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Department of Management, Economics and Industrial Engineering

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# *Effects of disturbances and Order Release frequencies on ORR methods' performances*


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# *Executive Summary*

Over the years there has been implementation of lean techniques in many companies with the purpose to improve efficiency, productivity, and to seek many other benefits. The Association for Operations Management, abbreviated as APICS, describes lean techniques as: "A philosophy of production that emphasizes the minimization of the amount of all the resources (including time) used in the various activities of the enterprise. It involves identifying and eliminating non-value-adding activities in design, production, supply chain management, and dealing with customers. Lean producers employ teams of multi- skilled workers at all levels of the organization and use highly flexible, increasingly automated machines to produce volumes of products in potentially enormous variety. It contains a set of principles and practices to reduce cost through the relentless removal of waste and through the simplification of all manufacturing and support processes" (APICS Dictionary, 2013).

The lean concept was first introduced in companies producing specific products in large quantities in a repetitive way such as car manufacturing companies with the purpose of improving productivity; and more important, enhance the competitiveness of the company to be able to stand in a market each time more difficult, more competitive and with many other competitors. However, the lean techniques as a philosophy, soon was adopted by other types of companies with the same objective to seek efficiency, productivity and competitiveness. Such is the case of the Make-to-Order (MTO) industry, which is characterized by the high level of customization. Therefore, MTO companies require a high level of flexibility in their process. This type of companies and their production highly depend on their customers since they give the requirements for the products. Thus, each time the customer has a stronger power and for what the MTO companies need to adapt and work on ways to satisfy the customers and their needs. MTO companies deal with the production of several products with different specifications, thus the organization for production and planning has a relevant role. All of it with the purpose of achieving better performances. One of the most important performance parameters for the MTO companies is the lead time which became to be as an indicator for competitiveness (Stevenson et al. 2005). Other advantages are obtaining more efficiency, more productivity, better delivery reliability, better quality, more machine utilization rates, and many others.

Considering the complexity in managing the production system and schedule in MTO companies, it is crucial the existence of an effective production planning and control system. One of the goals of

the approach seeks to regulate the flow of jobs within the shop floor to achieve lower throughput times and controlled work-in-progress (WIP) levels. This brings to the development of the Order Review and Release (ORR) system. ORR approach aims to control the job processes on the production system and it consists on different criterias to manage it through the management of customer orders, their prioritization, and their release for production. Different methodologies of ORR were proposed and studied to find out the most suitable and effective ones considering the characteristics of the company. The development of the control of work load is agreed by many scholars to be done primarily for the MTO industry in which the customization level is high as well as the product range, called also as 'non-repetitive companies' (Portioli and Tantardini 2012). Another relevant aspect is the configuration of the shop floor. A theoretical pure job shop configuration consists of undirected process flows and random routing sequences (Oosterman 2002) However, in real world it is becoming more common to find companies with a flow shop configuration which has recognizable process streamlines and dominant flows. Portioli and Tantardini (2012), as many other scholars, emphasize the importance of focusing on shops with a dominant flow. They consider that studies of ORR methods based on pure job shops are not appropriate to be applied for real shops as pure job shops are rare or unrealistic. Apart from the inherent dominant flow existent in real shop, they also point out that lean implementation has also effect on this matter because it streamlines production flow and makes this flow unidirectional, and it reduces setup and lot sizes. Therefore, they consider that many manufacturing companies are better regarded and modelled as flow shops.

The ORR methods are used to improve productivity and look for optimization in a regular shop in an MTO company. The criterias and methodologies in which the ORR method is based on, plays an important aspect for the success and efficiency of the method. The focus of this thesis is completely based on the analysis of the performances and effectiveness of ORR methods under different situations and it has two parts. The first one is related to the order release phase of the ORR method, specifically the analysis of the effects of the order release frequency on the overall efficiency and performance. On the other hand, the other objective of the thesis, is to analyze different ORR methods and their efficiency and performance in situations in which disturbances play an important role. The disturbances considered for this study are the level of machine breakdown or failure and the level of distortion and which are described in detail in the following sections of the paper. It is believed that the results of the study will serve as a support for management decisions on the appropriate ORR method suited for the different scenarios that may be encountered in real life.

A quantitative approach is used to carried out the thesis research. This is done through simulation modelling. For such purpose, the computer program Python©3.4 SimPy© module is used to model an MTO pure flow shop, since it better resembles real shop floors as it was mentioned already, and simulate the shop configuration under the different workload control methodologies to analyze their performances at different scenarios according to the objectives of the thesis. The studied ORR methods are in total eight and they differ in their methodologies regarding three criteria: the aggregation of workload measure, the release of orders to the shop by workload control, and the sequencing of orders in the pre-shop pool. The results of the thesis confirmed what is was demonstrated by Portioli and Tantardini (2012) that regarding the workload control, the Balancing methodology outperforms the Limiting one. The results also prove the advantage of implementing the short-process-time criteria rather than the first-come-first-served one for the sequencing rule. Though the two sequencing rules used on this study are quite simple, other studies suggest that the sequencing rule should also include balancing considerations such as the one developed to balance loads only when there are many urgent jobs (Thurer & Stevenson 2014).

Concretely, two research questions were formulated for the study. The first question is: *Under the diverse levels of breakdown and distortion, what ORR method is the best performing one? And which methods are the most robust and stable in their results at different scenarios?* And to which the answer is: This study focused on the analysis of the ORR methods in a shop floor characterized to have a pure flow process and machine (station) processing time modeled by the lognormal distribution and a simple FCFS dispatching rule. Other papers analyze the effectiveness of using the operation due-dates of the orders as the criteria for the sequencing in the workstations (Lödding 2017). The model of our shop floor undergoes two types of disturbances: machine breakdown and distortion. Five parameters were used to analyze their performances in the different scenarios and identify the best performing method. Regarding the parameters gross throughput time (GTT) and shop floor time (SFT), the AB/S method reaches the best performing point in each and all disturbance scenarios individually. The second best performing method in these two parameters is not only one but two, AB/F and RB/S, depending on the disturbance scenario. The performance results of these two methods are very close in all scenarios. This confirms the superiority of applying the Balancing Release criteria since it is present in all these three best performing methods. On the other hand, for the other three parameters which are tardiness, percentage of tardy orders, and standard deviation of lateness, the Limiting Release approach seems to have a slight advantage that is not very significant over the Balancing approach only when the breakdown and distortion levels are low. As those levels increase, the advantage of the Limiting approach on those parameters, disappears. Even though AB/S performs better in each disturbance scenario regarding the GTT and SFT, when analyzed in situations of varying levels of disturbances, it is not the method being the most stable (robust) in its results. The most robust method on GTT is RB/S, and the method most robust on SFT is the AB/F. Once again, we can see the presence of the Balancing release approach on these methods. However, though AB/S is not the most robust method on GTT and SFT, it appears to be so for the other three parameters: tardiness, percentage of tardy orders and standard deviation lateness. These three most robust methods use the Balancing approach and the results is consistent with the study of Cigolini and Portioli (2002).

The second question is *How does the frequency of order release to the shop, affect the results of the ORR methods in terms of the performance indicators?* And to which the answer is: The previous study was done having an order release frequency of eight hours, thus the whole study was carried out on a fixed release frequency. For the study of this section, this release frequency is not maintained constant but it is varied to see the impact on the performances of the ORR methods. In addition to the frequency of eight hours, other three frequencies were tested: release frequencies of six, four, and two hours. In this section, not all ORR methods were studied but only four of them, AB/F, AB/S, AL/F, and AL/S. The disturbance scenarios implemented were only of the distortion while doing all the experiments only on the low level of breakdown. The objectives were to compare the results of the Balancing and Limiting approaches and how they differ when the order release frequency varies, and how the distortion level affects these approaches. The results of the study show that all methods improve their performances as the order release frequency increases. Increasing the order release frequency makes the discrete release approach (the one of this thesis) to become closer to the continuous release approach and to the benefits of it (Fernandes and Carmo Silva 2011). The improvements are more notorious and significant in the GTT and SFT parameters which are the most relevant, while the improvements on the other parameters are of less impact. This means that as the frequency of order release increases, there is a reduction on the values of GTT and SFT for all methods. The reduction on SFT means a better control on WIP which could be especially important when the manufacturing system can have a very high product mix (Olaitan et. al 2017). Recent studies show a significant performance improvement for continuous order release in terms of mean tardiness and standard deviation of lateness by triggering the avoidance of starvation (Fernades & Thurer 2017). The next step was to make a comparison between the performance improvement on each method, specifically between the Balancing and Limiting approaches. The analysis is done focusing only on the GTT since this parameter is the main performance indicator (Land 2006). The reduction of the GTT is higher on the Balancing method

(AB) than the Limiting one (AL) on terms of absolute value and of percentage in all cases, for each order release frequency (2, 4 and 6 hours' frequency) when compared to the one of 8 hours and at the different distortion levels. The reduction of the GTT is higher for AB than AL for both sequencing rules, FCFS and SPT. On the other hand, a high degree of distortion diminishes the benefits of increasing the frequency of order release in all methods. This means that when increasing the frequency of order release, the improvement on the GTT (reduction of its value) decreases as the distortion level increases.

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# 1 Introduction

## 1.1 Background

Over the years, since the industrialization began, the world has been witness of periods of great changes and improvements which are called industrial revolutions. The third industrial revolution that is the last one, was due to the contribution on automatization for the manufacturing sector thanks to inventions such as the microprocessors. Nowadays the industry 4.0, the future fourth revolution, is a very hot topic since it will allow the networking of the different players in the manufacturing industry through the analysis of Big Data and by means of cyber-physical systems. The industries are directing their actions and decisions towards those that will bring them closer to the fourth revolution. Therefore, during the last years, there have been implementations on the industry with the purpose of improving productivity, and more important, enhance competitiveness on a company to be able to stand in a market each time more difficult, more competitive and with many other competitors. An example of those implementations is the lean techniques which were developed focusing on the companies characterized by the production on high volumes and of very low customization. The lean techniques as a philosophy, soon was adopted by other types of companies with the same objective to seek efficiency, productivity and competitiveness. Such is the case of the Make-to-Order (MTO) industry, which is characterized by the high level of customization. Each time the customer has a stronger power and for what the MTO companies need to adapt and work on ways to satisfy the customers and their needs. MTO companies deal with the production of several products with different specifications, thus the organization for production and planning has a relevant role. All of it with the of achieving lower product throughout times, better delivery reliability, better quality, more machine utilization rates, as many other advantages. Lean philosophy states that the obstacles preventing a company to achieve better results on the aspects described, are wastes, thus the objective is to target those wastes, to then reduce and eliminate them. Considering the complexity in managing the production system and schedule in MTO companies, it is crucial the existence of an effective production planning and control system. One of the goals of the approach seeks to regulate the flow of jobs within the shop floor to achieve lower throughput times and controlled work-in-progress levels. This brings to the development of the Order Review and Release (ORR) system. ORR approach is to control the workload on the production system and it consists on different criterias to manage it through the management of customer orders, their prioritization, and their release for production. Different methodologies of ORR were proposed and studied to find out the most suitable and effective ones considering the characteristics of the company. In real world, the production system in not isolated but influenced and affected by diverse external agents, therefore the performances of the ORR methods are subject to those externalities as well.

## 1.2 Research Objectives

The ORR methods are used to improve productivity and look for optimization in a regular shop in an MTO company. The criterias and methodologies in which the ORR method is based on, plays an important aspect for the success and efficiency of the method. Several studies have been carried out to analyzed the performances and results of different ORR methods. One example is the suggestion of using the workload amount as a measure to control production in the shop to be more efficient and accurate than measuring the number of orders (Bergamaschi 1997). Another example is the conclusion of Portioli and Tantardini (2012) stating that the release of jobs to the shop is better carried out through a workload Balancing approach rather than a simple Limiting one. The focus of this thesis has two parts. The first one is related to the order release phase of the ORR method, specifically the analysis of the effects of the order release frequency to the shop on the overall efficiency and performance.

On the other hand, the production process in an MTO company is not completely carried out as planned or scheduled due to diverse disturbances like events or externalities negatively affecting the production. There are different types of disturbances and whose importance depends on the degree of impact. When the impact is great, it means that the eventual occurrence of the disturbance generates considerable losses which are not only monetary but reputation, customer/client relationship and many others. Some disturbances could be avoided but others are unavoidable and they can only be prevented to reduce their effects. Some of the unavoidable disturbances are the machine breakdown and the distortion affecting production. Machine breakdown is an undeniable event in the shop thus the overall efficiency and productivity is affected. The ways to handle this issue is an important aspect and that can be managed at the production planning phase. In other words, through the Order Review and Release system or ORR methods. In the same way, the distortion present in the shop may not be completely unavoidable but it could be prevented and a best solution can be sought to be adapted in those situations by means of a proper ORR method. A great number of studies have been done on ORR methods to analyze their performance on situations free of disturbances, but since these are far from reality, there is the need to deeply investigate the effects of those disturbances. Therefore, the other purpose of the thesis, is to analyze different ORR methods and their efficiency and performance in situations in which the of disturbances described above, play an important role. The results of the study will serve as a support for management decisions on the appropriate ORR method suited for the different scenarios that may be encountered in real life.

The objective of the thesis described above can be summarized and concretely represented by the following research questions:

I. **First research question**: Under the diverse levels of breakdown and distortion, what ORR method is the best performing one? And which methods are the most robust and stable in their results at different scenarios?
II. **Second research question:** How does the frequency of order release to the shop affect the results of the ORR methods in terms of the performance indicators?

## 1.3 Research Methodology

A quantitative approach is used to carried out the thesis research. This is done through simulation modelling. For such purpose, the computer program Python©3.4 SimPy© module is used to model an MTO pure flow shop and simulate the shop configuration under the different workload control methodologies to analyze their performances at different scenarios according to the objectives of the thesis. Several tests are done adjusting the model for the characteristics of the different scenarios and whose quantitative results are collected and analyzed through parameters to understand the performance of each ORR method. There are in total five parameters taken for the performance analysis and which will be described in detail in the later sections. The results obtained from the research can be regarded as concrete conclusions to be of support on the decisions of the suitable methods for the diverse situations studied.

## 1.4 Thesis outline

The thesis is divided into five chapters. The first chapter, the current one, gives a brief introduction of the topic, but more importantly introduces the objectives of the thesis and the methodology used for the study. The second chapter covers the literature review. All the concepts necessary to understand the methodologies of the ORR methods are described. All directed on how performance can be enhanced by workload control. The disturbances affecting the production are also described and their modelling is explained. In chapter three, the simulation modeling is described in detail as well as how the basic concepts which are the foundations of the ORR methods are linked to the modeling. Then the design of experiments to be realized to answer the proposed research questions, is explained. Chapter four is the most important one since in this section all the experimental results are exposed through deep analysis. The fifth chapter, last chapter, presents the conclusions drawn from the experimental results and the research questions are answered.

