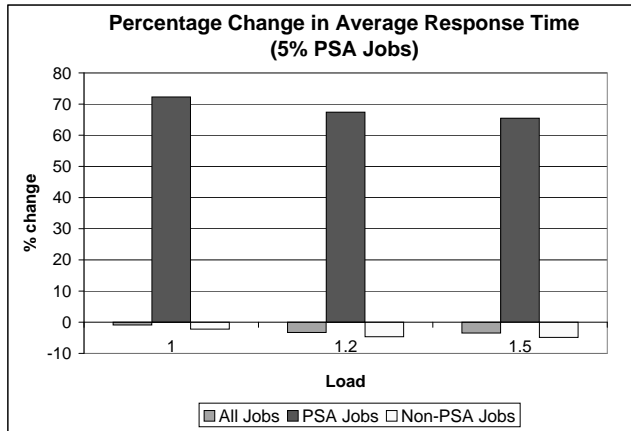
Figure 50. Flooding-based Job Shredding (5% PSA Jobs, Inaccurate User Estimate): (a) Average Response Time; (b) Average Slow Down
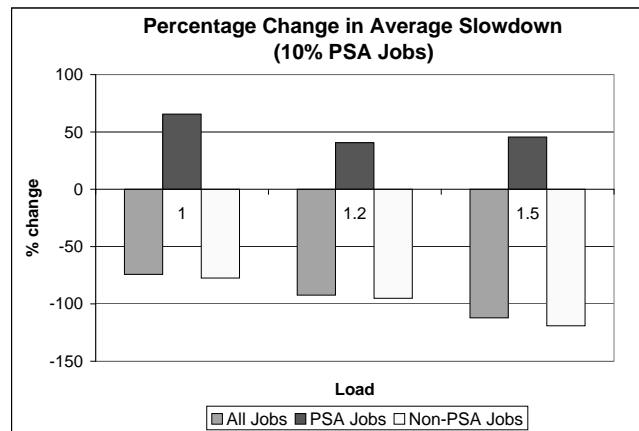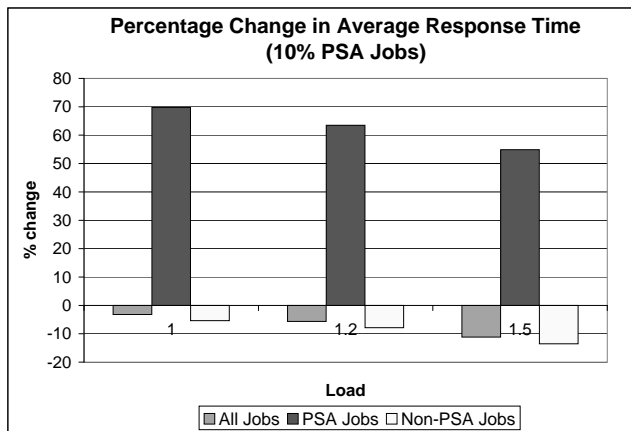
Figure 51. Flooding-based Job Shredding (10% PSA Jobs, Inaccurate User Estimate): (a) Average Response Time; (b) Average Slow Down
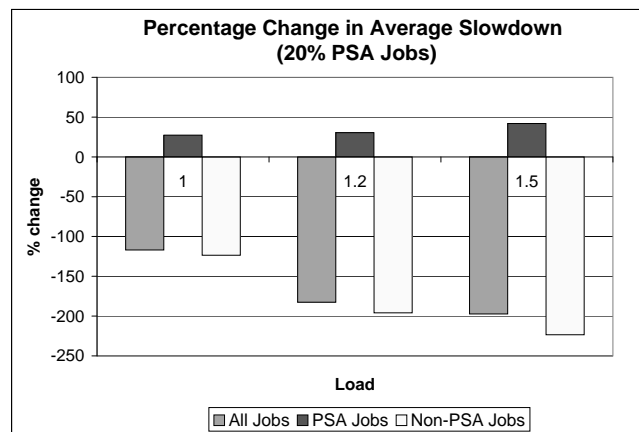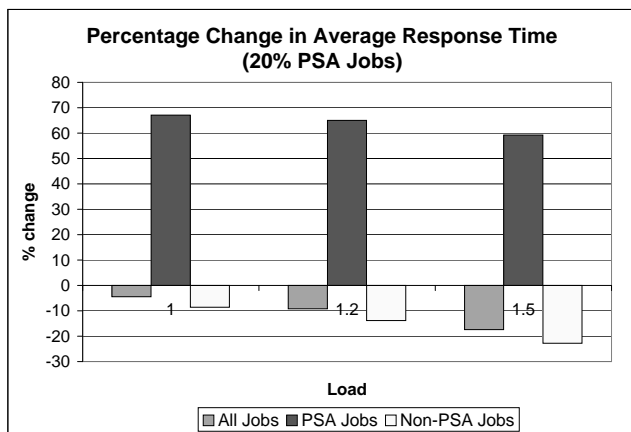
Figure 52. Flooding-based Job Shredding (20% PSA Jobs, Inaccurate User Estimate): (a) Average Response Time; (b) Average Slow Down

Percentage Change in Average Response Time (5% PSA Jobs)

Percentage Change in Average Slowdown (5% PSA Jobs)
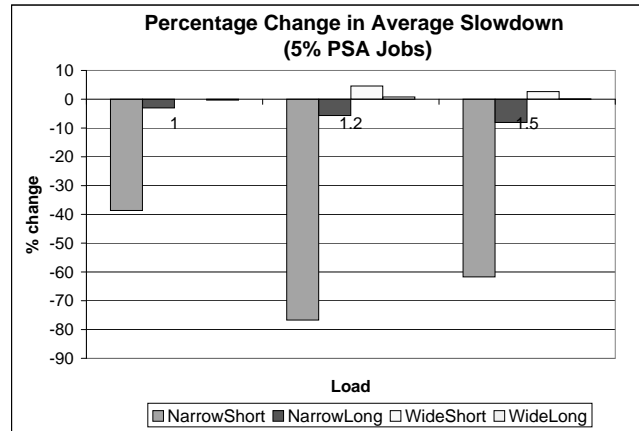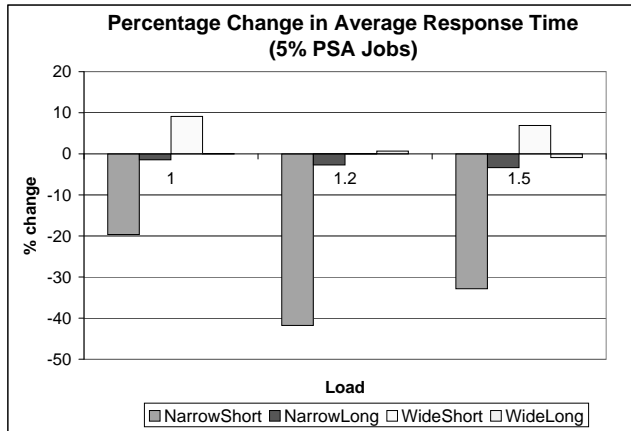
Figure 54. Flooding-based Job Shredding (5% PSA Jobs, Inaccurate User Estimate), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down


Percentage Change in Average Response Time (10% PSA Jobs)

Percentage Change in Average Slowdown (10% PSA Jobs)
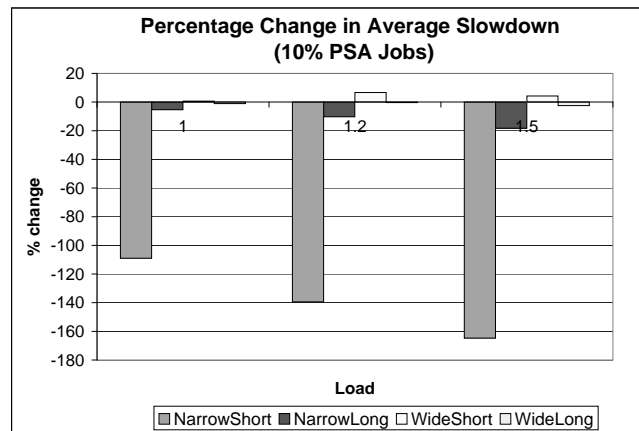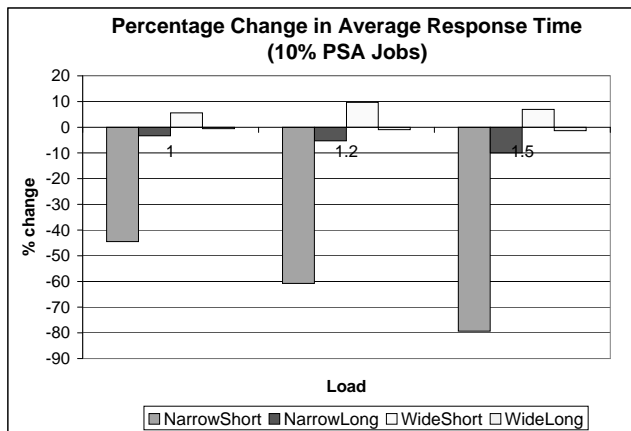
Figure 55. Flooding-based Job Shredding (10% PSA Jobs, Inaccurate User Estimate), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down

Percentage Change in Average Response Time (20% PSA Jobs)