# 2 Literature Review

## 2.1 Challenges of Make-to-Order Companies

During the last part of the past century, new methodologies and ways of thinking which started in Japanese car manufacturing company Toyota, became popular in the European and in the American industry as well. These methodologies were called lean production and its aim was to improve the efficiency and productivity of a company thus making it more competitive. Lean relies in the objective of eliminating those activities that does not add any value to the product or that simply makes the production process more costly and ineffective. And obviously, the reduction of defective products is sought as well. According to the lean techniques, there are three types of wastes. They are: muda, mura, and muri. Muda are all the non-value adding activities that waste time and resources. Taiichi Ohno includes in this classification transportation, inventory, worker's movement, worker's waiting time, over processing activities, over producing, defects. Mura is the waste of unevenness and inconsistency which will in turn originate the wastes described in muda. An improper smooth of demand creates problems on the processes and on resources such as the operators, therefore creating wastes like inventory. Muri is related to the unnecessary stress given to the workers and can be caused by mura. Since mura creates muda and muri, it is important and crucial to focus on the reduction or elimination of mura. In order to achieve this objective, lean techniques aim at eliminating all types of wastes that are not necessary in the production process. There are two main concepts which are the basis for lean. The first one refers to the production and to the timing of processes to be exact in the right moment at which they are required and at the right place. This concept is called just-in-time. The other concept, known as jidoka, seeks a more innovative interaction between the machines and the operators in order to make it easier the recognition of any problem in the system, in the process or a defect on the product before and prevent any further problem. The Association for Operations Management, abbreviated as APICS, describes lean techniques as: “A philosophy of production that emphasizes the minimization of the amount of all the resources (including time) used in the various activities of the enterprise. It involves identifying and eliminating non-value-adding activities in design, production, supply chain management, and dealing with customers. Lean producers employ teams of multi- skilled workers at all levels of the organization and use highly flexible, increasingly automated machines to produce volumes of products in potentially enormous variety. It contains a set of principles and practices to reduce cost through the relentless removal of waste and through the simplification of all manufacturing and support processes” (APICS Dictionary, 2013).

Even though the lean thinking and techniques started for companies characterized or identified as Make-to-Stock (MTS) companies, the benefits of this way of thinking were incentives to try to adapt these philosophy to other types of industry sectors such is the case of the Make-to-Order (MTO) industry. As a difference from MTS companies, MTO companies are characterized by a high level of product mix and small production quantities (batches). One of the difficulties of MTO companies is the forecasting of production volumes and mixes for the planning stage (Stevenson, 2005). Table 1 describes the differences between MTS and MTO companies.

| Features | MTS companies | MTO companies |
|---|---|---|
| Annual production volume | From 100,000 to 1,000,000 units per year | From 5,000 to 20,000 units per year |
| Shop floor | Line production, Flow shop | Job shop |
| Structure of demand | High and stable | Low and variable |
| Order winner | Time to market | Delivery time |
| | Efficiency | Productivity |
| | Market response | Quality |
| Order qualifier | Delivery time | |
| | Efficiency | Time to market |
| | Productivity | Wide product range |
| | Quality | |

*Table 1. Differences between Make-to-Stock and Make-to-Order companies*

Due to the characteristics of MTO companies it is difficult to implement the lean methodologies in the same way as in MTS companies but there is the need to adapt them to these characteristics. One of the most important performance parameters for the MTO companies is the lead time which became to be as an indicator for competitiveness (Stevenson et al. 2005). A more competitive lead time means more efficiency, productivity, better production planning and scheduling. All these have to be reached by considering the high variability in the workload and in the demand, and can be covered by planning and controlling the production. Production planning and controlling (PPC) have several functions such as demand management, planning material necessities, scheduling and sequencing of orders and capacity planning. The main goals are the reduction of WIP and throughput time, minimization of costs related to stocks, improve flexibility to late changes in demand and adherence to due date. That is why decisions regarding PPC systems are extremely important.

The development of the control of work load is agreed by many scholars to be done primarily for the Make-to-Order (MTO) industry in which the customization level is high as well as the product range, called as ‘non-repetitive companies’ by Portioli and Tantardini (2012). However, even within this industry sector, there are companies with different characteristics. Stevenson (2005) mentions three relevant characteristics to identify the kind of MTO environment. These characteristics are: the shop floor configuration, the level of repeat production, and the size of the company. The shop floor configuration refers to flowing direction of the process, whether it is a general flow shop (same flow direction but with some customized resources) or a general job shop (multi-directional flow but with a probable dominant one). The level of repeat production refers to whether the company is Versatile Manufacturing Company, in which case it negotiates each order separately; or if it is Repeat Business Customizer, in which the company negotiates several orders in a single contract. And the size of the company refers to whether the company is a Small-Medium company or a large manufacturing enterprise. A deeper detail is given by Hendry (2005) to categorize the type of MTO production by: identifying the point at which the order is received from the customer and therefore categorizing it as Engineer-to-Order (ETO), Make-to-Order (MTO), or assembly to order; and identifying the customization type offered at the point of receiving the order that can be either pure, tailored or standardized. In addition, Tobin (1988) classifies the industry according to the type of production, which is basically the Capital Goods industry versus the sub-contracting industry. Table 2 summarizes the different dimensions by which a company can be categorized and described.

| Dimensions | Types |
|---|---|
| Market | Capital goods, Sub-contractor |
| Shop floor configuration | General flow shop, General job shop |
| Type of MTO | Engineer-to-Order, Make-to-Order, Assemble-to-Order |
| Level of repeat production | Versatile Manufacturing company, Repeat Business customizer |
| Company size | Small-Medium Enterprise, Large Manufacturing Enterprise |

*Table 2. Characteristics of companies in the MTO industry*

In the same way that Osterman investigated the Work Load Control and its functioning performance in shop floor models that are different from pure job shops, there are also other studies which focuses on shop floors with diverse characteristics to those of the pure job shop. For instance, Salegna and Park (1996) look specifically into certain bottlenecks within the job shops. Bertrand and Van de Wakker (2002) run simulations including assembly operations on them. Sabuncuogly and karapinar (1999) consider transportation times in their studies. Missbauer (1997) investigates the set-up times which are dependent on the production sequence and their effects. Henrich (2004) studies shop containing sub-departments. All these job shop modelling approaches coincide in the way that they regard the capacity groups as given. These capacity groups are mainly considered as single machines but in some cases, they are conformed of a group of machines fed by one queue of orders. However, the decision on how and what machines should be classified into the same capacity group, was not addressed by these studies. Henrich (2006) firstly considers this issue and in his paper, investigates the impact machine grouping has on the work load control in MTO companies and the its effectiveness.  Due to the different characteristics of the machines, he discusses the most common choices on machine grouping and shows that this decision, that is based on similar machines on the shop floor, cannot be taken independently from the process routings. Henrich considers three machine characteristics to be relevant for the decision on machine grouping. These are:

1) Process Characteristics: These characteristics are defined by the way on which the products are processed or operated. For example: separation, layering, reshaping.

2) Functional Characteristics: Machines may have the same or similar process characteristics but different functional ones. For instance, a laser and a saw are used for separation (same process characteristic) but the saw is used to for cutting large metals whose process is not complex and have higher tolerance, while the laser is used for cutting thin metals with a high precision. Machines of same process characteristics and be classified according on their functional characteristics into three categories.

- *Interchangeable machines:* The machines are completely interchangeable. All products processed on machine X, can be processed on the way in machine Y.
- *Semi-interchangeable machines:* Machines are not totally interchangeable. Only some products can be processed on the same way on both machines X and Y, but other products can only be processed on either one of them.
- *Non-interchangeable machines:* Products processed on machine X cannot be processed on machine Y.

1) Operational Characteristics: Machines which are functionally interchangeable may differ in their operational characteristics. These characteristics are defined by their processing times needed for the completion of an operation. The operational characteristics can be:

- Identical: When several machines need the same processing time to perform the same operation on a specific order.
- Different: Different kinds of relationships could be considered. Cheng and Sin (1990) has a detailed description on this.

## 2.2 Shop floor types and characteristics

Over the years there has been implementation of lean techniques in many companies with the purpose to improve efficiency, productivity, and to seek many other benefits. Even though the lean concept was introduced first for companies producing specific products in large quantities in a repetitive way such as car manufacturing companies, this concept was also spread to other types of companies which have a higher variety of products produced in smaller quantities. This is the case of Make to order companies and Engineering to order companies. These types of companies and their production highly depend on their customers since they give the requirements for the products. Therefore, Make to order and Engineering to order companies require flexibility to be a characteristic in their production systems. This is achieved by having a job shop configuration. However, production planning and management in this type of configuration is also very complex compared to other configurations systems (for instance a production line). Theoretically a job shop does not have a definite production sequence neither a production length thus all types of process routing and lengths are possible. However more realistic shops may not be as a known job shop but may differ from it. Oosterman et al – 2000 introduces different shop floors and analyzes their process and layout characteristics for the control of workload. The types of shop floors are:

1) Pure job shop: in this type of shop floor, the flow of any product production can be random. Any stage in the floor has the same probability to be the first stage and as well it has the same probability to be the last stage in the production. This type is mostly theoretical and is difficult to find in real world a shop floor with such characteristics.

2) General flow shop: There is a known flow direction on the shop floor therefore the probability of each stage of being the start of production is not the same for all but it gradually decreases. This is also because in this type of shop floor, not all stages are necessary for the manufacturing of a product thus the production length is not necessarily equal to the number of stages.

3) Restricted job shop: in this type of shop floor, all jobs visit all the stations but the production sequence is completely random.

4) Pure flow shop: all jobs visit all stations in an orderly manner

Oosterman shows that the flow characteristics of job shops in real life have different influences on the workload control approach used and thus on the performance. In fact, the approach that performs the best for the pure job shop which is mainly theoretical, shows to be the worst approach when implemented in a shop which is characterized with a dominant flow. When the shop is dominated by completely undirected flows, such in the case of the pure job shop, it turns out to be important to have a good estimation on the direct load of each station and on the influences of the new job releases on these. However, as the flows becomes more directed and a dominant flow appears, centering the attention solely on the direct load estimation might create effects which are undesirable. In this case, the approach of aggregation of workloads is more suitable for control.

The importance of focusing on shops with a dominant flow is also mentioned by Portioli and Tantardini (2012), who considers that studies of ORR methods based on pure job shops are not appropriate to be applied for real shops as pure job shops are rare or unrealistic. Apart from the inherent dominant flow existent in real shop, they also point out that lean implementation has also effect on this matter because it streamlines production flow and makes this flow unidirectional, and it reduces setup and lot sizes. Therefore, they consider that many manufacturing companies are better regarded and modelled as flow shops.

## 2.3 System control for MTO companies

The objectives of manufacturing control are several but the reduction of lead times and the of the WIP levels are ones of the most critical. The production in MTO companies are characterized to be in small batches that are planned to be delivered in a certain date, however this established date is often not met and thus there is a poor performance in this issue. To have shorter and more reliable delivery dates are desirable for customer satisfaction and value creation. Thus, in many cases companies try to achieve good delivery date performance by increasing the levels of WIP. In addition, the real lead times turns out to be way longer and different than the planned ones (Bechte 1994). However, lead times are important because many activities carried for production rely on them and on the accuracy with what they are established. As an example, all types of Manufacturing Resource Planning (MRP) require the lead time for the detailed planning of the different materials, tools, components and capacities which are needed for production. Therefore, exactitude of the lead times establishment is important to ensure the delivery date is kept and to support decision on the shop floor such as production priority criteria. Manufacturing based on load controlling focuses on keeping stable and reliable lead time to guarantee the proper flow of the schedule activities. Only short and determinable lead times facilitates production to be done on time and to make the MRP applicable (Bechte 1994). It is crucial in load-oriented manufacturing control to real lead times on a planned level to regulate it. By doing so WIP is limited and balanced to levels as low as possible in order to reach higher machine utilization at the different workstations as well as shorter shop floor throughput time of jobs.

In MTO companies, the production doesn't start until the customer order is confirmed because of the high degree of customization and all the required settings due to it, and because of the level of uncertainty in this industry. Therefore, considering these issues, it results in longer lead times when compared to MTS companies. Customer enquiry planning and control is relevant in MTO companies to stabilize lead times and have more reliable due dates (Hendry and Kingsman, 1989). The process of releasing jobs may contribute and support the control and decisions on the customer order enquiry and entry. Figure 1 shows a hierarchical control framework and indicates the key production stages to be controlled. The approach developed in the Lancaster University Management School is of this hierarchical structure and it incorporates the customer enquiry and job entry control on it (Kingsman, 2000; Stevenson and Hendry, 2005).

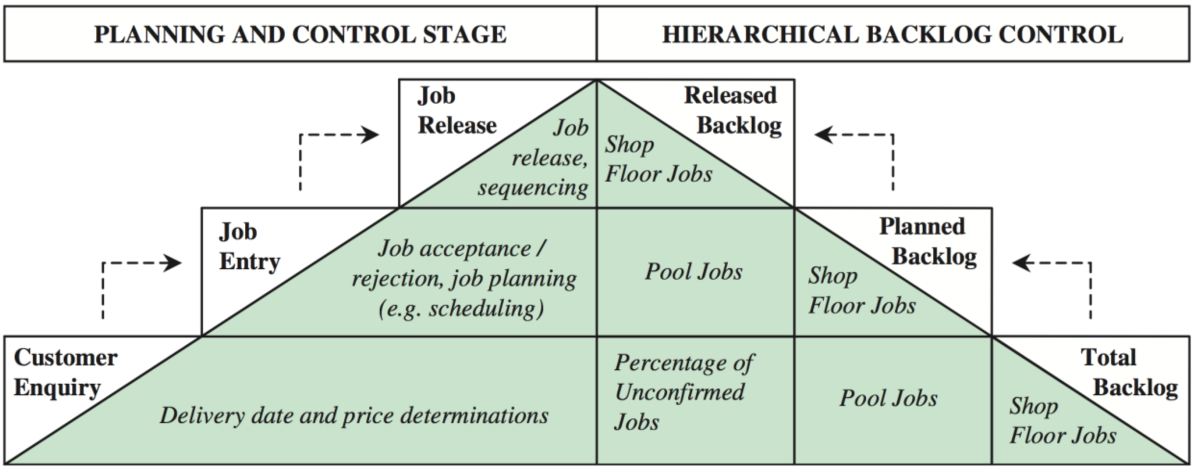



*Figure 1. Hierarchical backlog control framework (Stevenson, 2006)*

Decision Support System is developed to facilitate empirical research on Workload Control and to support and address implementation issues (Stevenson, 2006). The customer enquiry stage is within the Decision Support System and the provided control on it allows the planner to consider the current workloads and the shop capacity at the moment of determining a due date. The Decision Support System uses the expected delays of jobs in the pool and the expected job waiting times in the shop stations to estimate the delivery lead time. This plan is done roughly until the order is confirmed by the customer. This process allows to maintain flexibility for the detailed scheduling level and reflects the uncertainty of the customer enquiry stage. The level of competition in the MTO industry makes the lead times to be shorter, therefore production planning must consider more discrete time intervals. Thus, at each day, the backlog is determined during the current period of planning by taking into consideration the current mix of confirmed jobs as well as unconfirmed ones, and the impact these jobs will have on the total backlog of a specific day which is based on the due date settled. However, Hendry and Kingsman (1993) states that jobs expected to be finished before the current date shouldn't be considered in determination of the total backlog of a shop in each day. Thus having as a result that the total length of the planned backlog should step down towards the end of the planning period.

## 2.4 System Control decisions

In general, in MTO industry, it is very important for the customers the reliability of the delivery. Therefore, this performance is carefully controlled by MTO companies. Decisions on workload control on MTO companies are better divided into input and output control decisions (Kingman, 2000). Input control refers to the order acceptance, promise of delivery date, order release and priority dispatching. Output control refers to adjusting capacities. Figure 2 shows the framework of the workload control showing an overview of the input and output control decisions (Land and Gaalman, 1996). Land (2004) shows that achieving high delivery reliability is the result of controlling the average throughput times and the progress of individual orders. Speeding up the average throughput time reduces the average lateness, and keeping individual jobs on schedule reduces the variance of lateness across jobs (Baker, 1974).

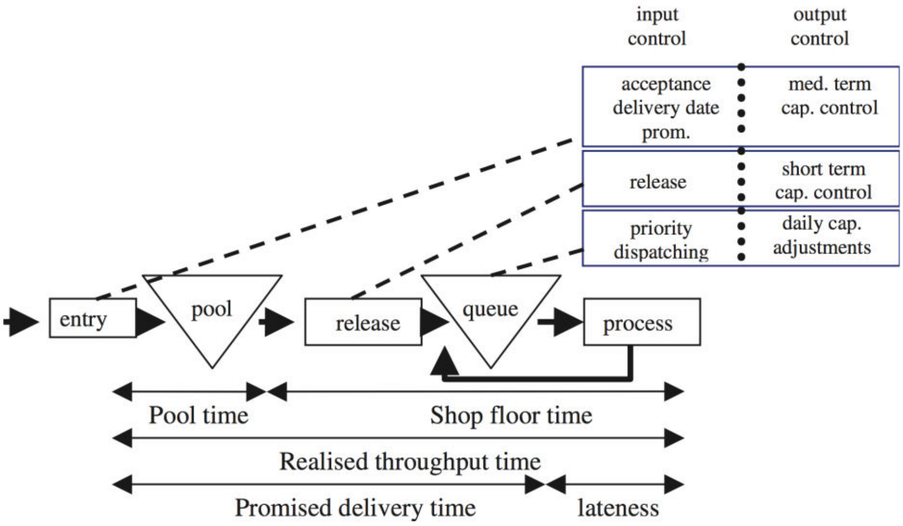



*Figure 2. Input and output control decisions (Soepenberg 2008)*

1) Due dates

The planner is advised with a due date which is provided by the Decision Support System. this is done for each order at the customer enquiry stage and considering the anticipated customer confirmation time and the delivery lead time expected for that job. After the delivery date has been determined, the Decision Support System considers the capacity of the shop. The delivery date of the job is quoted and included in the total backlog only if the by adding this job to the total backlog of the shop, it doesn't exceed the maximum limits. But if this job exceeds the limits, the delivery date is increased by one day and verified again if it falls within the limits. This is done until the resulting total backlog remains within the limits (Stevenson, 2006).

When the due date obtained from the Decision Support System is considered not competitive by the user or planner, this one can change the constraints of capacity on the appropriate dates and thus increasing the capacity of each day and reducing the total backlog of the shop. This makes the system to be a more flexible I/OC capacity management tool.

Osterman et al. (2000) and Land (2006) describe the setting of due dates in which a random allowance is added to the job entry time. The minimum value should at least cover a work station whose throughput time is five time units that is the maximum processing time plus one time unit. This considering a maximum of six operations plus a waiting time before the release of five time units.

$$Due\ date = Job\ entry\ time + a, where\ a\ is\ uniformly\ ditributed$$

2) Decision support at the job entry stage

A proper management of customer enquiries may aid to have a more sustainable mix of jobs at the orders entry stage by having for example stable shop floor resources, delivery dates evenly determined throughout the planning period. The entry of orders differs from case to case, for some it may be right after the enquiry of the customer and for others it may be some days or weeks after. Therefore because of this variation, when the quotation proposed to the customer is accepted, the company needs to check whether the proposed delivery date proposed in the quotation, can still be achieved. This is done before the workload of the job is integrated into the total backlog and added to the planned backlog length. In the case that the order is rejected, the Decision Support System reduces the total backlog by subtracting the work content of the order rejected.

3) Decision support on the shop floor

When an order is released to the shop, it is important to have the feedbacks with information regarding the status of the work stations and of the workloads, to be updated or the job may give a longer backlog than needed to the work station and so affecting negatively the correct process of job release. As the release policy becomes more continuous, the feedback process should be also more continuous. An automatic feedback is unrealistic and impractical in the same way that is unrealistic to have the backlog of the work stations automatically depreciated. This may result in the operator concentrating or focusing on jobs that are behind schedule, therefore leading to a delates on the delivery dates. Stevenson (2006) proposes a module which deals with this issue.

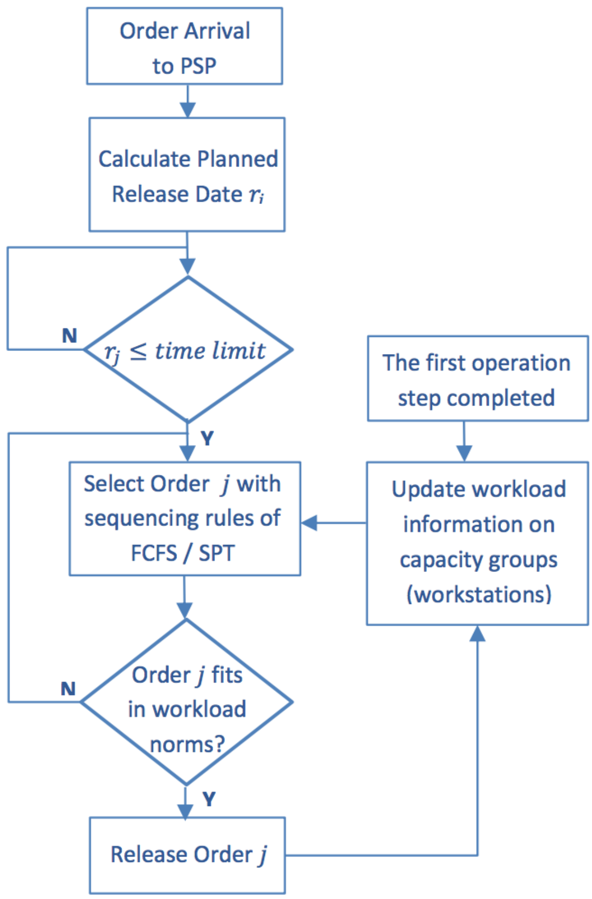



*Figure 3. Decision making chart (Fernandez & Carmo-Silva 2010)*

Figure 3 gives a general description on how the process of decision making is done. It shows how the decision of which order to choose for release and when depends on the ORR method used. When new orders arrive to the pre-shop pool or when the first operations are finished, there is an automatic update of the workload information and the process for the selection of the next order to be released, is started. Orders having their planned release time smaller than the established time limit are potentially considered for release (Land 2006).

## 2.5 Order Review and Release (ORR)

### 2.5.1 Role of the ORR in the shop floor control

The objective of managing job shops is to optimize production through planning and management with the objective of having high machine utilization rate, low work in progress levels (WIP), low quantities of orders delayed, and low throughput times. Several studies were carried out in order to find out the best method which meets all of these objectives. Most of them deal with workload on the shop but treat them differently. Some studies focus on analyzing the order release process only.

Other studies target not only the order release process but also the management of queues in the different stations. ORR can be considered as a component of a more complete control system whose functions are described by Melnyk (1985):

1) Detailed scheduling: is the process for matching the demand, which are the orders and preventive maintenance, with the shop resources such as workers, machines, tooling, and materials. Order priorities are also set on the shop floor.

2) Data collection and monitoring: is the collection of information about orders and resource status to then compare this collected data with predetermined standards for identifying possible deviations.

3) Control and feedback: activities needed to fix Out-of-control situations.

4) Order disposition: activities needed to close out the orders on its completion.

ORR precedes the control activities describe above. The role of ORR is to determine what orders are released to the shop-floor, at what time they are to be released, and under which conditions the release takes place. How these decisions are made influences the subsequent activities of the control system (Melnyk, 1989).

### 2.5.2 Phases of the ORR method

Bergamaschi (1997) describes the order review and release consisting of three phases: an order entry phase, a pre-shop pool management phase, and an order release phase.

1) Order entry phase: This phase serves as an interface upstream in the internal supply chain. It is the phase that cooperates with the planning system and receive the information directly from the customer's orders. Depending on the characteristics of the products, some engineering activities are applied if they are necessary, for instance when highly customized products are placed in the orders. In this phase, all the required information for the production of the orders is also verified such as the availability of the required material, equipment, tools, human power and resources (Philipoom & Fry, 1992). If after checking

that all the required resources needed are available, the orders are accepted, otherwise they are rejected. Also, a date for the delivery of the finished products is assigned for the accepted orders. All accepted orders are placed in the pre-shop pool. Hendry (2008) further differentiates the Order Entry phase into two stages. They are:

i) Customer Enquiry Stage: At this stage, some planning and control is given when a customer enquiry arrives. Mainly the due dates for those orders are promised considering the status of the shop workload but also considering the outstanding bids awaiting the conformation or rejection from the customer.
ii) Job Entry Stage: At this stage, the order is confirmed and further planning and control is carried out regarding the requirement of resources to ensure that input-output balance is maintained and a more detailed capacity plan is done as well.

2) Pre-shop pool management: The phase of the pre-shop pool management is a storage for the data and information of the orders which are accepted in the order entry phase. This database also stores the related information regarding the documents and the requirements such as raw material. Every single order passes through this phase before it is released to the shop for production. The existence of a pre-shop pool protects the shop from external dynamics such as demand variability, it reduces the impact of changes in production by delaying final decisions, it increases flexibility for modifications on the orders, and facilitates the job of the operator in the shop. There are different rules from which the orders are queued in the pre-shop pool. The most simple one the first come first served rule (FCFS). Other rules are based on their priority: earliest due date, earliest release date, critical ratio, capacity slag based rule. The ones used for the studies on this thesis are:

- First come first served (FCFS)
- Short process time (SPT)

3) Order Release phase: From all phases, this is a very important one since it is the decision to choose the right order from the pre-shop pool to be released to the shop floor. The criteria for this decision influences the system performance. “Triggering mechanism” or “input control mechanism” is how this criteria is usually named. The information needed is: the status of the pre-shop pool which is the number of orders currently in this database and the order in which they are lined; the status of the shop that is the orders that have been released

to the shop floor for production, the stations at which they are in queue, and the current machines capacity; the planned shop performance in terms of lead times and delivery times. The decision for the release of an order also analyses the time at which this order has to be released in order to meet the desired performance. Land and Gaalman (1996) mentions that the order release phase is crucial for simplifying the remaining process of production system management.

Hendry (2008) considers the pre-shop pool management and the order release phases as a single stage called "Job Release Stage". On top of these phases described by Bergamaschi, Hendry also introduces one more, the Simplified Shop Floor Control.

4) Simplified Shop Floor Control: In which the detailed scheduling task is assumed to be carried out by the shop floor supervisor. The task is simplified because of the reduce workload on the shop as a result from the job release control.

In addition of the effectiveness of the ORR method on achieving a good performance, there have been interest investigating the interactions between these ORR methods and other relevant activities as the dispatching of jobs carried out in the stations of the shop floor. The research of Nicholson and Pullen (1971) concludes that the job release is the most important decision because if it is carefully done and controlled, the simple FCFS dispatching rule is enough to achieve good shop performances. Other researchers such as Bertrand (1983) however argues that even having a good order release decision, the dispatching rule used may play an important role in overall performance which could aid to improve it. The relation between other scheduling activities and the ORR methods were carried out by authors such as Ahmed and Fisher (1992) whose research point out the inexistence of interaction between three activities of a job scheduling. These are the due-date assignment, the order review and release of orders, and the dispatching of jobs. Thus, concluding that the ORR methods should be evaluated while considering all relevant scheduling decisions.

The understanding of the relationship between the work in progress, throughput time, and output rate is essential for an effective workload control. Shimoyashiro (1984) research results supports the implementation of a pre-shop pool in order to prevent uncontrollable increase in throughput time while having the same output rate. It also gave indications on the existence of a critical level of work in progress or of the workload the should be kept in the system because is these levels are too low, it will result in a considerable reduction in the output rate; and on the other hand, having these levels too high will not bring further benefits since the output rate will not increase but the only increase will be in throughput time.

### 2.5.3 Techniques of the ORR phases

1) Technique of load-oriented order entry: as described by Bechte (1994). The order entry is initiated through the MRP or in a direct way to satisfy any special demand. The orders that are planned for production also defines the parts to be manufactured, the quantity needed, the required operations which represents the routing, and the due dates at which the different stations are to receive them. The scheduled operation dates are checked and compared to the available capacity for a midterm planning horizon each time a new order enters. When there is overload, a realistic due date is given and the expected bottlenecks are pointed so order entry and midterm capacity planning are done simultaneously. Overload weeks and free dates are established at each of the work stations according to the process routing. The free date compares the cumulative workload of all orders and operations to the cumulative capacity over the planning horizon. The cumulative capacity is constant when the capacities are constant over the planning horizon, but when these capacities are variable over the horizon, the cumulative capacity is not just a straight line but it is composed of slopes. Load-oriented order entry aims at avoiding problems present in conventional scheduling processes. It avoids backlogs and overloaded weeks as far as possible in advance. The new orders are scheduled in way so that all the required operations fall only into weeks which are under loaded and so don’t worsen a current already loaded situation. The delivery dates shown would be realistic when comparing the dates of the backward scheduled operations of a new order to the free dates of the work stations. When the requested delivery date is earlier than the realistic date, the production planning of those orders should be shifted to the future when possible provided that the bottlenecks are known and their capacities computed in advance. Therefore, the planning of unrealistic due dates can be avoided and due-date performance can be improved substantially.

2) Technique of load-oriented order release: as described by Bechte (1994). Through the release of orders, the required raw material, documents and supplies are allocated to the job shop and the start for production is chosen which is irrevocable. At the load-oriented order

release the planned orders are selected after verifying the available capacities of the short-term planning period. The loads at the work stations are limited and the momentary bottlenecks are indicated so order release and short-term capacity planning are done simultaneously. The procedure consists of two steps: first, the establishment of urgent orders, and second, the release of workable orders. The first step ensures the due dates to be met. The planned orders are scheduled backwards from reliable operation lead times, and so this results in realistic release dates which can be used as priorities. The time limit that has to be at least of the same length of the planning period, allows to narrow the orders down to avoid early order release. The selection of an optimal time limit also contributes to the system control to consider a higher or a lower quantity of future orders in the either case of expected overload or underload. The second step is necessary for the establishment of inventory levels and lead times in the planning process. The orders with highest priorities are considered first for release and they are released as long as the load limits of all the workstations required for their process, are not exceeded. If an order is released, the load content of each workstation is increased according to the load of that order.

### 2.5.4 Dimensions of the Order Release process of ORR methods

The process of Order release from the pre-shop pool can be classified according to their characteristics and properties of this process. A classification framework on the different order release methodologies was built initially by Melnyk and Ragatz (1988) and then furtherly classified by Bergamaschi (1997). Table 3 summarizes the classification of the ORR methods in their different dimensions proposed by Bergamaschi (1997).

| Dimension | Types |
|---|---|
| Order release mechanism | • Load limited<br>• Time phased |
| Timing convention | • Continuous<br>• Discrete |
| Workload measure | • Number of jobs<br>• Work quantity |
| Aggregation of workload measure | • Total shop load |

| | |
|---|---|
| | • Converted load<br>• Aggregated load |
| Workload accounting over time | • Atemporal<br>• Time bucketing<br>• Probabilistic |
| Workload control | • Upper bound limit<br>• Lower bound limit<br>• Upper and lower bounds limit<br>• Workload balancing |
| Capacity planning | • Active<br>• Passive |
| Schedule visibility | • Limited<br>• Extended |

*Table 3. Dimensions of ORR methods described by Bergamaschi (1997)*

All dimensions are described and explained next:

1) Mechanism of the order release

Two types of mechanisms are employed as the technique for process order release. These mechanisms are the load oriented and the time phased.