Percentage Change in Average Slowdown (20% PSA Jobs)
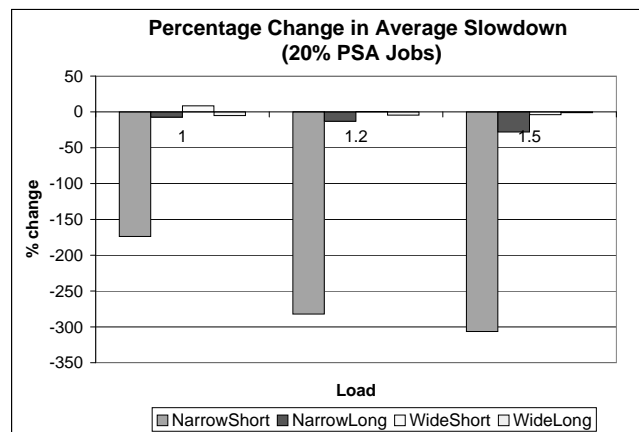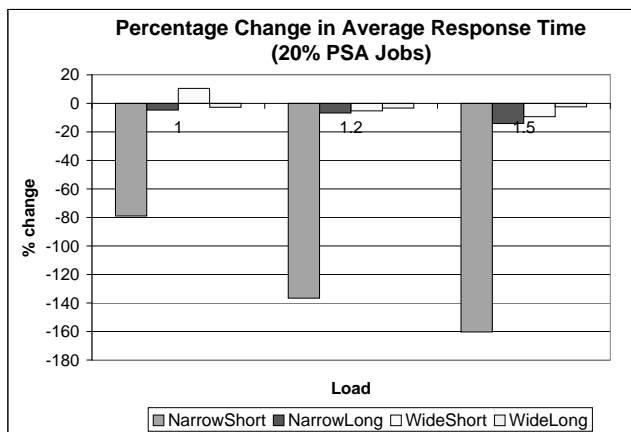
Figure 56. Flooding-based Job Shredding (20% PSA Jobs, Inaccurate User Estimate), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down
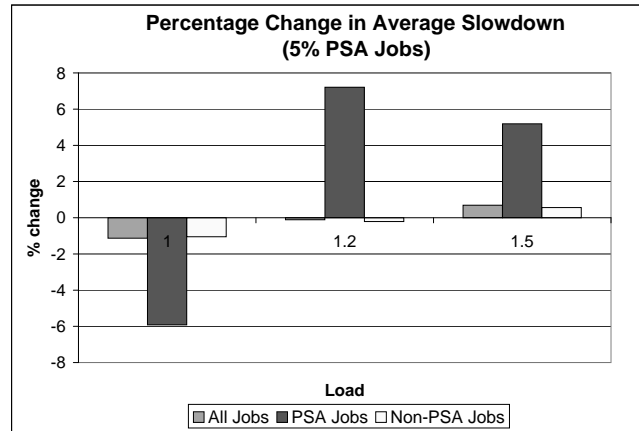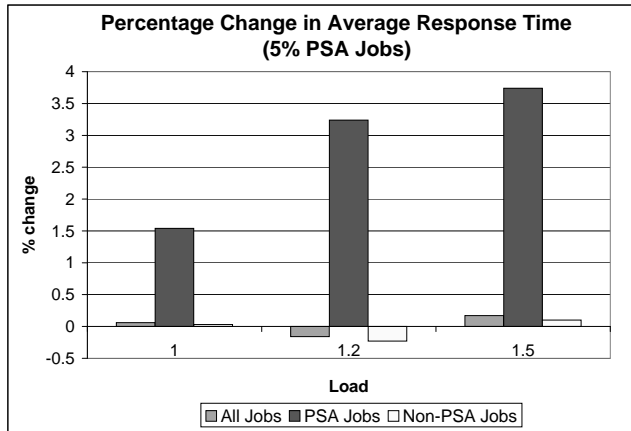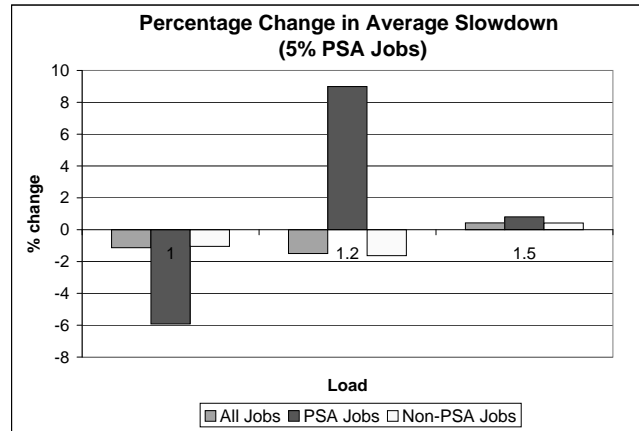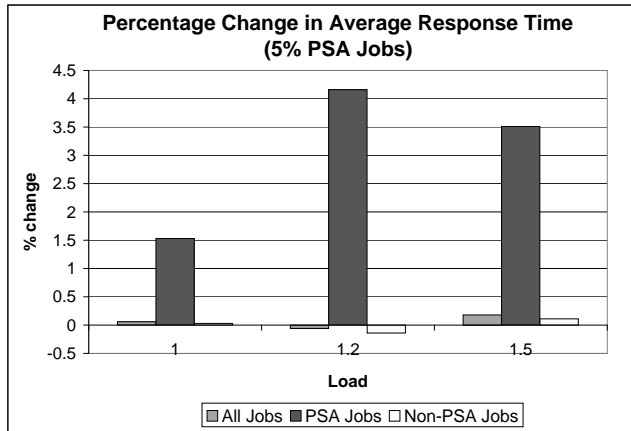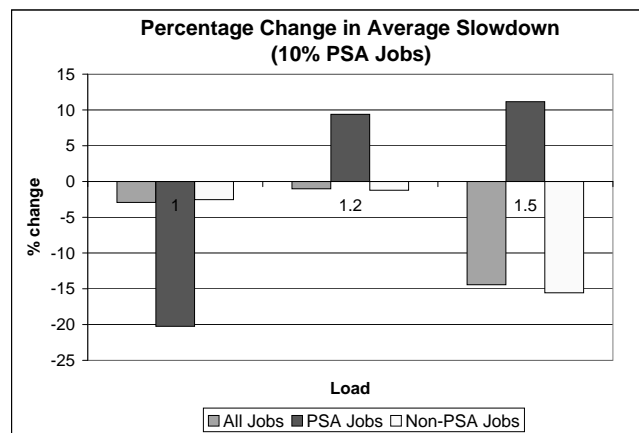
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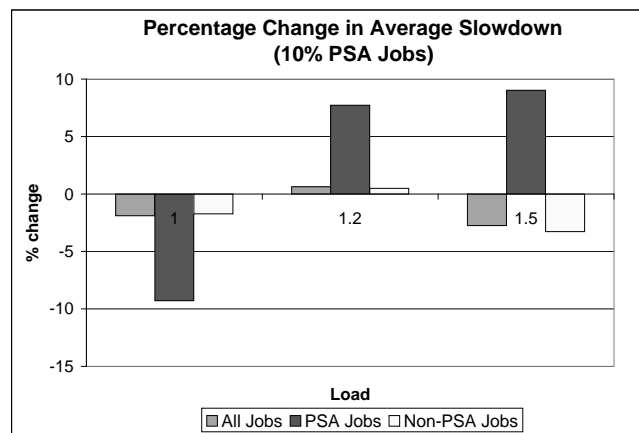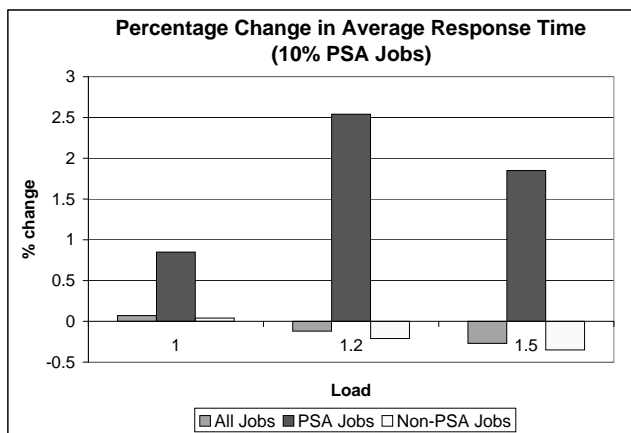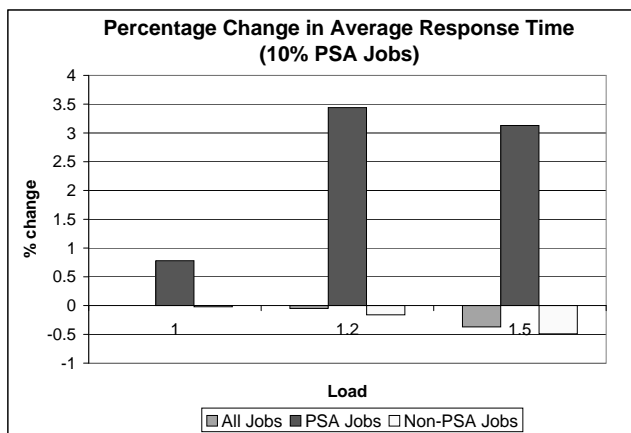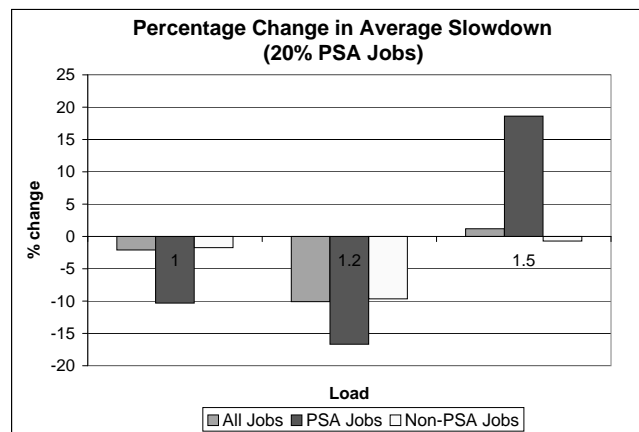