- Load limited: with this methodology, the release of orders is done every period and so the decision to be taken is which order to select for the release. This decision is based on the characteristics of the order and considering also the status of the shop workload.
- Time phased: differently to the load limited approach, the release of orders to the shop is carried out at periods that are calculated through this approach. The release of orders is done independently of the workload status of the shop. This approach is based on information regarding the orders in the pre-shop pool like the delivery dates, the workload content, the routing for the manufacturing process.

The load limited approach makes it easier to balance and limit the content of workload in the shop, thus the levels of work in progress can also be better controlled. This is evidenced in the fact that this approach was considered for most of the research studies over the time phased approach. However, studies such of Ragatz and Mabert (1988) and of Philipoom (1993), concludes that the time phased approach is better, especially when a dispatching rule not based on delivery dates is used.

2) Timing convention

By the timing convention, the time when an order can be released to the shop, can be determined. The timing convention could either be continuous or discrete.

- Continuous: Under this policy, the release of orders could happen at any moment within the operating period. This policy adapts the concepts of the "order point-economic order quantity" in the sense that it requires continuous control and updates.

- Discrete: at this policy, the release of orders occurs only at certain periods (intervals) which are initially specified. This policy is similar conceptually to the periodic inventory control system. this convention mostly used by practitioners and by researches because of its simplicity.

Depending on the policy used for the timing convention, there are different effects and implications on the efforts of managing the pre-shop pool and the process of order release (Bergamaschi, 1997).

3) Workload measure

The amount of workload is important and it has to be carefully measured in order to know the impact of the released order on the workload of the shop. The amount of workload can be expressed in terms of number of jobs on the shop floor or in terms of the work quantity. Furtherly, the work quantity could be expressed either in hours or as a percentage of the total capacity planned for the period. Generally, the Order release procedure is based on the workload quantity of the jobs and its contribution to the shop workload rather than the number of jobs because when considering the number of jobs when there is high range of products and small lot sizes, this can lead to poor measurements (Bergamaschi, 1997).

4) Aggregation of workload

Regarding the load limited approach for the order release, the workload can be measured in different degrees of aggregation. Melnyk and Ragatz (1988) considers and measures the only total workload on the shop (total shop load) for the process of order release. This way of measuring workload doesn't give information on how the workload is distributed among the different stations on the shop, therefore some problems may arise if for example it exists one or more bottlenecks in the shop floor. An alternative approach was introduced by Glassey and Resende (1988) which controls the workload specifically at the bottlenecks. On the other hand, a more detailed workload measurement can be done when considering the workload at each work station. This allows a more effective control on the shop floor and on the work content at each station. However, this approach requires more information regarding the work stations. Considering the total shop workload approach is much easier but is not as effective and powerful as the calculation of each station workload.

In general, the work content of orders released to the shop can be divided into: direct load which is load from jobs waiting in front of the considered workstation, and indirect load which is the load of jobs currently in line of upstream workstations from the considered station. Oosterman et al. (2000) presented three approaches to measure the workload in the shop floor. These approaches consider the workload of jobs differently depending on the current position of the jobs.

a) One approach known as the converted load, estimates the workload from jobs being at upstream stations from the considered station, for the direct load input of this station. This is done through a method called load conversion and by which the load of upstream stations contributes partly to the direct load of the considered station (Bechte 1994, Wiendahl, 1995). In other words, the load of upstream jobs is depreciated to be added to the direct load at the considered work station. Bechte (1994) establishes a depreciation factor which is:

$$depreciation\ factor = \frac{planned\ output}{load\ limit} = \frac{planning\ period}{planned\ lead\ time + planning\ period}$$

The converted load is calculated by depreciating all the indirect load many times depending on the current position of the job and on the current number of stations that it still needs to go through. Once the job arrives to the considered station, the load is regarded as full and it is not depreciated anymore.

b) The aggregate load is an approach which avoids estimating the load inputs to the direct load of a station. It rather regards the indirect and the direct load as equally and they are just added (Bertrand et al. 1981, Kingsman et al. 1989).

c) This third approach is similar to the total shop load previously explained. As a difference of the other two approaches, this approach considers the workload for a certain station until the job is fully completely with all the operations, even though that job was already processed at the station. It eliminates the requirement for feedback on the finishing of an operation of a certain job but instead it only needs the information of completed orders, thus having no information on the distribution of orders within the shop floor (Tatsiopoulos 1983).

The three approaches given by Oosterman (2000) differs in the load contribution of a job (represented by j) during the course of time. With the converted load approach, after an order release its workload content contributes to downstream stations as their direct load. This contribution increases as the job moves forward closer to considered station. This is illustrated in Figure 4 which also shows the differences between the timing of input and output of the three approaches.

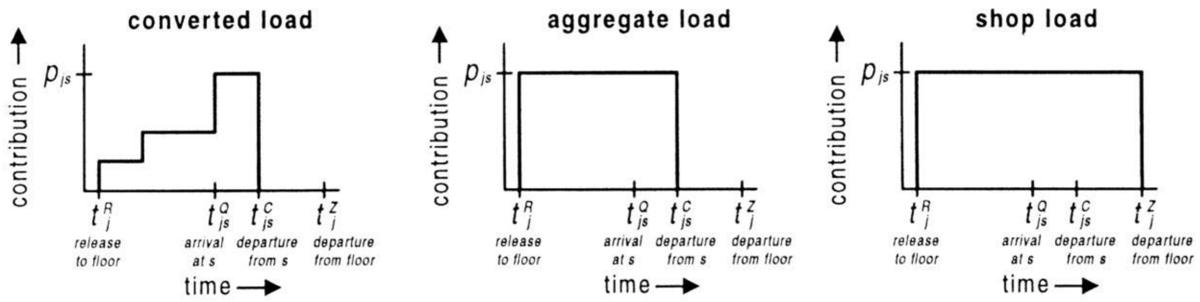



*Figure 4. Workload contribution from jobs through time (Oosterman 2000)*

5) Workload accounting over time

If the approach of the aggregation of workload chosen is the total shop load, the measurement of the workload is simple and the identification on how much the shop will be affected by the workload and when is rather easy. However, when the workload measurement is done at each work station, different types of work content contributes to each station in a specific period. These amounts of work are considered as: load on hand, load in transit, and release load. The load on hand is the amount of work awaiting in the queue before each work station. The load in transit is the work of those jobs that will be processed at our analyzed work station but that currently are being processed at other stations upstream of our analyzed station. The release load is the work content from the orders that will be released from the pre-shop pool. After they are released they are considered either as load on hand or as load in transit depending on the position of the work center in the routing on the order. The workload calculation at the stations that perform the first operations of the order (these stations are called gateways) are easy since there is no load in transit to be considered for these stations. On the other hand, it is more difficult to calculate the workload at the other stations since it is required to carefully estimate the time of jobs currently being at upstream stations or in the pre-shop pool, will arrive to that station. The further the station which performs an operation to a job in its routing, the harder the load estimation. This problem is known as accounting load over time. There are three methods regarding the time on load computation. These are: atemporal approach, time bucketing approach, and the probabilistic approach.

a) Atemporal approach: this approach is proposed by Hendry and Kingsman (1991) and by Philipoom (1993). In this approach, work content of the jobs are considered equally independently of the time when they are released. Therefore, the total processing time calculated at each work station is determined by summing up all processing times and the set-up time required for all jobs that are to be performed at that station. In other words, there is no differentiation between load on transit and load on hand, they are treated in the same way. In this approach, the job routing through the shop is evaluated. An order is released to the shop floor only after evaluating that the current load at each station plus the load of the order to be released, is below a certain limit established.

b) Time bucketing approach: this approach was studied firstly mainly by Bobrowski (1989). Shimoyashiro (1984) and Ragatz and Mabert (1988) proposed a method based on the similar standpoint than this approach, called finite loading technique. In the time bucketing approach, the horizon regarding the order release is divided into periods, also called time buckets, and the workload is calculated at each work station over time. For this purpose, there is a flow estimator that determines at what time each operation of the job will require capacity at each work station on the routing of the job (Melnyk and Ragatz,1989). The required processing time for the job is verified by checking the work station capacity for a certain period. If the required processing time falls within the machine capacity, the job is assigned to that station and its capacity available is decreased accordingly. Otherwise, the process is loaded for the next closest period in which the station has enough capacity available. The workload at each work station is calculated by summing up the load of the jobs that are to be processed in that station in within the period at which the process is planned to be carried out. Therefore, the time bucketing approach, considers the load in transit and release load as load on hand, because it allocates load in transit and release load to the appropriate period when they will become load on hand. This approach requires a scheduling activity to assign each operation of each job that is released to an appropriate period. Thus, the workload for the time periods are set to be equal to the total capacity of the work station during that period.

c) Probabilistic approach: Betche (1988) and Wiendahl (1990) propose this approach. As a difference from the time bucketing approach, it focuses only on the first period of the planning horizon. The period at which the operations of a certain job takes place, is not determined; but rather a probability is estimated. It is the probability for each job to be processed at each work station during the current planning horizon. Therefore, a technique called load conversion is used to calculate the load in transit. It does so by computing the probability of each job currently awaiting in the queues of upstream stations, to reach the considered work station during the current planning period. Thus, the load in transit is recalculated as an expected load on hand by multiplying the required processing time of that job by the probability to reach the considered work station. A load limit is set at each work station as a maximum load to control the load at each of these work stations, to balance the total load in the shop, and to set an upper bound for the average operation lead time. If the work content of the job considered to be released does not exceed the load limit, it is released; otherwise the job waits in the pre-shop pool. The load conversion technique is the pillar of the Load Oriented Manufacturing Control.

6) Workload Control

The process of order release done by limiting the load, maintains the workload of the shop under control. This control of workload is done taking into consideration different approaches regarding the release of jobs to the shop floor. One approach is to set an upper load limit to an appropriate level according to the measure of the aggregation of workload. This approach is proposed by Bechte (1988) and Philipoom (1993), and from whose studies result in a more controlled of work-in-progress levels and smaller variations. In addition to the upper workload bound, a lower workload bound was presented by Hendry and Kingsman (1991) to control the release of the jobs to the shop and to maintain the load of the shop within the limits specified. The purpose of the lower limit in this case is to have an appropriate buffer at each station and avoid starvation. However, since the jobs are only allowed to be released if all the workloads for all the required work stations remain within the limits, in a certain period, some stations may become idle if its workload is mainly composed by jobs currently being processed in upstream stations (load in transit). In these situations, jobs whose first operation are performed by this idle station, are released in order to keep the workload of each work station between the established limits. The use of only the lower workload bound can be reasonable when in the shop there is a station that has the minimum expected idle time. Glassey and Resende (1988) developed a mechanism for releasing orders so that jobs will arrive just in time to the bottleneck station so it doesn't become idle. Lingayat (1991) also uses this lower bound approach in his study.

For Bechte (1994) the relationship at the work station influences on the principle of load limiting approach. This relationship refers to arrival of jobs to the queue of the station and depending on their priorities they can be preferred, or deferred otherwise, for its processing which will result in very different lead times. Having long queues worsens the competition for the process operation that in the case of having first-come-first-served dispatching rule, there will be higher variety of individual lead times (Ketter and Bechte 1981, Wiendahl 1987). However, considering all lead times, the average of them at the work station is the ration of average inventory to average output. The average lead time leads to four rules that are used for planning techniques through a quantitative model that is described by Bechte (1982) and Wiendahl (1987). The four rules are:

- To keep the inventory level constant, keep the input and the output the same on average.
- To change the inventory, the input must temporarily be lower or higher than the output.
- To have the average lead time to equal a certain level, the ratio inventory-output should be properly adjusted.
- To have individual lead times as even as possible, FIFO should be used as the dispatching rule.

The load limiting approach is used for planning the input, output, inventory levels and lead times at the work stations. With a fixed planning horizon, and an established available capacity leads to have certain planned levels of inventory that in turn leads to a level of cumulative input at the end of the planning horizon that is called load limit. The procedure of load limiting starts by measuring the actual inventory at the beginning of the planning period. Subsequently, the extra load which comes from the planned input is established using the load limit.

$$Load\ limit = planned\ output = \frac{planned\ lead\ time + planning\ period}{planning\ period}$$

On the other hand, if the capacity is not fixed but rather flexible over the short term, the load limiting is also used to establish the required capacity that is the present load and it is calculated by increasing the previous load limit by the exceeding load which was rejected before. Lead times sty the same in both cases. The objective of the lead time is to keep sustainable WIP levels at every work station which may be different from one station to another. By lowering the planned lead times which lead to lowest WIP levels.

Authors such as Irastorza and Deane (1974), Shimoyashiro (1984), Portioli (1991) point out that only by setting load limits or bounds to control the workload, a job may not be released even though its work content might slightly surpass the load limits of a certain work stations but on the other hand, its release may avoid starvation of several work stations. In this case, a slight overload or underload of a station may be counterbalanced by better loadings of other stations. This is done by controlling the workload through the workload balancing approach. Balancing workloads at each work station is possible if only indirect load limits are used. The choice made along the dimension of workload control depends on the aggregation of workload measure used.

7) Capacity Planning

The control of job shops can be done through decisions based on feedbacks which are the information regarding current and past job shop performances by only changing the input parameters for adjustment. However, control based only on feedbacks focuses only on regulating the input load for the shop, it could be ineffective. Thus, feedforward control to check and adjust the available capacity for production will result in better shop performances (Onur and Fabryck, 1987). There are two approaches presented regarding capacity planning: active and passive. An active capacity planning is characterized by the capability to change and adjust the capacity of the machines of the workstations during the current operations by reallocating operators to the work stations or by overtime production (Hendy and Kingsman, 1991). On the other hand, the passive capacity planning which is the model most considered by researchers, assumes the capacity as given and so not controllable by the ORR methodology but at the planning stage.

8) Schedule Visibility

The schedule of the planned order releases during the time horizon affects and influences on the forecast for future shop capacity requirements and thus on the planning. Therefore, the flow of orders from the planning system to the ORR stage is crucial for this issue and the effectiveness of the ORR method depends on the completeness of information about orders planned to be processed in the future, thus dependent on schedule visibility. There are two ways how scheduling is done: limited schedule visibility and extended schedule visibility. In the limited visibility, the workload levels in the shop are controlled and planned for the right next planning period in the best way to obtain the best performance at that period, but disregarding the effects on the forthcoming periods or in the whole planning horizon. On the contrary, the extended visibility performs the release of orders with the purpose of not getting the best performance of the next period, but achieving an overall best performance and general optimization. With this approach, there may be some current poor shop performances with the objective to have a total better performance of the overall horizon and a more effective management in future periods.

### 2.5.5 Methodology for ORR methods used on the thesis

The ORR methods considered for the analysis on this paper are differentiated on two dimensions. One of them is regarding the aggregation of workload than can be either Aggregated represented as "A", or Released represented as "R". the other dimension is regarding the release rule which are: Limiting represented with "L" and Balancing represented with "B". Therefore, the methods resulting from the combinations are: Aggregated Workload Limiting (AL), Aggregated Workload Balancing (AB), Released Workload Limiting (RL), and Released Workload Balancing (RB). All of them are of a limited visibility approach. In addition to these methodologies described, there are also two sequencing rules implemented. These are the first-come-first-served (FCFS) and the short-process-time (SPT) and they are combined with all the four methods considered. Next is the description of each of the methods.

1) Aggregated Workload Limiting (AL): At the beginning of each release period, workload is measured in each work station and the limit of workload content is given by imposing upper bounds through norms in order to achieve a desired output (performance). In this way of workload aggregation, the latter stations have the highest content of work since because of the production sequence. For both SPT and FCFS sequencing rules.

2) Aggregated Workload Balancing (AB): At the beginning of each release period, workload is measured in each work station and it aims to smooth workload content among the stations by considering norms in order to achieve a desired output (performance). In this way of workload aggregation, the latter stations have the highest content of work since because of the production sequence. Both SPT and FCFS sequencing rules are used with this method.

3) Released Workload Limiting (RL): At the beginning of each release period, workload is measured as a total over the entire shop floor and the limit of workload content is given by imposing upper bounds through norms in order to achieve a desired output (performance).

In this way of workload aggregation, the workload limit at each station is identical. Both SPT and FCFS sequencing rules are used with this method.

4) Released Workload Balancing (RB): At the beginning of each release period, workload is measured as a total over the entire shop floor and the workload is only balanced at the pre-shop pool in order to achieve a desired output (performance). In this way of workload aggregation, the workload limit at each station is identical. Both SPT and FCFS sequencing rules are used with this method.

## 2.6 Modelling of Workload Balancing

### 2.6.1 Extended visibility

As already mentioned above Make to Order companies can be better modeled as flow shops rather than job shops (Portioli and Tantardini, 2012). Therefore, these authors developed a workload control system considering lean principles for those companies' characteristics. The method, named Balancing release (BLR), aims to balance the released workload by focusing in achieving a smooth workload pattern. This is done through the release of homogeneous workloads to each work station even if those workloads may create imbalance in the shop floor because the main objective is to reduce work in progress and throughput time and so improve production performance. A good order release rule in the workload control system makes it possible to be less dependent on a dispatching rule so that the simple First-Come-First-Served rule can be used without much effects on performance (Kingsman, 2000; Land and Gaalaman, 1996; Bechte, 1988). On top of that, using this simple release rule has the benefit of minimizing the standard deviation of shop floor throughput time thus having a more reliable estimation.

The function presented by Portioli and Tantardini (2012) aims to minimize the unbalancing at work stations and over time, and it is expressed as:

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

The function measures the workload by work quantity which is more suitable when high variability is an issue. The aggregation of workload considered is the total shop load logic. The load limiting is used as the order release mechanism and the release is done periodically thus the discrete convention is used. The atemporal approach is used to account workload over time. The capacity planning approach used is the passive which is that capacity is considered as given and an extended schedule visibility was adopted. The variables in the function are:

- ✓ W(p) represents the penalty associated with the workload unbalancing in release period p.
- ✓ TL is the time limit and it represents the number of release periods that are considered in the pre-shop pool planning. Jobs from an ERD(i) beyond the time limit are not considered for release.
- ✓ K is the total number of stages in the flow shop.
- ✓ r represents the penalty associated with the over-load for every workstation, compared with under-load.
- ✓ UL(p,k) is the under-load, on workstation k and in period p.
- ✓ OL(p,k) is the over-load, on workstation k and in period p.

The under-load and over-load variables are defined as follow:

$$UL(p,k) = \begin{cases} \max\left(\left(\frac{TWL - IL}{K}\right) - RL(p,k); 0\right) \\ \max(cap - RL(p,k); 0) \end{cases}$$

$$OL(p,k) = \begin{cases} \max\left(RL(p,k) - \left(\frac{TWL - IL}{K}\right); 0\right) \\ \max(RL(p,k) - cap; 0) \end{cases}$$

where in both definitions,

$$p = 1, k = 1, \dots, K$$
$$\forall p > 1, k = 1, \dots, K$$

In addition, some other parameters used are:

- ✓ N is the total number of jobs in the pre-shop pool.
- ✓ t(i,k) is the processing time of job i on workstation k
- ✓ DD(i) is the due date of job i
- ✓ TWL is the target workload for the shop after a release.
- ✓ Cap is the capacity for the single workstation in the release period and expressed in minutes.
- ✓ ERD(i) is the earliest release date of job thus the first planning period in which the specific job can be considered for release in the shop.
- ✓ LRD(i) is the latest release date of job thus the latest planning period for releasing the job and completing it on time.
- ✓ x(i,p) is a binary variable which equals to 1 when the job “i” is planned to be released in period p, otherwise it is 0.
- ✓ RL(p,k) is the workload on work center k given by jobs to be released in period p.
- ✓ IL (initial load) is the load already in the shop before the release procedure (Bechte, 1988)

The workload considered for release at each workstation in period p, is calculated by the following equation:

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

The following constraints are used to ensure that every job that is released within the time limit, is assigned to only one period and to ensure that jobs that can be released after time limit are either not released or released in one period only

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

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

Lastly, we have two more constraints which are:

$$x(i,1) = 1 \quad \forall i | LRD(i) \leq Time\ Now$$

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

The first constraint forces the job release if the LDR of the job is within the current period, and the second constraint avoids the release of job before the established earliest release date.

### 2.6.2 Limited Visibility

On the other hand, another proposed model for balancing workload is presented by Cigolini and Portioli (2002) whose most important difference to the previous model is that the schedule visibility used by these authors is the limited, meaning that balancing is done period by period looking for best performance at each one without considering the global optimal result. When balancing workload, the objective of the triggering mechanism is to selectively release orders to the shop based on the condition that the sum of deviations from aggregate balance at each work station is minimized. The aim is to reduce the balancing equation (BE):

$$Minimize\ BE = \sum_i p_i \,.\, (WLUB_i - WL_i)^2$$

Where:

- ✓ The subscript "i" represents the workstations in the shop system.
- ✓ WLUB is the workload upper bound set for the workstation i.
- ✓ WL is the total workload of workstation i.
- ✓ "p" represents the penalty connected either to the underload or to the overload of each workstation that can be:
  - ➢ $p_i = \alpha_i$ if $WL_i \geq WLUB_i$
  - ➢ $p_i = 1$ if $WL_i < WLUB_i$

Thus, $\alpha \geq 1$ represents the penalty of allowing a unit of overload at workstation i on behalf of a better workload balancing on the entire shop system. this means that if $\alpha=1$, the release of a job causing one hour overload at workstation i is accepted, if it also causes the under-load of other workstations to decrease at least by one hour.

## 2.7 Workload Control Parameters

Workload control is a concept well acknowledged by practitioners and researchers due to its importance on the MTO industry. The workload control is developed as a concept to be robust and reliable in dynamic environments such as the MTO, however it requires the specification of some parameters. The order release, which is a key decision, needs the workload norm, the planned throughput time, the release frequency, and the time limit to be specified. The influence on performance by the planned throughput time and by the workload norm is limited; but the method to calculate the workload, the release frequency, and the time limit show to be very critical (Land, 2006). Those results have implications on the implementation of the workload control and on the setting of the parameters.

Classically in the workload control concept, the release decision is done periodically, for example weekly or daily (Land and Gaalman, 1998). The decision is on what jobs should be released to the shop and it considers the current workload situation of the shop together, the contribution of workload from the jobs to be released to the stations on the shop, and the relative urgency of the jobs. A station is affected by direct load (jobs awaiting in front of the station) and the indirect load (jobs awaiting to be processed first in upstream stations). Two methods were presented to deal with the indirect load:

- ✓ Load conversion: Developed by Bechte (1988) and Wiendahl (1995). It is also known as the probabilistic approach. It estimates the load inputs from upstream stations to the direct load of the station being analyzed, during the release period. This contribution on load from upstream stations is converted to a direct load by using a certain factor to depreciate it, meaning that the resulting value is lower. The depreciating factor is discussed in Breithaupt (2002). Therefore, at each station its direct load and its estimated load input from upstream stations, are subject to a workload norm. in other words, as soon as the job is released, its processing time partly contributes to the input estimation. This contribution increases as the job moves forward downstream on the rout of the process.

- ✓ Aggregate load: Developed by Bertrand and Wortmann (1981), Tatsiopolus (1983), Hendry (1991), Kingsman (1989). This method avoids estimating norms for the aggregate loads.

The direct and the indirect loads are simply added equally together. The aggregate load after release of jobs, are subjected to a norm at each station.

The procedure for releasing jobs selects first the jobs in the pre-shop pool whose planned release date is within the limit date of the current period. The jobs in the pre-shop pool are organized in order according to their release date in order to show the relative urgency of each one. Therefore, the jobs are considered for release in that sequence. The first job in the sequence is taken and checked whether it workload contribution will exceed the workload norm. If this norm is not exceeded, the job is released and the workload on the shop is updated. Otherwise, if the norm is exceeded, the job is returned to the pool and the second job in the sequence is analyzed in the same manner. This procedure goes on in the same way until a certain number of jobs are selected for release at that period.

1) Workload Norms: They are used to control the queues on the floor. Workload norms are settled or calculated taking into consideration the current workload level at the shop floor, the planned output, and the desired queues con each station on the shop floor and their planned control. There are two workload norms. One is the maximum norm, which is also called the upper bound; and the other is the minimum norm, known also as the lower bound. The maximum norm is a maximum restriction of the backlog, and the minimum one, is the minimum restriction. The minimum bound is used primarily to avoid starvation and the maximum bound is used for the balance the shop floor (Stevenson and Hendry, 2006). Many studies based on simulations showed the ability of Workoad Control methods to improve performance but the implementation on real situations is limited. One of the issues for a proper and successful implementation is the determination of appropriate workload norms (Land, 2004; and Stevenson and Silva, 2008). Land made use of simulations to show that when workload norms are set too tight, shop floor times will be reduced but at the cost of having an increased throughput time. And on the other hand, if the workload norms are set too loose, there will be only a small decrease on the shop floor time. Therefore, a norm when set too tight, is ineffective; but when set too loose, the performance is greatly affected as well (Enns and Prongue, 2002). Setting a workload norm is a problem particularly for the classical aggregate load method in which a different norm is calculated for each station on the shop floor when the routing becomes more directed (Oosterman, 2000). This is due to

the fact that indirect loads start to accumulate on downstream stations when there is a dominant flow.

2) Planned throughput time: contributes to an accurate timing of order release. These planned throughput times for each station are used on the release process to determine the dates at which the jobs are to be released. Betche (1980) suggest the use of an exponential smoothing on previously realized throughput times. However, since the workloads are measured in units of processing time, the formulation of Little (1961) is used to show that the limit value of the time average direct load relates proportionally to the limit value of the weighted average station throughput time, with processing times being used as weights (Land, 2004). Therefore, the planned throughput times of the stations should be related to the workload level. When the workload norms are tightened and the actual throughput times are reduced, one would normally decrease the planned station throughput times (Land, 2006).

3) Time limit: prevents jobs from being released too early. It is used to restrict the group of jobs that are considered for release for the orders which are most urgent. A lower time limit may improve the timing, but this is done at the cost of reducing the possibilities for balancing the loads on the release process. Land (2006) analyses the impact of time limit on timing performance considering the standard deviation of lateness.

4) Release period length: enables an appropriate frequency of order release decisions. Generally, this length is taken in a practical logic like weekly or daily. However, the values of other parameters depend on this release period length. In addition, the work to be released for a station primarily depends on the length of this release period because it must be equal to the average output during this release period. Perona and Portioli (1998) distinguish a check period and a Planning period when creating the idea of a rolling horizon. The check period is used to calculate the release frequency and the planning period is used for the calculation of the depreciation factors. They conclude that jobs with long routings and large processing times may suffer from being re-sequenced in case of a short release period, and that the main drawback on having large lengths is manifested in the pool delay of jobs.

## 2.8 Performance criteria and measurement

The parameters considered for performance measurement can be grouped in two groups depending on the orientation of the parameter.

a) Shop-oriented parameters: the parameters measured are shop utilization, shop floor throughput time, and the system total throughput time. The ones considered in this paper are described below

- Average shop floor throughput time $= \frac{\sum_{i=0}^{n} Exit\ time_i - Job\ release\ time_i}{n}$
- Average gross throughput time $= \frac{\sum_{i=0}^{n} Exit\ time_i - Order\ arrival\ time_i}{n}$

b) Job-oriented parameters: the parameters measured are average tardiness, average lateness, and percentage of tardy orders. The ones considered in this paper are describe below

- Tardiness $= Exit\ time - Due\ date$
- Standard deviation of Lateness $= \sqrt{\frac{\sum Lateness^2}{n \cdot 60^2} - \left(\frac{\sum Lateness}{n \cdot 60}\right)^2}$
- % of tardy orders $= \%\ of\ jobs\ completed\ after\ the\ due\ date$

Soepenberg (2008) regards the average lateness and the variance of lateness as the main indicators for the performance of the delivery reliability and that can be influenced by input and output control decisions. He describes them as:

I. Average Lateness: Is measured by subtracting the promised delivery time from the real throughput time. This measurement could be positive, in which case orders are delivered late; or could be negative, when orders are delivered early. Average lateness will increase when a higher number of orders has to be processed within a period assuming that both capacity and delivery dates remain unchanged because there will be an increased congestion and waiting times and thus resulting in larger throughput times.

II. Variance of Lateness: Is affected more specifically by the characteristics of the orders. Orders requiring more process operations generally requires higher throughput times. When the throughput time of each order are not carefully considered when delivery dates are promised, the variance of lateness will likely increase.

Figure 5 shows the role of the average lateness and of the variance of lateness and their impact on delivery reliability. The figure represents a distribution function of lateness. The vertical line is the point of zero lateness and the shaded area represents the percentage of orders delivered late. This percentage can be reduced by speeding up throughput time or reducing the average lateness (left side), or by reducing the variance-dispersion of lateness (right side).

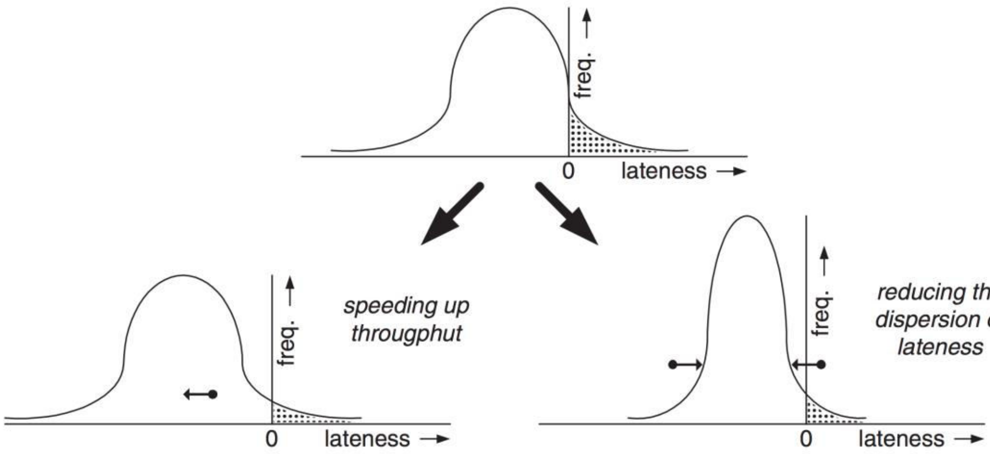



*Figure 5. Approaches to reduce percentage of tardiness (Land 2006)*

The throughput diagram is a tool which supports the decisions on input and output control and indicates how they affect the control of the average lateness indicator (Bechte, 1988; Wiendahl, 1995). The variance of lateness indicator is diagnosed by a tool called order progress diagram developed by Soepenberg (2008) and which provides a link between the input and output control decisions.

Work-in-progress (WIP) is a parameter that is not considered for performance measurement because to compare the different ORR methods, they are done by collecting data at the same operating point with the same WIP amount. This is because when comparing the performances of the methods at the same level of WIP, the effects of the considered methods on the WIP and its distribution within the shop floor and over time, can be analyzed and highlighted properly (Cigolini and Portioli, 2002).