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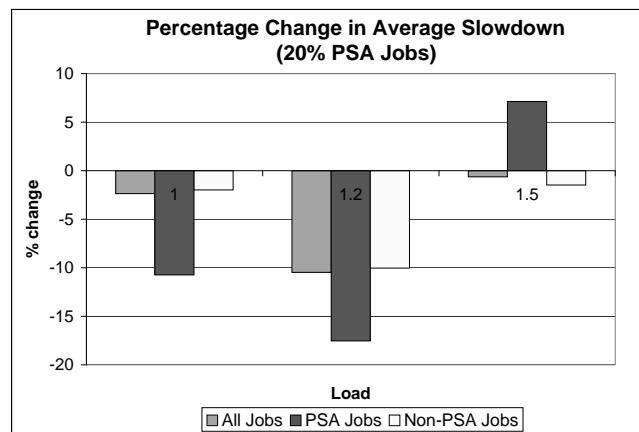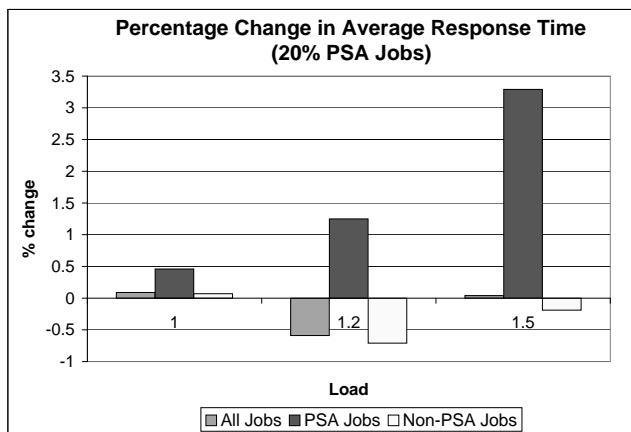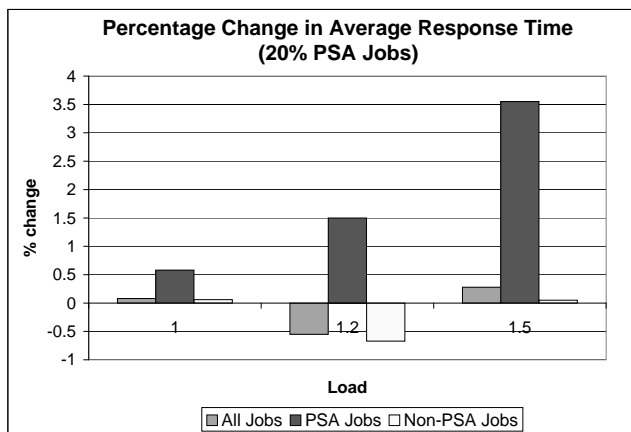

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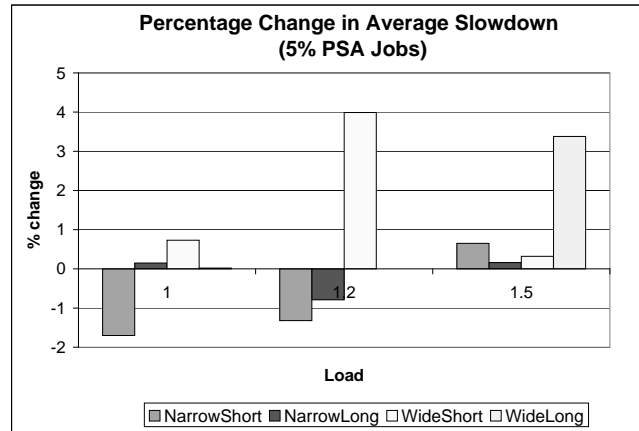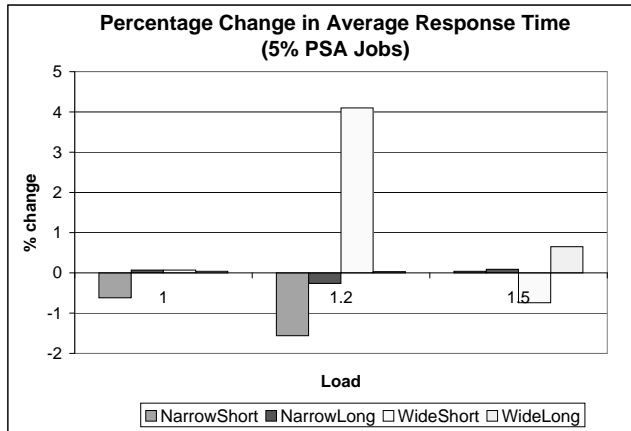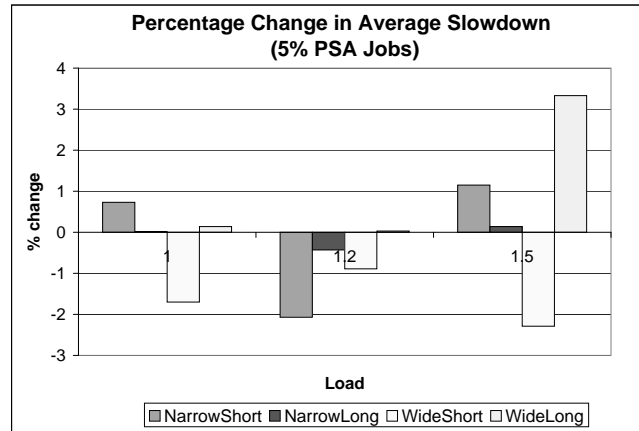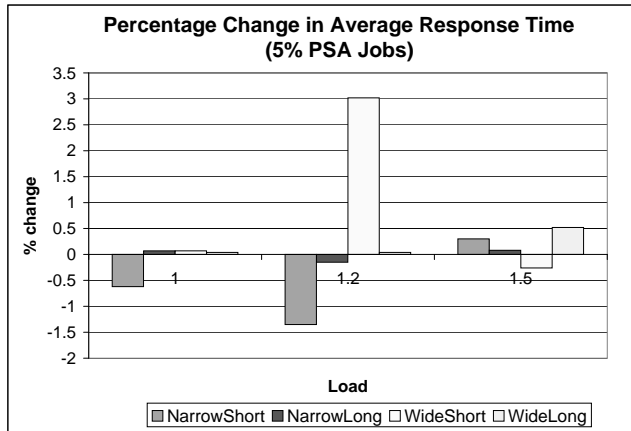
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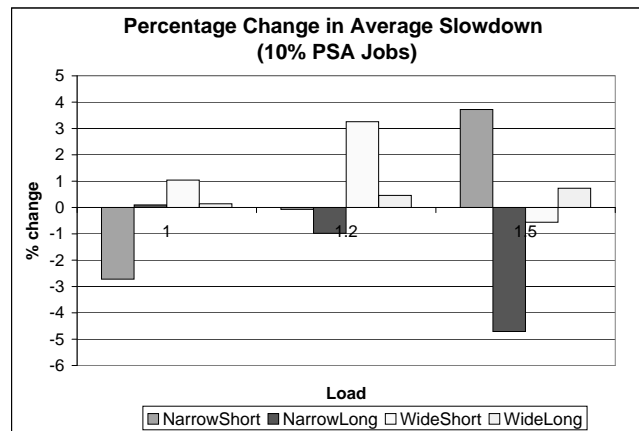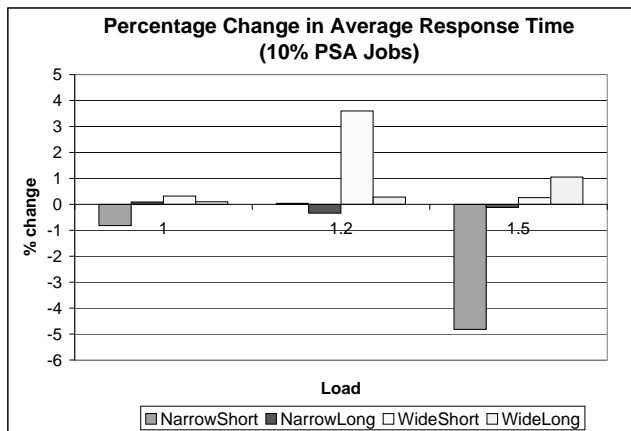
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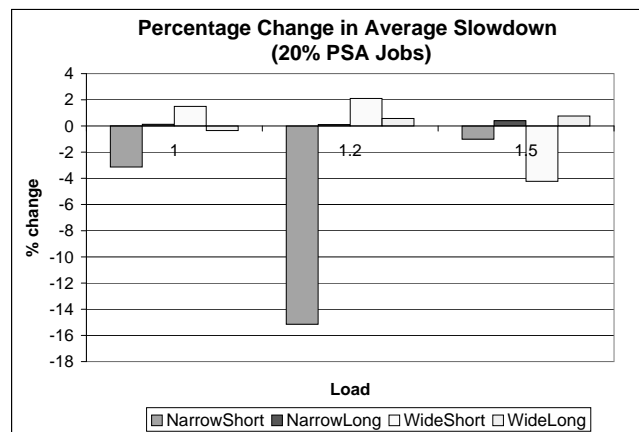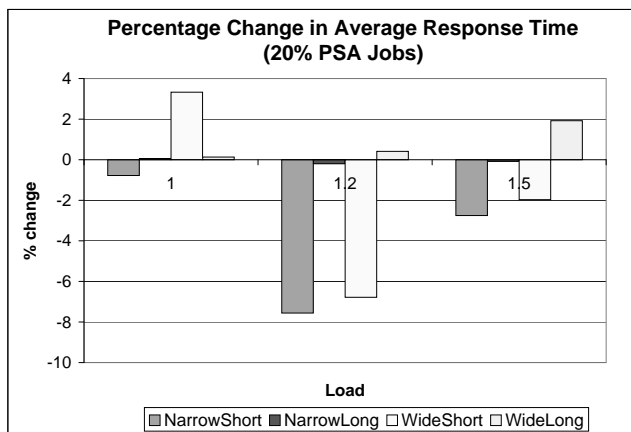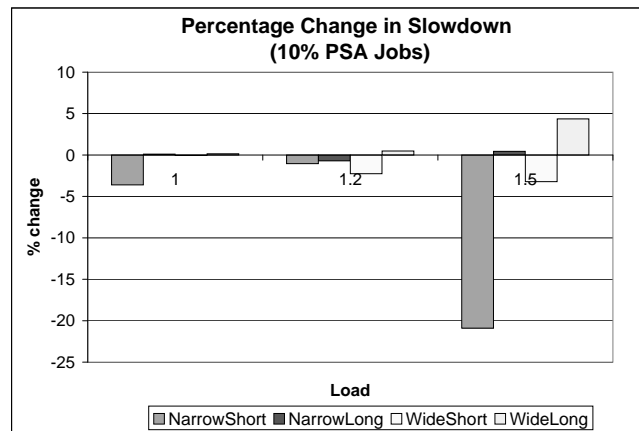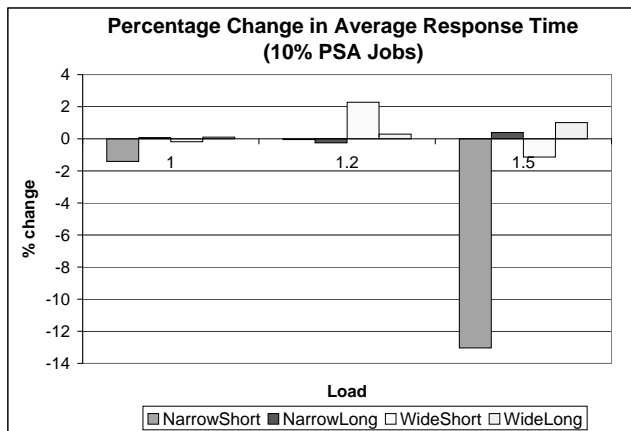