### 2.8.1 Robustness Analysis

The Robustness Index is used to measure the sensitivity of the ORR method. It shows the dependency of the method performance on the environmental conditions at which the process is carried out. The Robustness Index is modelled by Cigolini and Perona (1998) and explained as follow:

$$z_1 = y(x_H) - y(x_M)$$
$$z_2 = y(x_M) - y(x_L)$$
$$z_3 = y(x_H) - y(x_L)$$

The environmental factor is represented by x and the index represents the characteristic (in this case H stands for high, M for medium, and L for low). The performance obtained by each ORR method at these environmental factors is represented by y. The purpose is to compute the difference in performance at different environmental factors. The smaller this difference, the more robust is the ORR method. This model uses Taguchi's signal to noise index (Taguchi and Clausing, 1990), represented as SNS. The smaller the value of SNS, the better since it indicates that the performance of the ORR method is less affected by changes in the environmental factors.

$$SNS = 10. log_{10} \frac{(z_1 + z_2 + z_3)}{3}$$

Performance of ORR methods with lower SNS give more reliability and confidence since the results in the surrounding of the mean value will be close and the variations will be smoother. Therefore, the sum of the all values of SNS gives an overall robustness of the ORR method when different environmental factors are possible to happen as well as disturbances.

Having this in mind, the Robustness Index is calculated mathematically as:

$$z_1 + z_2 + z_3 = 2 \cdot y(x_H) - 2 \cdot y(x_L)$$
$$SNS = 10 \cdot log_{10} \frac{(z_1 + z_2 + z_3)}{3} = log_{10} \left[\frac{2}{3} \cdot (y(x_H) - y(x_L))\right]^{10}$$

The sum of the SNS gives the RI, where i is the ith performance index

$$RI = \sum_{i=1}^{n} SNS_i = \sum_{i=1}^{n} \left[ log_{10} \left(\frac{2}{3}\right)^{10} + log_{10}(y_i(x_H) - y_i(x_L))^{10} \right]$$

This equation can be further simplified to give

$$RI \cong= -1{,}7609 \cdot n + 10 \cdot log_{10} \prod_{i=1}^{n} (y_i(x_H) - y_i(x_L))$$

Most of the research done on Workload Control methods is based on simulations and the one of the reasons for the lack of empirical research is the implementation process. There are some requirements that need to be met to successfully implement the workload concept to real cases. These requirements are difficult to be satisfied in real situations, but it is much easier in simulations studies. The grouping on interchangeable machines, the feedback of information of the shop floor, and precise capacity estimations are some examples of those requirements. Also, it is important to have well determined norms and parameters like the expected waiting time of jobs in the shop floor.

## 2.9 Environmental Factors

Environmental factors refer to the situations from which variances on the planning is created. These factors can be pertained either to the operation and planning system or to the physical shop floor. The factors affecting the operation and planning system are from the external environment such as the case of the system workload which is related to the orders and its workload content arriving to the pre-shop pool and its measured as the percentage of the overall shop capacity (Portioli, 1991; Bergamaschi and Cigolini, 1994; Bechte, 1988). Another factor from the external environment, highly considered in the literature (Irastorza and Deane, 1974; Perona and Portioli, 1996; Lingayat, 1995), is the mix imbalance which has been used to test the ability of the ORR techniques to level workloads across workstations over the planning horizon, and to effectively face unbalanced job mixes. On the other hand, factors affecting the shop floor comes from the internal environment and they are real disturbances that are not precisely known or foreseen before an event happens so causing the actual schedule and the status of the shop floor to differ from the planned one over time. In this study only environmental factors pertaining the shop floor are considered for the analysis of the ORR methods. These factors are machine breakdown and processing time variability. They are common sources of variance in the industrial sector.

Since in this paper we consider only the internal environmental factors, we use a term coined by Seiichi Nakajima (1982) to evaluate the effectiveness by which machines are utilized. This term is the Overall Equipment Effectiveness (OEE) and is represented in Figure 6 Its purpose is to measure the performance of machines and to show the sources of performance loss. There are three different categories by which these sources of losses can classified. They are availability, performance, and quality.

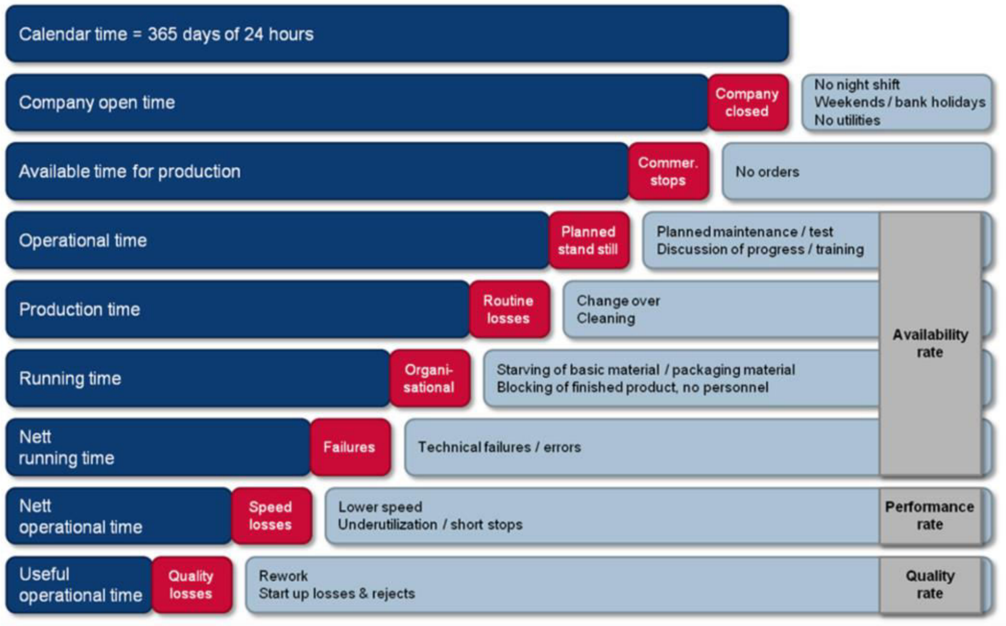



*Figure 6. Description of the Overall Equipment Efficency concept*

Some sources of performance losses are planned and foreseen like planned maintenance, trainings, planned stop days. Some other sources are unplanned and thus they are nor known as a priori before they happen. Some examples are unexpected machine breakdowns which are one of the most relevant sources for variability in the industrial environment as mentioned by Uzsoy (1992). Hopp and Spearman (1991) also supports this idea by considering that to better analyze a system and its performance, machines outages should be considered when modelling the system. Other examples are minor stoppages due to different reasons like the operator inattention and productivity, and scraps and reworks.

For this study, we considered those factors creating variance and disturbances from unexpected and unforeseen events which will affect the planning schedule and the actual status of the shop floor. As it was already mentioned, these factors are machine breakdown and processing time variability.

### 2.9.1 Machine Breakdown

Machine breakdown is described in different ways. Gelders and Pintelon (1997) describes it as equipment failures, idleness and minor stoppages. Cowling and Johanson (2002) describes it through categories of capacity disruptions and order disruptors. The first one is regarded as the breakdown since it pertains the production resources such machine failure, tools unavailability or labour absence. The second one is related to variances on the orders received such as the due date modification or order cancellation.

For the objective of our study we use a simulation modelling scenarios of unplanned and unforeseen breakdowns in the shop floor to test the resulting performances under the different ORR methods. Therefore, considering the practical manufacturing process in real situations, three levels of breakdown are introduced depending on its frequency of occurrence and on its severity. These levels are described in Table 4.

| | **Breakdown** | | |
|---|---|---|---|
| | **Level I** | **Level II** | **Level III** |
| **Severity level** | Low | Medium | High |
| **Frequency of occurrence** | High (each 5 days) | Medium (each 10 days) | Low (each 20 days) |
| **Time to repair** | 2 hours | 4 hours | 8 hours |
| **Examples** | Machine setting up problems | Machine minor parts failures | Machine main functional mechanism failure |

*Table 4. Classification and description of breakdown levels*

Each of the breakdown levels are characterized by failure itself of the machine and the time needed to repair it. The frequency of failure occurrence of the machines is modeled by a Weibull distribution and the time to repair is modeled by a lognormal distribution.

a) Failure frequency by the Weibull distribution

The good accuracy obtained by the Weibull distribution in modelling and analyzing failure intervals is the reason of why several researches use it as a preferable probability distribution for analyzing machine failures. The Weibull distribution can easily adopt the shape of other probability distributions according to the parameters used since it does not have a specific shape (Abernethy 2000).

The Mean Time to Failure (MTBF) is the average time interval at which consecutive machines failures occurre. This MTBF can be expressed by the mean of the Weibull distribution.

$$MTBF = \mu_y = \eta\Gamma\left(\frac{1}{\beta} + 1\right)$$

where:

- β is the shape parameter and it is higher than zero
- η is the scale parameter and it is higher than zero
- y is higher than zero

The probability density function of the Weibull distribution is:

$$g(y) = \frac{\beta}{\eta}\left(\frac{y}{\eta}\right)^{\beta-1} \cdot e^{-\left(\frac{y}{\eta}\right)^{\beta}}$$

b) Time to repair by the lognormal distribution

Its suitability of this type of distribution on expressing repair times is thanks to its skewness and its long tail on the right side of the probability distribution (Wijaya et al. 2012). The preference to use the lognormal distribution it because it also gives results with a very good accuracy.

In the same way of the MTBF, the average time to repair the machine is represented by the Mean Time to Repair (MTTR) and it can be expressed by the lognormal distribution.

$$MTTR = \mu_x = e^{\left(\mu + \frac{\sigma^2}{2}\right)}$$

where:

- μ is the mean
- $\sigma$ is the standard deviation of the natural logarithm of the variable
- $x$ is higher than zero

And the probability density function of the lognormal distribution is:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \cdot e^{-\frac{1}{2}\left[\frac{\ln x - \mu}{\sigma}\right]^2}$$

### 2.9.2 Processing time variability

Variability in processing time is a disturbance commonly affecting shops in the manufacturing industry in which the automation level is low and where the production control and its effectiveness is dependent on the careful attention and handling of the operators. Because variance in the processing time can be easily originated, its distribution is an important area especially for the planning and control system (Melnyk, 1992; Matauura, 1995).

How the impact of workload affects the operator's productivity is a critical question therefore Bertrand (2002) investigates the impact of workload and control on the production system output. When the workload level deviates from its ideal value the operator becomes less efficient and so it is said that the level of arousal of the personnel increases. Arousal is caused by the different known stressors like noise, incentives, anxiety and fear. This relationship between operator's efficiency and productivity can be explained by a physiological argument known as the Yerkes-Dodosn law (Wickens, 1992). This argument is based on assumptions that the performing of operations needs the operator to have some perception, to process the information, to make decisions and take actions. All these are done from a human point of view. When the level of workload in the shop increases, the work pressure increases as well and so resulting in negative impacts on the performance. The increase of workload levels affects the personnel in charge of performing those operations thus affecting the human perception, information processing, the decision making and the taking of actions by the operators. This also affects the shop floor management (Wickens, 1992). The Yerkes-Dodson law gives a model for the relationship between arousal and performance as an inverse U-shaped curve. This indicates that for an individual and its given tasks, there is an optimal arousal level. This is the point at which performance is at its maximum. At this point, the work pressure is positive and productive. Beyond that point, performance will decay. In the same way, workload levels can be expressed as stressors which affect the operators. The impact of the workload on the operator may be different for each one depending on the individual, on the tasks, and on the production department, thus the level of arousal is also different for each case. Even though the increase or decrease of arousal may be different for each person, it can be assumed to have a single curve for the group of operators in the shop floor and production department as a whole.

Bertrand assumes that the workload existing at the beginning of the operation, affects the processing time. If the workload level is lower than the optimal one, the operator is less alert which leads to an increase in the processing time, more than needed. But also, if the workload level is higher than the optimal value, the operator will need more time to process the information, to take decisions, and it is more probable for the operator to make mistakes due to the high levels of arousal. This author represents this effect by a model in which the minimum processing time (the most desirable) is achieved at the optimal levels of workload. Deviation from this optimal level will induce to have higher processing times depending on the degree of deviation. He concludes that if there exists a relationship between workload and production efficiency and performance, the underestimation of the ideal workload is less harmful than overestimating it. Therefore, it is important to have an accurate estimation for the ideal workload, but an underestimation is preferred over an overestimation. For a deeper information, refer to his study (Bertrand, 2002).

# 3 Simulation Modelling and Configuration

## 3.1 System configuration

In the previous section, it was described the relevance of regarding and configuring the shop as unidirectional because real shops are more recognizable with dominant flows or general flow patterns that is also a result from the implementation of lean techniques on those companies (Portioli and Tantardini, 2012). Therefore, the shop configuration in MTO industry is suggested to be a flow shop to effectively represent real production systems. The program Python©3.4 SimPy© module was used for the simulation of the shop configuration under the different workload control methodologies to analyze their performances at different scenarios. This simulation was maintained relatively simple to prevent disturbances affecting the collection of the full and clear picture of results. Therefore, the configured shop floor is a pure flow shop composed of five work stations, each of them having the same capacity. In addition, each work station is considered to have the same mean processing time and the same variation. The lognormal distribution is used to calculate the processing time of all stations since this type of distribution describes more realistically the processing times in work stations (Portioli and Tantardini, 2008; Thurer 2014), and it makes it possible to have high variability in the processing time. In order to effectively run the simulations of the system modelled and to obtain trustful results, there is the need to determine and specify the characteristics of certain features. These are:

a) Total length of the simulation
b) Warm-up period necessary to void initialization bias
c) Number of runs to minimize the errors on the simulations results

Because it is intended to have the performance of the production system at long periods obtained from applying the ORR methodologies, the simulation needs to have a certain time of running that is represented by the length of the simulation which in the case of this paper is on days. To get reliable results from the runs of the simulation, the length should be enough to ensure this. Therefore, the problem related to it, is the construction of a confidence interval of the length. The needed number of iterations required to have reliable results with no significant errors, can be obtained from calculating the Mean Squared Pure Error (MSPE)

$$MSPE = \frac{\sum_{i=0}^{n}(X_i - \bar{X})^2}{n-1}$$

where:

- $X_i$ is the average of each iteration
- $\bar{X}$ is the total average of n iterations
- $n$ is the total number of iterations

The length of the simulation is set to be 500 days after finding that at this value the variation of MSPE is not significant and so it is enough for the purpose of the study (Welch 1983).