Figure 63. Opportune Job Shredding (20% PSA Jobs, Inaccurate User Estimate, FCFS priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down
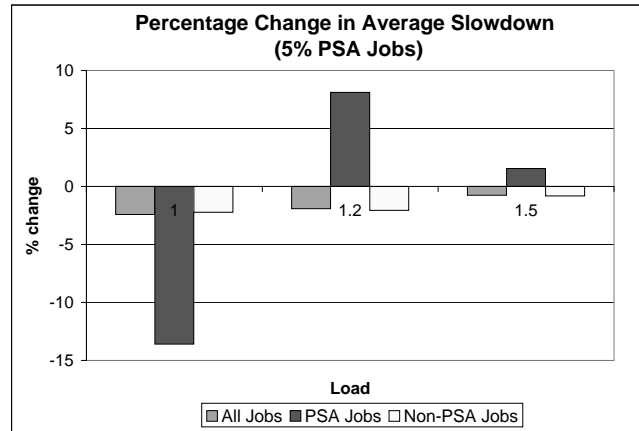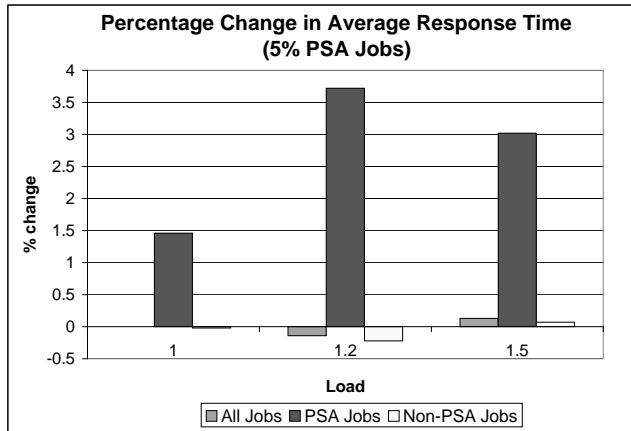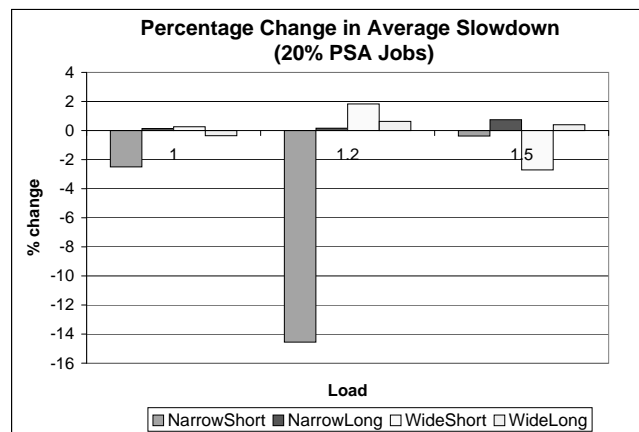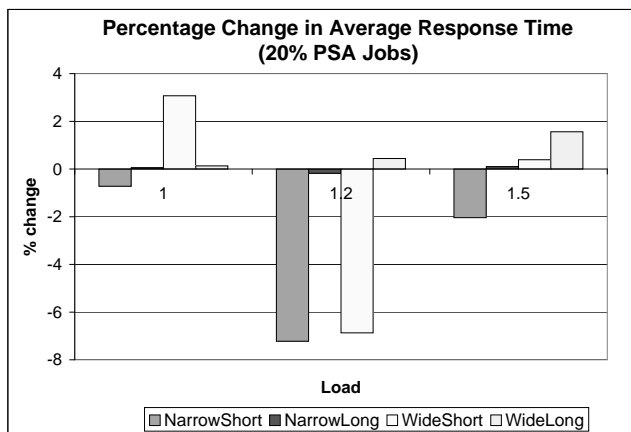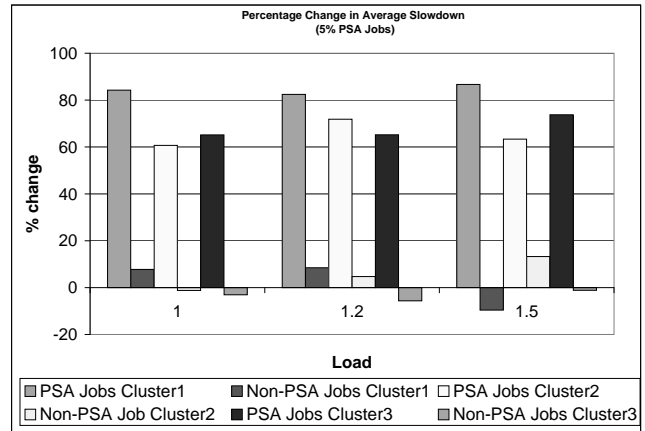
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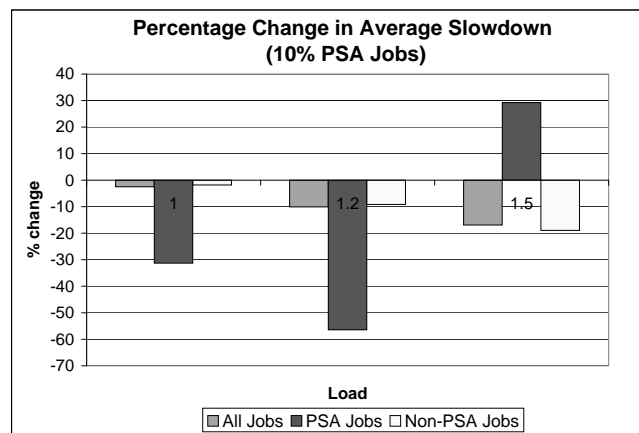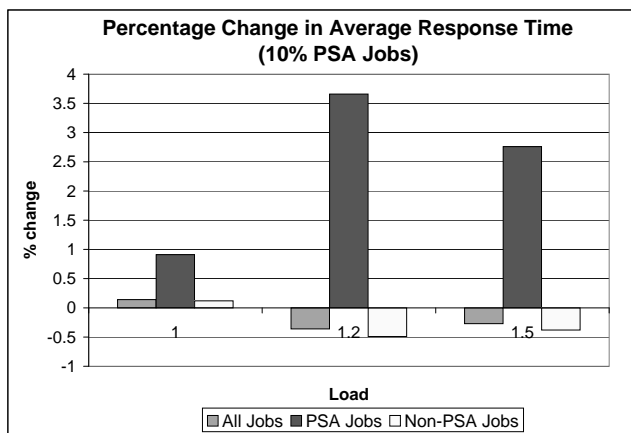
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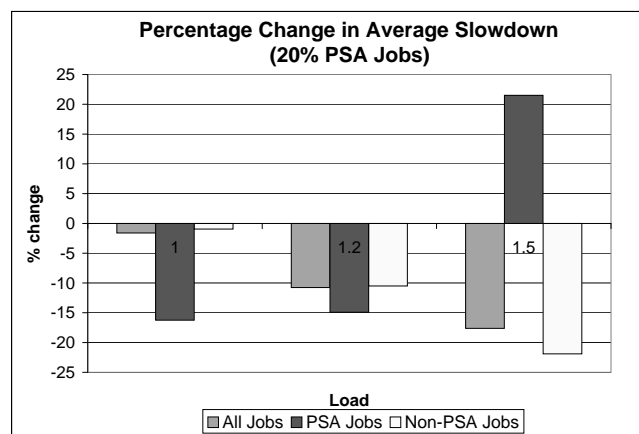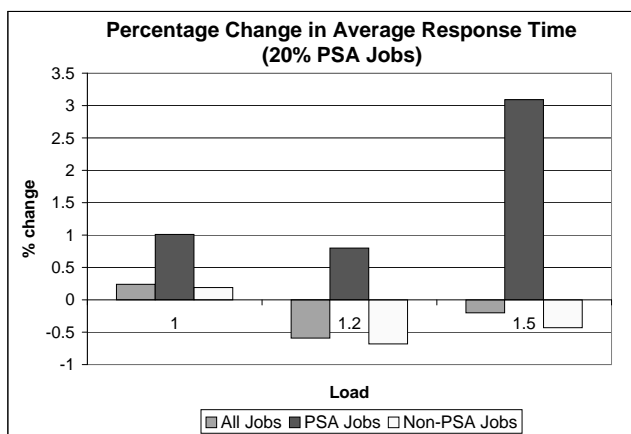
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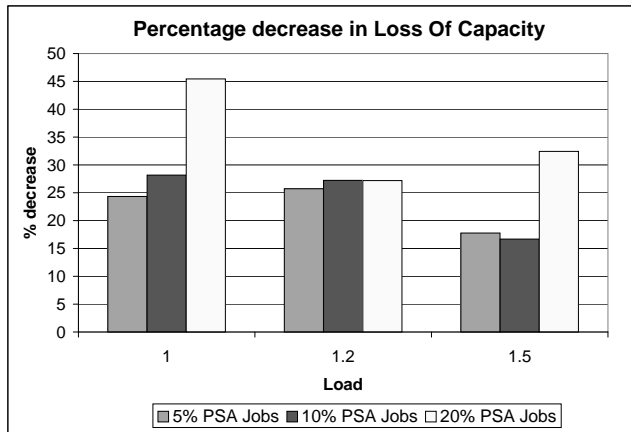
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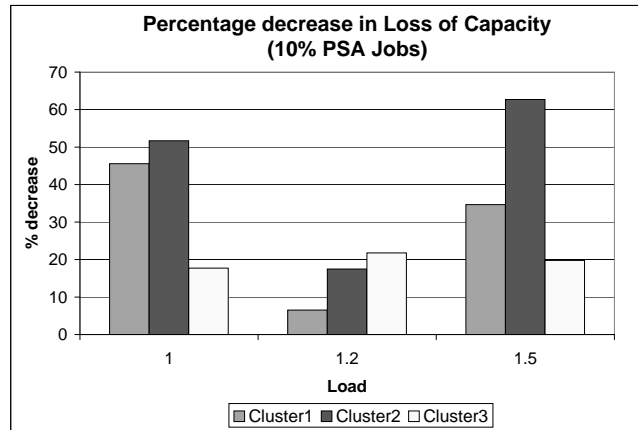
Figure 82. Multi-Site Evaluation (10% PSA Jobs, Inaccurate User Estimate, FCFS priority scheme): Loss of Capacity