The results from measuring the performances after the start of the simulation may not be stable since the simulation model starts on empty thus having the necessity to have some time some time before it reaches a steady state. This problem is solved by recording the performances after a certain time has passed after the start of the simulation. This time is called the warm-up period (Mahajan and Ingalls 2004). Results collected after the warm-up period ensure more stable average values for the performance parameters. This warm-up period is found to be 200 days and so the actual production length is to be 300 days after deducting 200 days from the total 500 which is the length of the simulation (Portioli and Tantardini, 2012). On the other hand, having a steady state that is the time after the warm-up period, doesn't ensure to have statistically meaningful results. Thus, in order to have an analysis statistically meaningful, it is necessary to repeat the experiment several times. In this manner, the number of iterations was set to be 50 to have statistically significant results. Table 5 summarizes the features of the simulation model.

| | |
|---|---|
| Shop configuration | Pure flow shop |
| Number of work stations | 5 |
| Production day length | 8 hours (480mins) |
| Capacity of the work station | 480 min/day per each work station |
| Arrival of orders | Represented by the Poisson distribution |
| Due dates | 7 working days after order arrival |
| Job routing | Through all 5 stations in the same sequence |
| Release period length | Each 8 hours, 6 hours, 4 hours, and 2 hours (release done at once and at the beginning) |
| Processing time | Deterministic |
| Expected processing time | Represented by the lognormal distribution<br>▪ mean: 30<br>▪ variance: 576 |
| Actual Processing time | The expected processing time plus the variance |
| Dispatching rule | First-come-first-served (FCFS)<br>Shortest-processing-time (SPT) |
| Simulation length | 500 days |
| Warm-up period | 200 days |
| Number of iterations | 50 |
| Utilization rate | 93.75%<br>▪ arrival rate: 14.25 orders/day<br>▪ average service rate: 16 orders/day |
| Set-up times | Sequence independent |

Table 5. Simulation modeling and configuration

## 3.2 Design of experiments

The ORR methods selected for the study and for the analysis of their performance is in accordance with the objective of the thesis. The methodologies of these ORR methods are based on three dimensions. Two of them are proposed by Bergamaschi (1997) and they are: the aggregation of workload, which can be either aggregated workload or released workload; and the workload control, which can be of limiting and the balancing approach. The third dimension was proposed by Thurer and it is the sequencing rule for orders in the pre-shop pool which can be either first-come-first-served (FCFS) or short-process-time (SPT). Therefore, in total there are eight ORR methods whose performances are evaluated and analyzed. For the other dimensions of the ORR methodology, they are the same for our methods: the workload measure is total amount of workload, the atemporal shop load methodology is taken as the workload accounting over time, the passive capacity planning approach is adopted, the schedule visibility adopted is the limited. Table 6 describes the characteristics of each methods

| | | **Workload Control** | |
|---|---|---|---|
| | | **Limiting** | **Balancing** |
| **Aggregation of workload measure** | **Aggregated workload** | At the beginning of each release period, **workload is measured in each work station** and the limit of workload content is given by imposing **upper bounds** through norms to achieve a desired output (performance). In this way of workload aggregation, the latter stations have the highest content of work since because of the production sequence. For both SPT and FCFS sequencing rules. | At the beginning of each release period, **workload is measured in each work station** and it aims to **smooth workload content among the stations** by considering norms to achieve a desired output (performance). In this way of workload aggregation, the latter stations have the highest content of work since because of the production sequence. For both SPT and FCFS sequencing rules |

| | | | |
|---|---|---|---|
| | **Released workload** | At the beginning of each release period, **workload is measured as a total over the entire shop floor** and the limit of workload content is given by imposing **upper bounds** through norms to achieve a desired output (performance). In this way of workload aggregation, the workload limit at each station is identical. For both SPT and FCFS sequencing rules | At the beginning of each release period, **workload is measured as a total over the entire shop floor** and the **workload is only balanced at the pre-shop pool** to achieve a desired output (performance). In this way of workload aggregation, the workload limit at each station is identical. For both SPT and FCFS sequencing rules |
| | | **SPT/FCFS** | **SPT/FCFS** |
| | | **Sequencing Rule** | |

*Table 6. Definition of ORR methods*

For a matter of simplicity, the ORR methods are represented by letters according to their methodologies as in the following Table 7.

| ORR method | Aggregation of workload | Workload Control | Sequencing rule |
|---|---|---|---|
| AB/F | Aggregated | Balancing | FCFS |
| AB/S | Aggregated | Balancing | SPT |
| RB/F | Released | Balancing | FCFS |
| RB/S | Released | Balancing | SPT |
| AL/F | Aggregated | Limiting | FCFS |
| AL/S | Aggregated | Limiting | SPT |
| RL/F | Released | Limiting | FCFS |
| RL/S | Released | Limiting | SPT |

*Table 7. ORR methods and their representation*

As it was previously stated, the performances of the ORR methods are evaluated under environmental factors affecting the shop floor. These factors are the disturbance on the processing time and the machine breakdown. Table 8 summarizes the environmental factors implemented in the experimental design.

| | |
|---|---|
| Job processing time | Lognormal distribution<br>• Mean of 30 mins |
| Disturbance level on the processing time | 20%, 40%, 80% |
| Breakdown frequency | Weibull distribution<br>• Shape parameter β is 1 |
| Time to repair the breakdown | Lognormal distribution<br>• Coefficient of variation:<br>✓ Low: 80%<br>✓ Medium: 80%<br>✓ High: 80%<br>• Mean value<br>✓ Low: 120 mins<br>✓ Medium: 240 mins<br>✓ High: 480 mins |

*Table 8. Experimental design of the scenarios*

1) Level of Distortion

The processing time is modelled by the Lognormal distribution. Its mean average value is 30 which is the same for all workstations. On top of that, the real processing time is obtained by including the level of disturbance to the expected time. Three level of disturbance were introduced in the experiments: 20%, 40%, and 80%.

2) Machine breakdown

Machine breakdown is characterized by its severity and by its frequency. Depending on the severity of the breakdown, the time to repair is different in each case. This time to repair is modeled through the lognormal distribution. On the other hand, the frequency also depends on the type of breakdown. More severe breakdowns are less frequent and vice versa. Breakdown frequency is modeled by the Weibull distribution. Three breakdown level are introduced according to its severity: low, medium and high. The frequency and the time to repair of each one is presented in Table 9.

| Breakdown level | Frequency of occurrence | Time to repair |
|---|---|---|
| Low | Once every 5 days | 2 hours |
| Medium | Once every 10 days | 4 hours |
| High | Once every 20 days | 8 hours |

*Table 9. Description of the breakdown levels*

# 4 Results and Discussion

Several simulations are done to test the different ORR methods and their performance under scenarios with different characteristics. The Aggregated Workload and the Release Workload methodologies for the aggregation of workload measure were combined with the Balancing and Limiting approaches for workload control (Portioli and Tantardini 2012). In addition, each method was tested using the two known sequencing rules on the pre-shop pool, the First Come First Served (FCFS) and the Short Process Time (SPT). Therefore, considering all combinations, there are a total of eight ORR methods which are tested and from whose results are analyzed and compared. Five parameters are taken as indicators to analyze and compare the results. These parameters are:

- Gross Throughput Time (GTT).
- Shop Floor Throughput Time (SFT).
- Tardiness.
- Standard Deviation of Lateness.
- Percentage of Tardy Orders.

The tests are done considering different scenarios to compare the performances of the ORR methods under evaluation. The study is split in two main sections. In the first section the effects of breakdown and distortion levels are analyzed and on the second section the effect analyzed is of frequency of order release from the pre-shop pool.
In the first section, the release of orders to the shop floor is once a day which means a frequency of every 8 hours as it was taken for several other research papers. Having this release frequency fix, all ORR methods are tested under the three breakdown levels and under the three distortion levels with the objective to see their performance by looking to the parameters already mentioned. For the objective of solely analyzing the effects of the breakdown levels, only a relatively stable processing time was considered, meaning that the processing time does not have great fluctuations so the degree of uncertainty for the completion of the operations at each station within the shop floor is low. The distortion level considered for this is of 20%. In addition, methods with Balancing release rule and Limiting release rule, are compared separately to have a deeper insight on the performances of each method. The Limiting approach is used by several authors (Cigolini and Portioli 2002, Oosterman 2000) as a control method for diverse studies. Then, the best performances of each ORR method for each breakdown level under a low distortion level, are compared to identify the best performing method. After analyzing the effects of the breakdown levels under a unique low distortion level, the other two distortion levels are introduced in the analysis. These are of 40% and 80% levels, which are of medium and high distortion respectively. All these distortion levels in combination with the three breakdown levels, give us the picture of results of a more complete performance analysis under more real and probable situations that may occur in the shop floor during production. In addition, on top of the parameters already mentioned for the comparison of the performances of the different ORR methods, the Robustness of each method at each parameter are calculated and compared for a more complete analysis.
In the second section, different order release frequencies are analyzed to see their effect on the method performances. For this section only four out of the eight ORR methods are used for the analysis, the methods having the aggregated workload as their methodology. Also, the analysis was done only for the first breakdown level in which the machine failure is more frequent but introducing all three distortion levels.

For matter of simplicity, in the following sections, all ORR methods are named in abbreviation according to the Workload aggregation, to the Workload Control, to the sequencing rule, and to the breakdown level. For example, AL means aggregated workload with limiting release rule, and RB means released workload with balancing release. For the breakdown level, a number is added after them, for instance AL1 indicates that the analysis is done at the first breakdown level. And for the sequencing rule, the letter F or S is added to the end for FCFS and SPT respectively. In this way, AL1/S indicates the aggregated limiting method with SPT sequencing rule at the first breakdown level. In addition, since the analysis of the first section is done having an order release frequency fixed to 8 hours, it will not be mentioned but it should be understood to be so. Only on the last section when different order release frequencies are analyzed, they will be mentioned and differentiated.

## 4.1 Analysis of Breakdown and Distortion

### 4.1.1 Performances at all Breakdown Levels with 20% distortion

The results show that independently of the ORR method, the best sequencing rule for the pre-shop pool is the SPT one as it was expected. Also in general, the Balancing release rule performed better than the Limiting one at almost all three breakdown levels with an interesting exception which will be described later. The ORR method which performed better at all breakdown levels is AB/S.

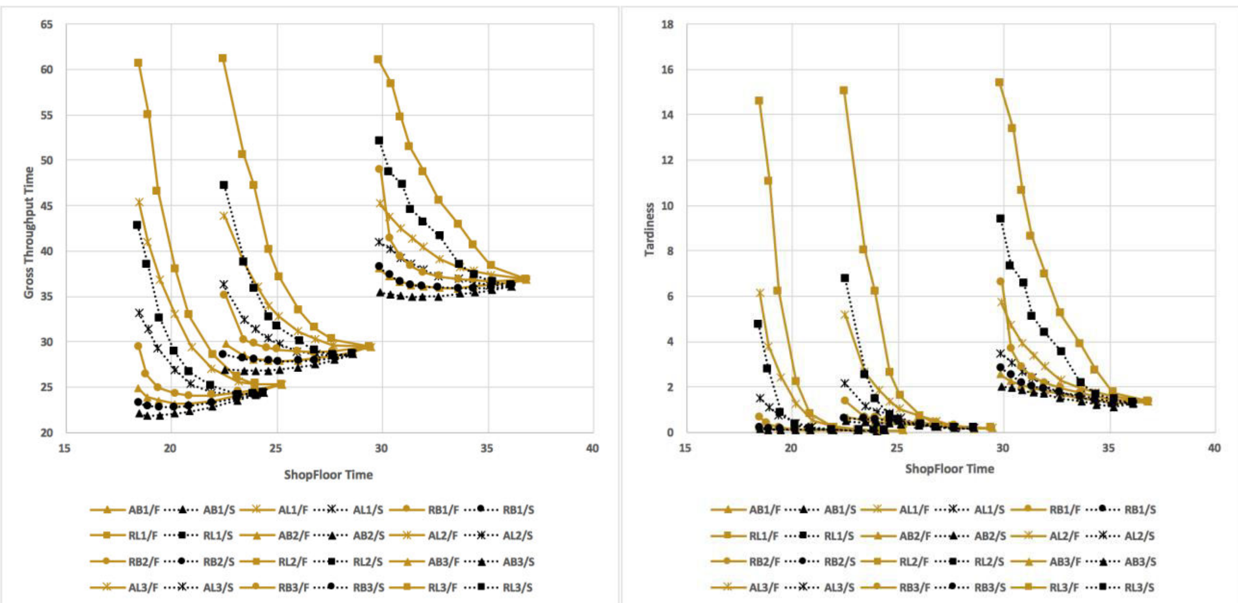



*Figure 7. Performance of average GTT (left) and Tardiness (right) for all ORR methods at all breakdown levels with 20% distortion*

The influence of the breakdown levels can be easily noticed in the graphs. The higher the breakdown level, the total shop floor time is also higher which is logical since if the idle time of the machine is higher, it is expected to require more time for an order to completely undergo the different operations needed for its completion. Level three has a higher impact in this manner since the shop floor time increases the most under this level. From the Gross Throughput Time parameter graph we can see that the breakdown level also has an increasing effect on the value. Looking at the increase of the Gross Throughput Time and of the Shop Floor Time, we can see that the increase on both are similar. This means that the time delayed for an order to be finished due to breakdown, is mostly translated to the shop floor and the time that the orders may wait in the Pre-Shop pool is almost unchanged. The pattern of each method is similar when looking at the different breakdown levels. They basically undergo a shift to higher shop floor time values but with a lower range of values for the different parameters. The most noticeable changes are seen for the third breakdown level. At this level, the patterns of all parameters vary slightly to the patterns from the first and second breakdown levels. Independently of the breakdown level, for most of the parameters, the worst performing method is the RL/F with the exception on the standard deviation.

Regarding the four parameters, the performance gaps between Balancing and Limiting methods are quite high at low shop floor times. And because the shop floor time depends of the workload norm implemented, this means that if these norms are not correctly chosen when Limiting methods are used, the performance at all parameters could be poor. The performance gap is higher for tardiness and percentage of tardy orders parameters. This proves the superiority of the Balancing approach over the Limiting (Portioli and Tantardini 2012).

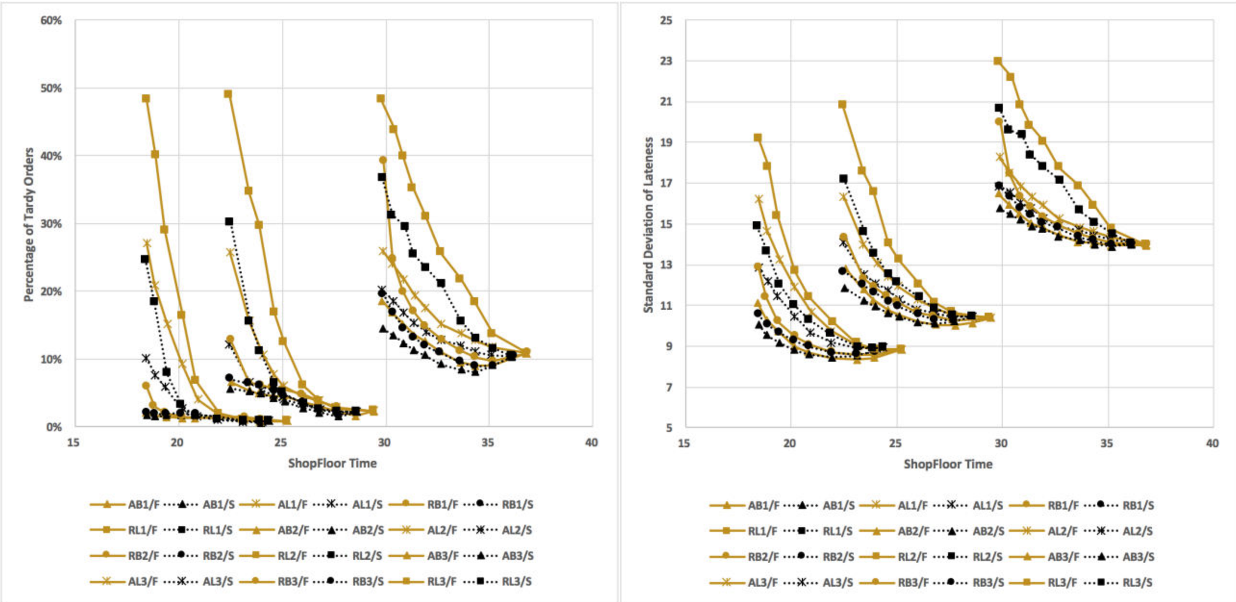


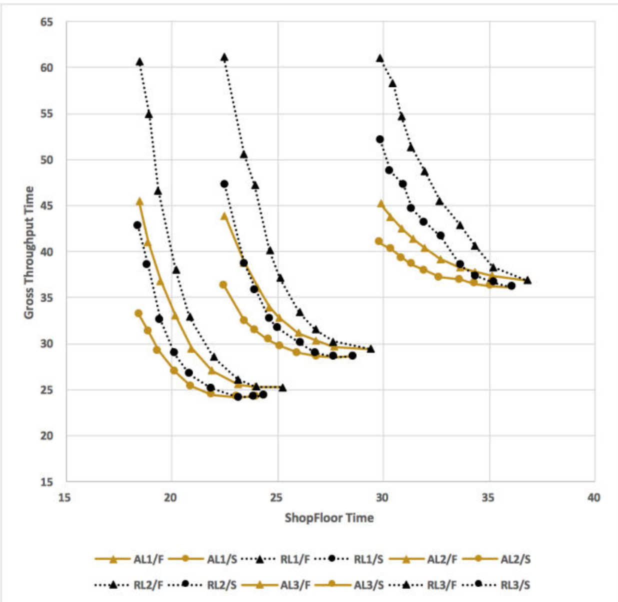

*Figure 8. Performance of average Percentage of Tardy Orders (left) and Standard Deviation of Lateness (right) for all ORR methods at all breakdown levels with 20% distortion*