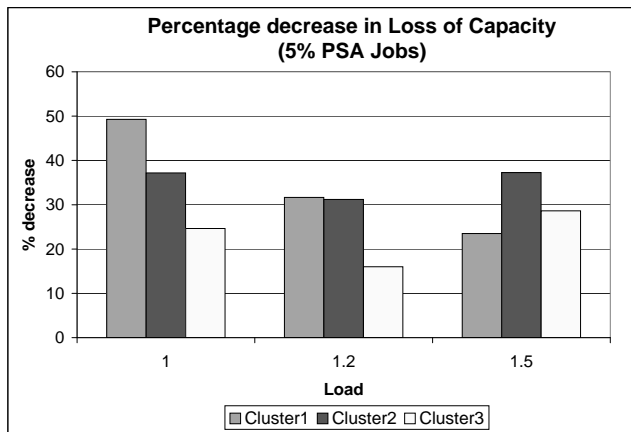
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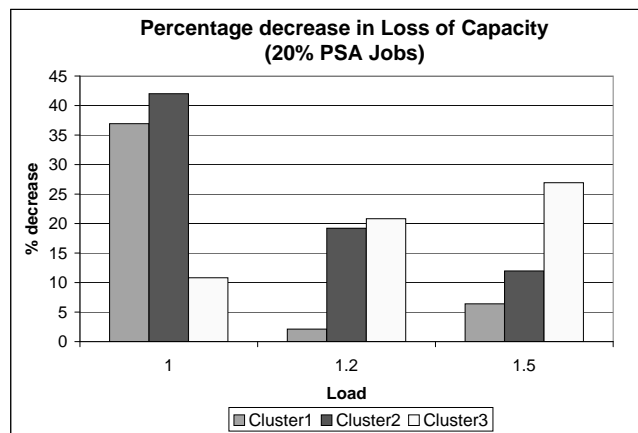
Figure 83. Multi-Site Evaluation (20% PSA Jobs, Inaccurate User Estimate, FCFS priority scheme): Loss of Capacity
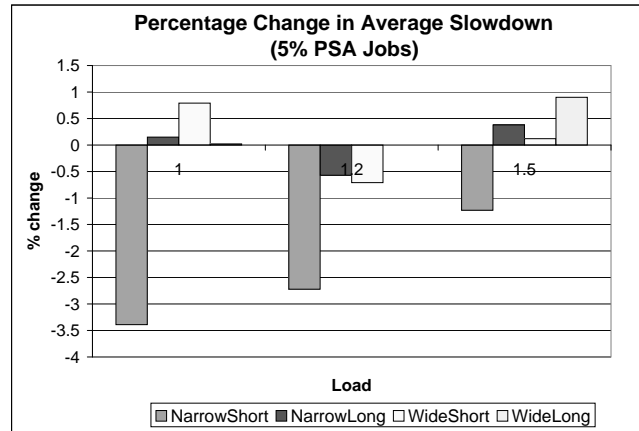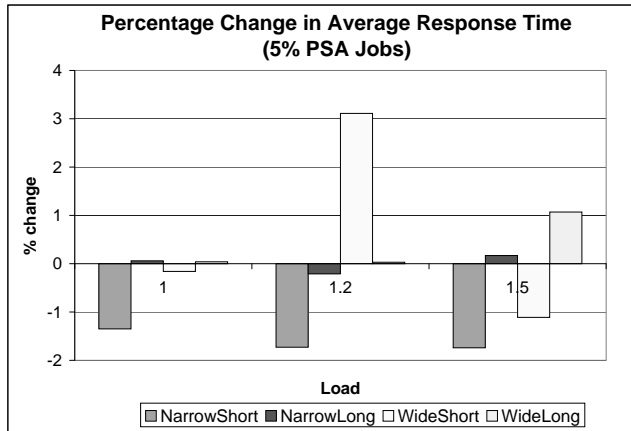
Figure 68. Opportune Job Shredding (5% PSA Jobs, Inaccurate User Estimate, RR priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down
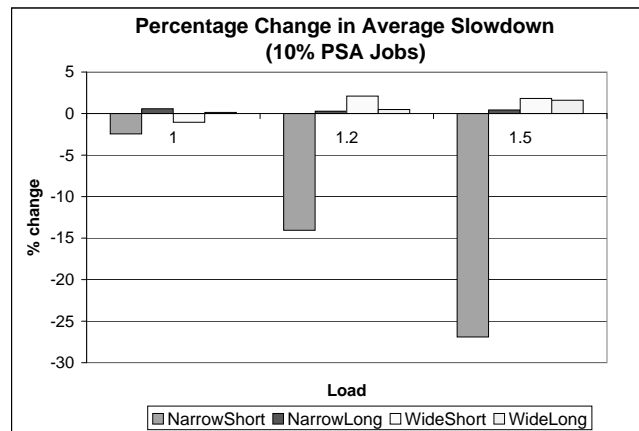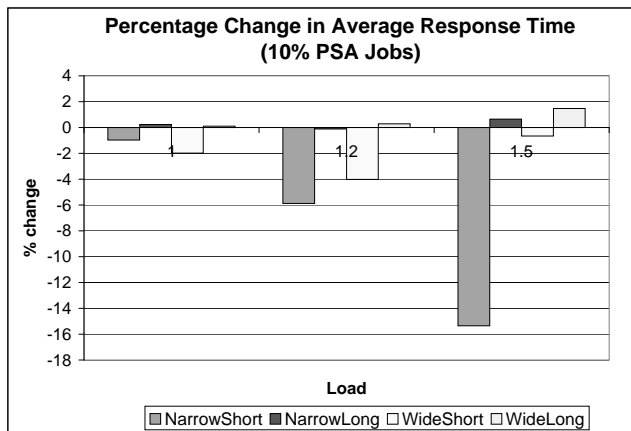
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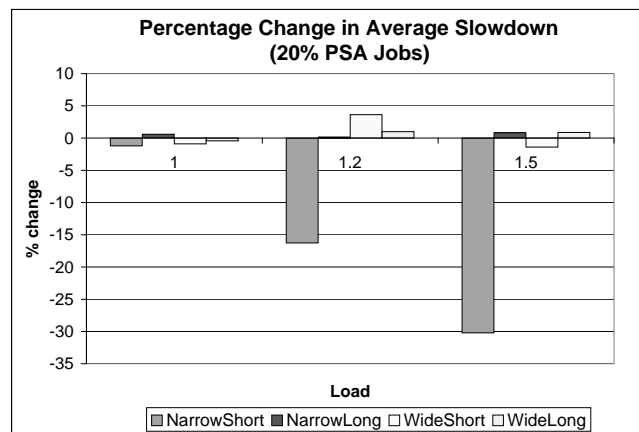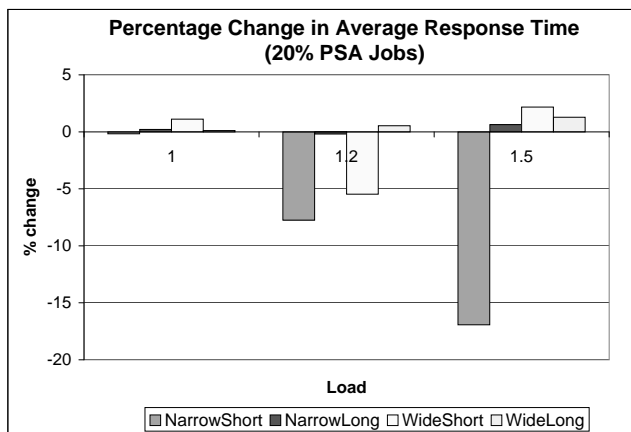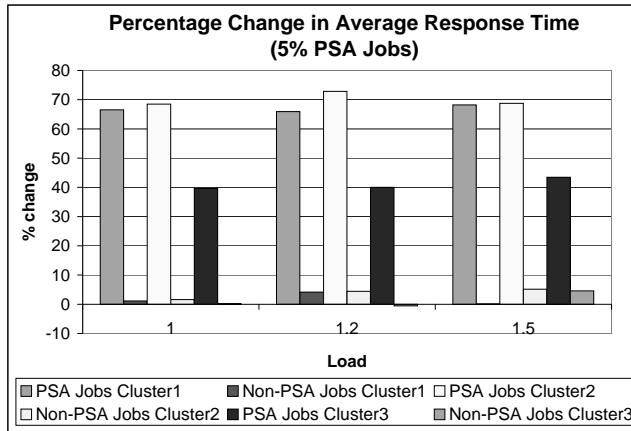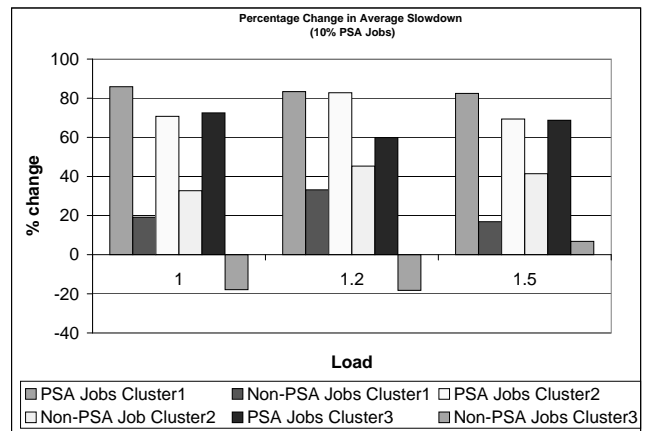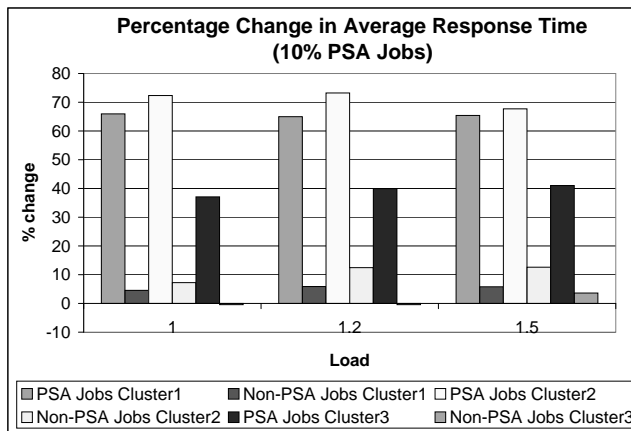

Figure 70. Opportune Job Shredding (20% PSA Jobs, Inaccurate User Estimate, RR priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down

Figure 71. Opportune Job Shredding (5% PSA Jobs, Inaccurate User Estimate, SJF priority scheme): (a) Average Response Time; (b) Average Slow Down
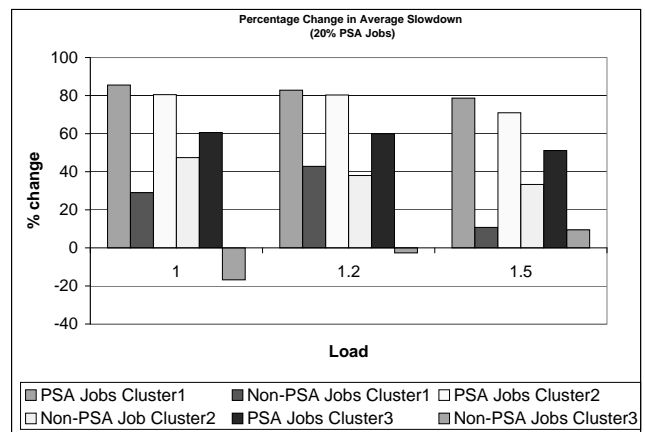

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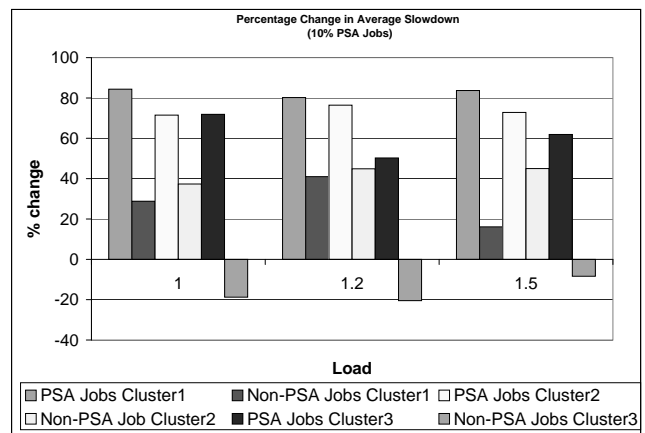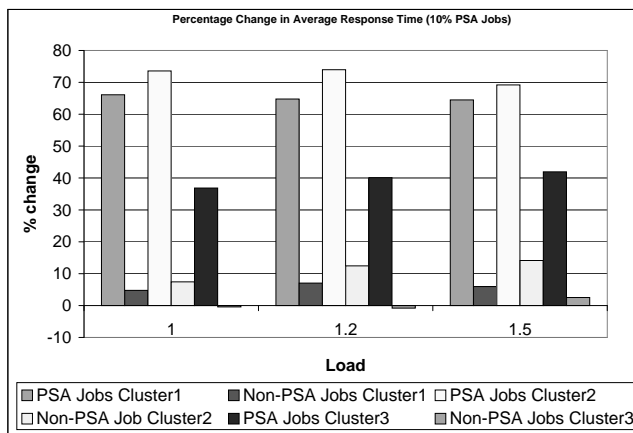
Figure 73. Opportune Job Shredding (20% PSA Jobs, Inaccurate User Estimate, SJF priority scheme): (a) Average Response Time; (b) Average Slow Down

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Figure 75. Opportune Job Shredding (5% PSA Jobs, Inaccurate User Estimate, SJF priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down

Figure 76. Opportune Job Shredding (10% PSA Jobs, Inaccurate User Estimate, SJF priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down

Figure 77. Opportune Job Shredding (20% PSA Jobs, Inaccurate User Estimate, SJF priority scheme), Category-wise breakup: (a) Average Response Time; (b) Average Slow Down

Figure 78. Multi-Site Evaluation (5% PSA Jobs, Inaccurate User Estimate, FCFS priority scheme): (a) Average Response Time; (b) Average Slow Down

Figure 79. Multi-Site Evaluation (10% PSA Jobs, Inaccurate User Estimate, FCFS priority scheme): (a) Average Response Time; (b) Average Slow Down
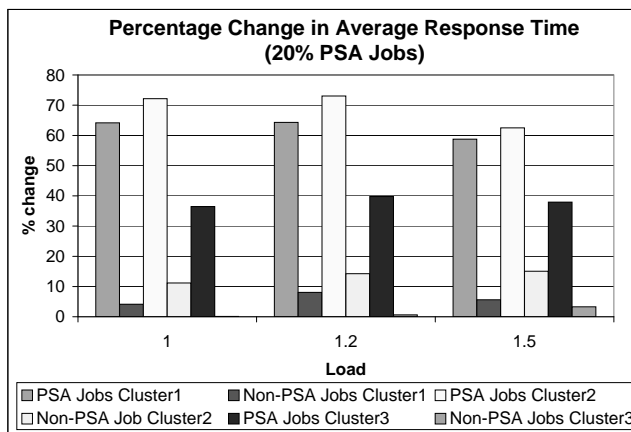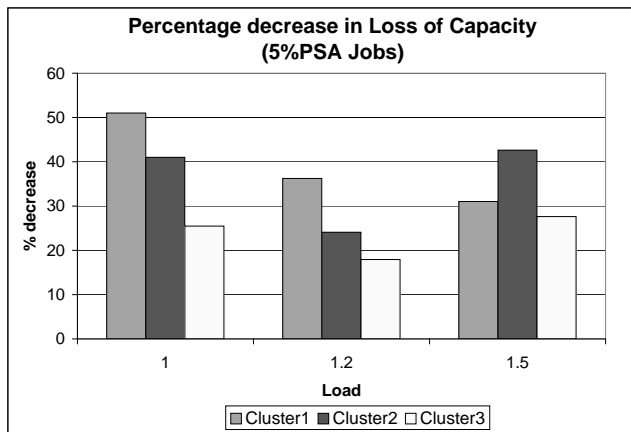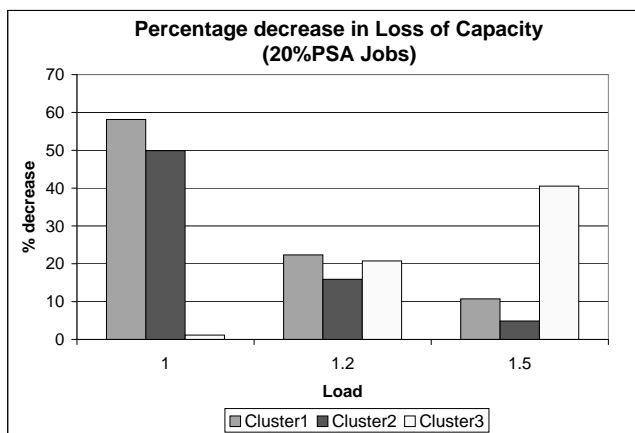

Figure 80. Multi-Site Evaluation (20% PSA Jobs, Inaccurate User Estimate, FCFS priority scheme): (a) Average Response Time; (b) Average Slow Down
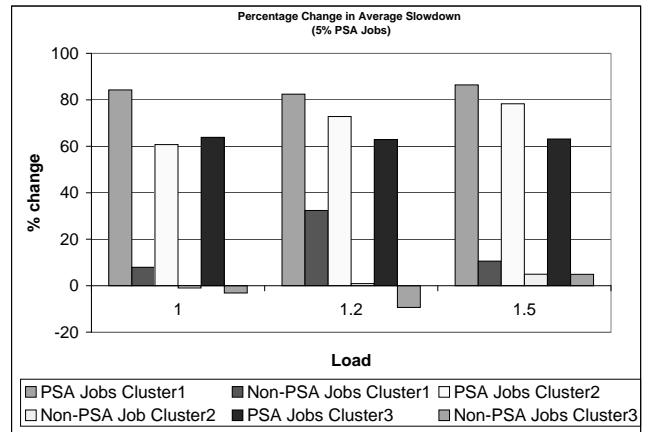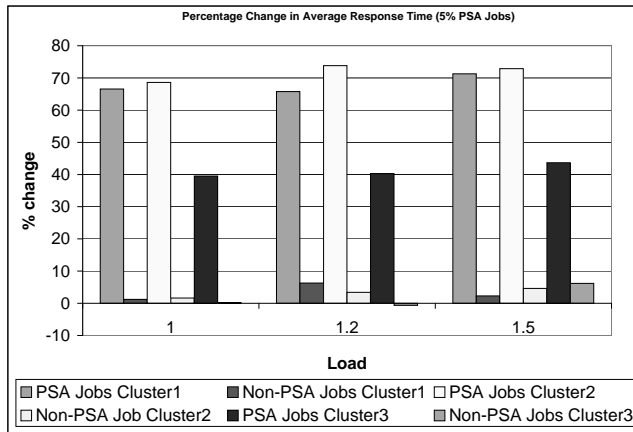
Figure 84. Multi-Site Evaluation (5% PSA Jobs, Inaccurate User Estimate, RR priority scheme): (a) Average Response Time; (b) Average Slow Down

Figure 85. Multi-Site Evaluation (10% PSA Jobs, Inaccurate User Estimate, RR priority scheme): (a) Average Response Time; (b) Average Slow Down
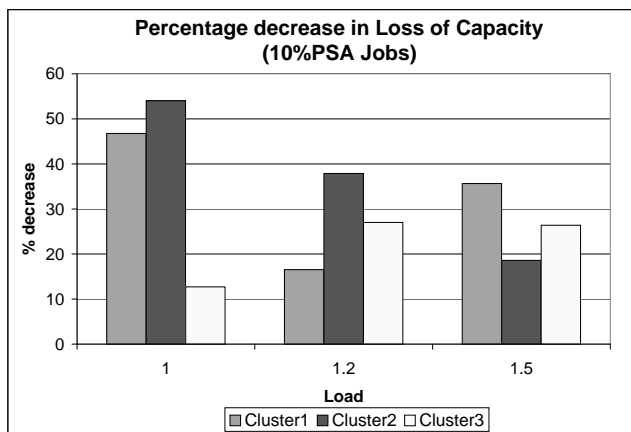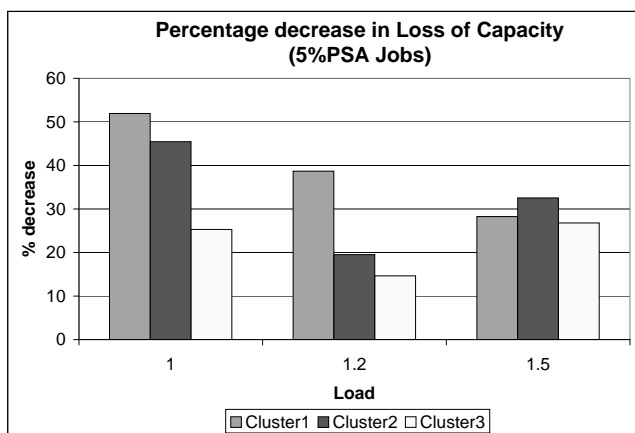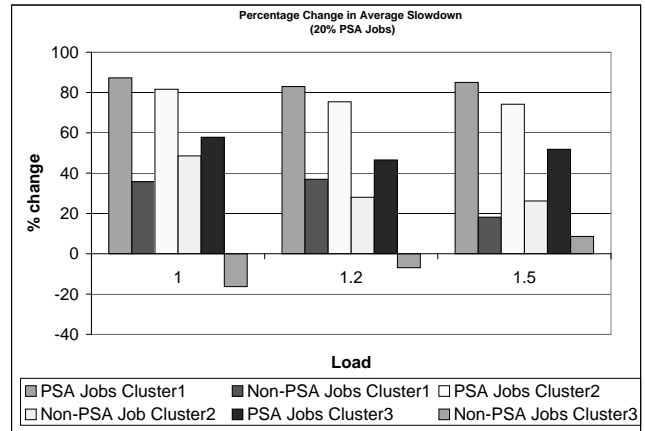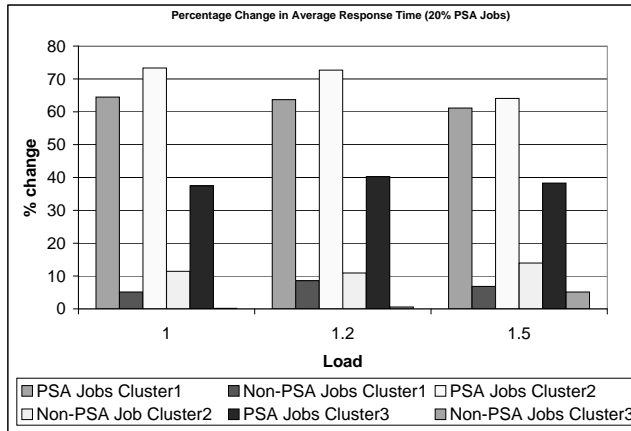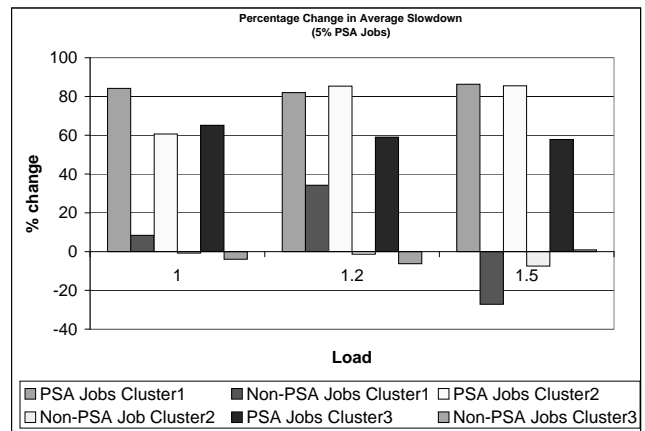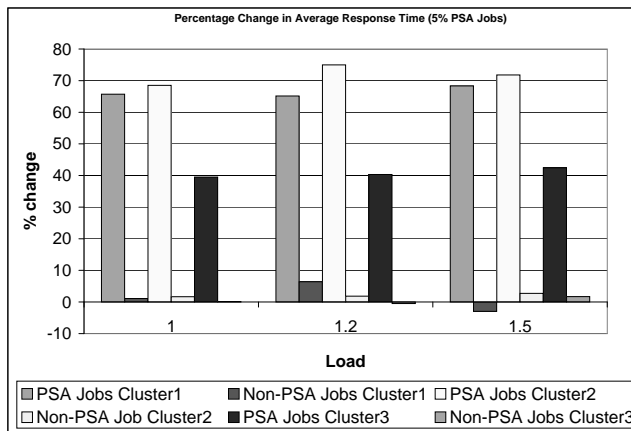
Figure 87. Multi-Site Evaluation (5% PSA Jobs, Inaccurate User Estimate, RR priority scheme): Loss of Capacity

Figure 89. Multi-Site Evaluation (20% PSA Jobs, Inaccurate User Estimate, RR priority scheme): Loss of Capacity

Figure 88. Multi-Site Evaluation (10% PSA Jobs, Inaccurate User Estimate, RR priority scheme): Loss of Capacity

Figure 93. Multi-Site Evaluation (5% PSA Jobs, Inaccurate User Estimate, SJF priority scheme): Loss of Capacity

Figure 86. Multi-Site Evaluation (20% PSA Jobs, Inaccurate User Estimate, RR priority scheme): (a) Average Response Time; (b) Average Slow Down
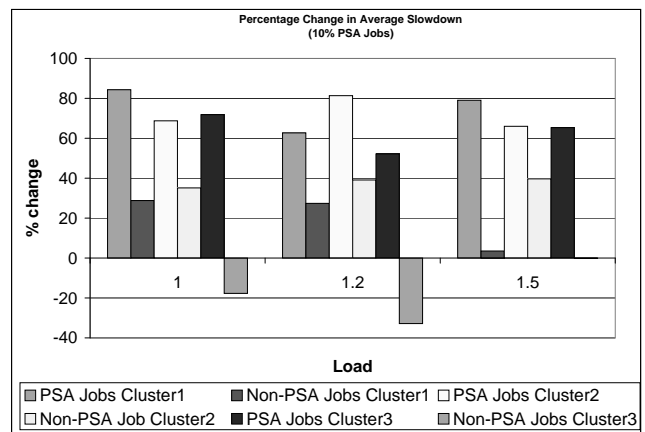

Figure 90. Multi-Site Evaluation (5% PSA Jobs, Inaccurate User Estimate, SJF priority scheme): (a) Average Response Time; (b) Average Slow Down
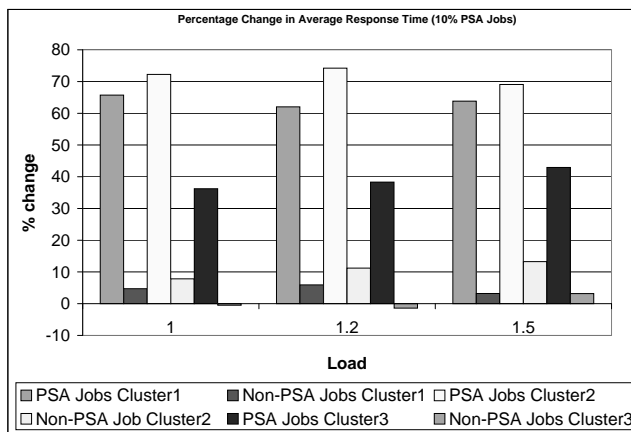

Figure 91. Multi-Site Evaluation (10% PSA Jobs, Inaccurate User Estimate, SJF priority scheme): (a) Average Response Time; (b) Average Slow Down
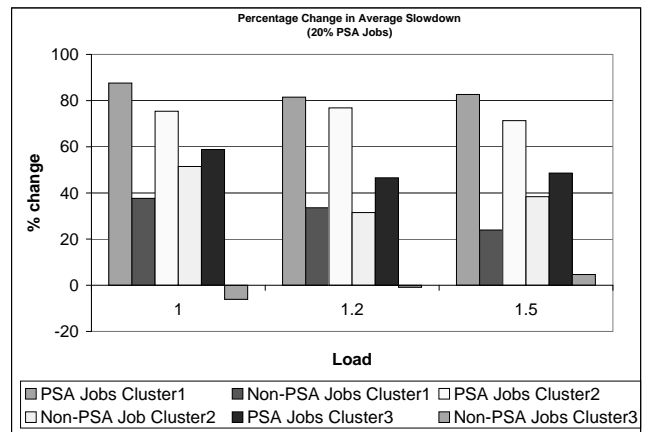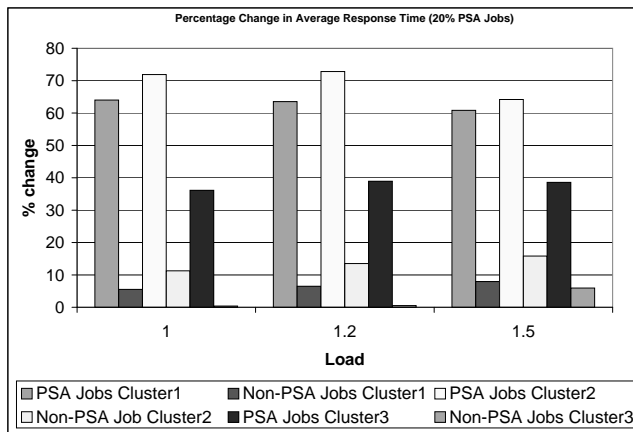
Figure 92. Multi-Site Evaluation (20% PSA Jobs, Inaccurate User Estimate, SJF priority scheme): (a) Average Response Time; (b) Average Slow Down
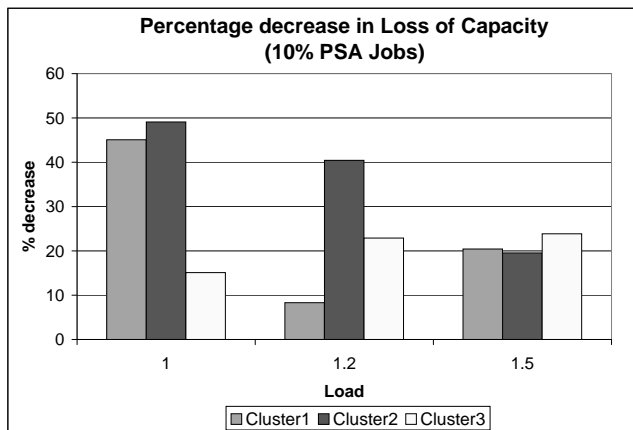

Figure 94. Multi-Site Evaluation (10% PSA Jobs, Inaccurate User Estimate, SJF priority scheme): Loss of Capacity
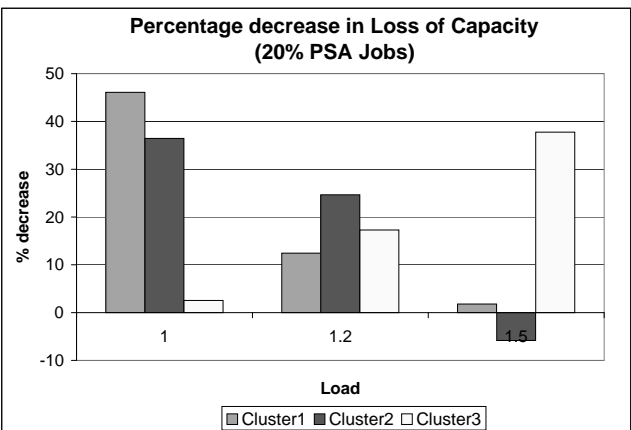
Figure 95. Multi-Site Evaluation (20% PSA Jobs, Inaccurate User Estimate, SJF priority scheme): Loss of Capacity