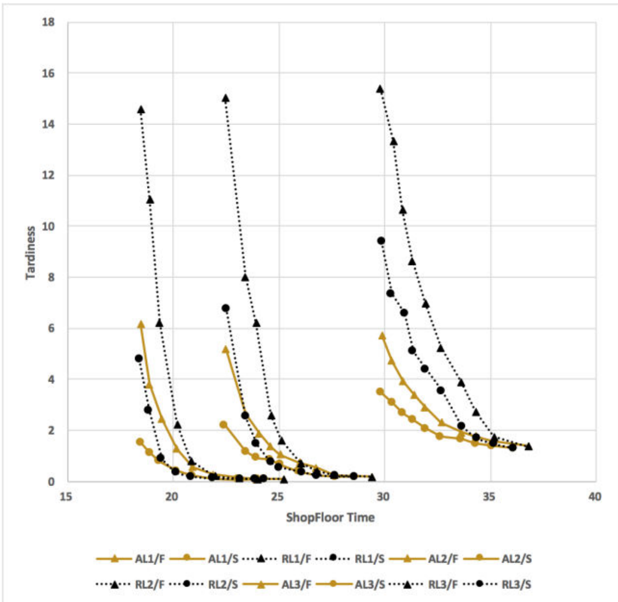
### 4.1.2 Comparison between the approaches for workload measure (Aggregated vs Released)

A. For Limiting workload control methodology

In this section, the AL/S, AL/F, RL/S, and RL/F methods are compared to each other. The Limiting allows a good performance in job shops but it not the case in flow shops (Thurer 2015), which is the model used on this thesis. As already noted earlier from the previous analysis, the best sequencing rule is the SPT regardless of the ORR method used. Comparing the workload aggregation measure methodologies which are Aggregated workload the and Released workload, the results show us that in general the former methodology performs better than the later. In Figure 9 the AL method is represented in gold and the RL, in black; and the SPT rule is shown by the circle marker and the FCFS one, by the triangle marker. At the first breakdown level, the sequencing rule plays an important role and has a greater impact on the performance than the workload aggregation methodology. The AL/S and RL/S perform better than AL/F and RL/F. This is true for all the parameters and can be seen in the graphs from Figure 9.

As it is known, the section on the graphs which represent the first breakdown level is the one of the lowest-left side. For lower values of SFT, RL/S shows similar GTT than AL/F. But as the SFT value increases, the SPT rule has a positive impact and the GTT values for the RL/S becomes closer to those of AL/S which is the best performing method. We can see the same behavior of performance of the ORR methods within the given range of SFT values for Tardiness and Percentage of Tardy Orders parameters. In the case of the Standard Deviation of Lateness, the values of this parameter at the different SFT values, differs quite similar for all the ORR methods like an offset. The worst performing method is the RL/F. On the other hand, as the breakdown level increases, the advantage of using the SPT sequencing rule decreases and the workload aggregation methodology used becomes more relevant. For the second level of breakdown, when comparing the RL/S to AL/F, the advantage of using the SPT rule for RL is somehow equaled by the superiority of the workload aggregation methodology of the AL method using the least beneficial sequencing rule, FCFS. At the lowest SFT range of values, AL/F has better performance since it yields lower GTT values, lower values for tardiness and for the other parameters. When higher SFT values are considered, RL/S performs better but the difference is not as high as in the case of the first breakdown level.



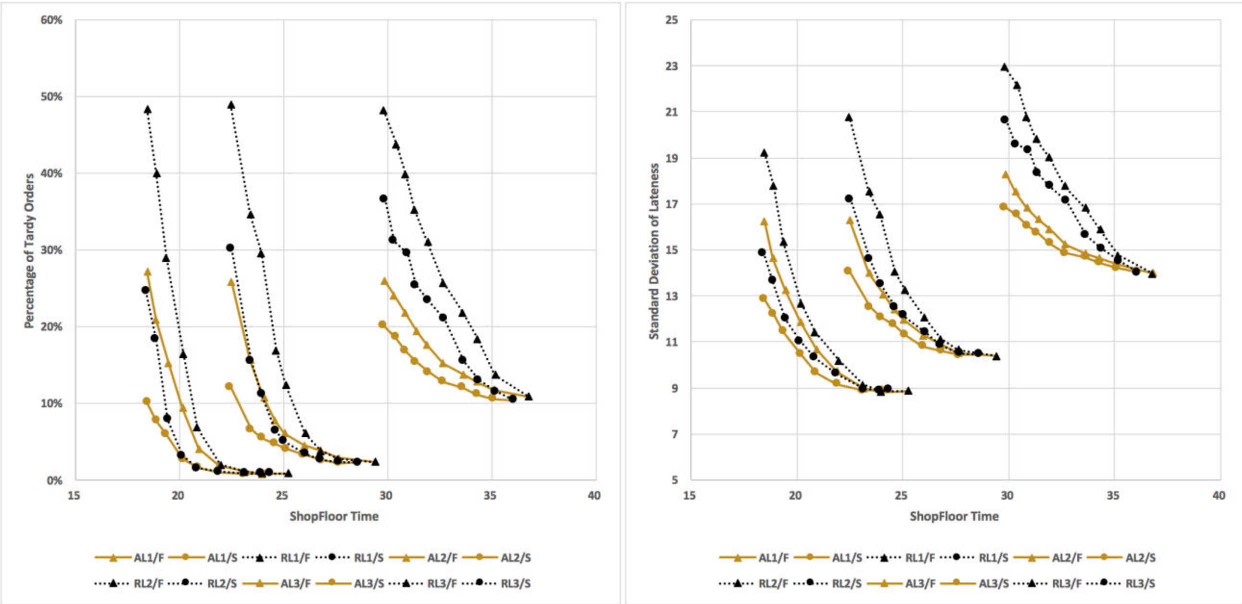



*Figure 9. Performance for all parameters of ORR methods with Limiting release methodology at all breakdown levels with 20% distortion*

At the third level of breakdown which is shown on the top-right side of the graphs, the performance of the ORR methods becomes highly dependent on the workload aggregation methodology and less influenced by the sequencing rule. Looking at all the parameters, it is clear to see that the AL has a much better performance than RL independently of the sequencing rule. In fact, the performances of AL/F and AL/S, are closer than in the other breakdown levels. From low values of SFT to higher values, the difference between performances of AL/F and of AL/S are quite constant and it can be seen for all the parameters. The RL performs worse, especially for the case of RL/F. The advantage of using aggregation of workload as the workload aggregation methodology is very clear and independent of the sequencing rule at the high level of breakdown since it has a greater superiority than the Release workload methodology.

B. For Balancing workload control methodology

In this section, the AB/S, AB/F, RB/S, RB/F methods are compared to analyze their performance and to see how the results differs from the ones of the Limiting release rule. The results are quite like the ones of the previous analysis for the Limiting release rule meaning that the Aggregation of workload performs better than the Released workload methodology but not in the same degree. In the graphs of Figure 10 the gold color represents the aggregation workload methodology and the black represents the Release workload one. Also, the circle marker is for the SPT sequencing rule, and the triangle marker is for FCFS. For the first breakdown level, the advantage of the SPT sequencing rule on ORR method is still recognizable but is much less and only on the Gross Throughput Time and Standard Deviation of Lateness parameters. On the other two parameters, Tardiness and Percentage of Tardy Orders, SPT doesn’t have advantage at all because for some values of SFT, the values of these parameters are equal or even higher than AB/F. This indicates us that the use of the workload aggregation methodology is more relevant for Balancing release rule. However, the SPT still has some contribution on the performance of RB which compared to the performance of RB/F, has much better results for all the parameters and for all the breakdown levels. For the second breakdown level, the pattern of performance distribution is almost the same as of the first breakdown level. The advantage of using aggregation of workload over the release workload is more notorious here as well.

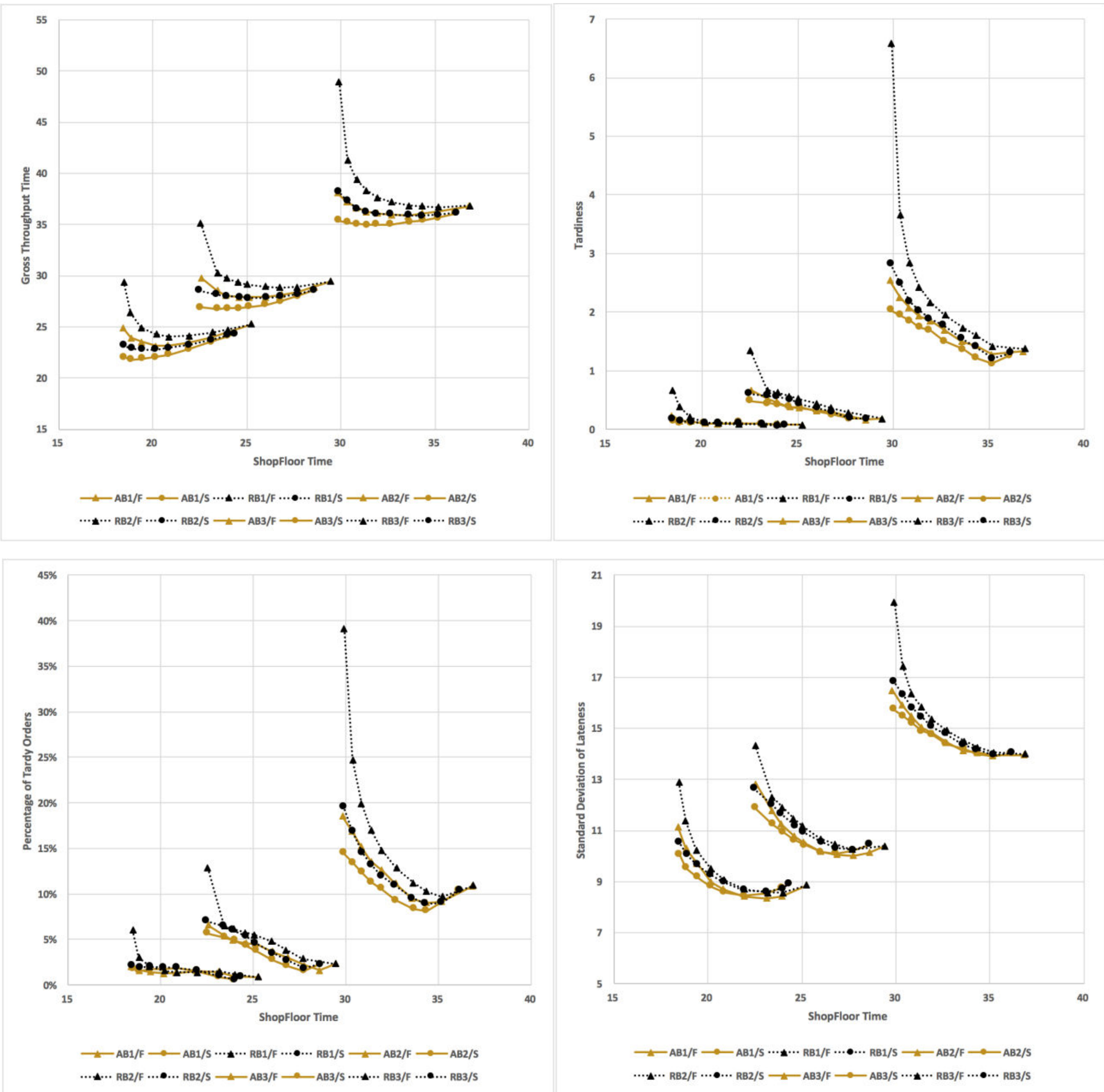


*Figure 10. Performance for all parameters of ORR methods with Balancing release methodology at all breakdown levels with 20% distortion*

When we look at the third breakdown level, we see the same behavior and distribution than the first and second breakdown levels for AB/S and AB/F and for RB/S. The case of the RB/F is very distinguishable since its performance at all parameters worsens considerably. This is especially for the Tardiness and Percentage of Tardy Orders parameters because at lower SFT values it shows a very poor performance. But on the other hand, as it was mentioned earlier, the use of SPT sequencing rule improves the performance of RB and is almost the same as the performance of the AB/F. This is true not only for the third level of breakdown, but for all levels.

### 4.1.3 Effects of level of Distortion on the ORR Methods

The performances of each method at all the different scenarios, were taken to be at the workload norm in which the resultant GTT is the lowest compared to the other GTT values for the rest workload norms tested within the same ORR method. In simulation studies, the best performing workload norm is better identified experimentally and as a variable (Thurer 2010, Henrich 2007, Land 2006). As it was already mentioned above, the best performing method is the AB/S since it yields the lowest GTT among all the ORR methods. Table 10 shows the performances in each parameter for all methods at the three breakdown levels with only 20% distortion. In all the breakdown levels, AB/S has better performance since the values of GTT is the lowest. Low GTT is desirable since it can be interpreted as reduced response time to the customers (Fernandes and Carmo Silva 2011). The resultant values of parameters of AB/S serve as reference. The resultant values of each parameter for the other methods are compared to the ones of AB/S and given as a percentage difference. AB/S has better performance in GTT and SFT but it is not so for the other parameters for which mostly perform worse than the other ORR methods.

| | | ORR Method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | AB/S | RB/S | AL/S | RL/S | AB/F | RB/F | AL/F | RL/F |
| Breakdown Level 1 | GTT (hours) | 21.8 | 4.4% | 10.8% | 10.6% | 6.0% | 10.2% | 15.8% | 15.8% |
| | SFT (hours) | 18.8 | 3.2% | 22.5% | 22.9% | 7.1% | 10.7% | 34.0% | 34.0% |
| | Tardiness (hours) | 0.1 | 22.1% | -32.7% | -28.1% | -7.7% | -5.7% | -26.0% | -26.0% |
| | % Tardy Orders (pcs) | 1.7% | 13.9% | -54.8% | -49.5% | -23.3% | -17.5% | -50.7% | -50.7% |
| | SD Lateness (hours) | 9.5 | 1.3% | -6.7% | -6.1% | -5.8% | -5.0% | -7.1% | -7.1% |
| Breakdown Level 2 | GTT (hours) | 26.8 | 3.8% | 6.5% | 6.6% | 4.1% | 7.7% | 9.9% | 9.9% |
| | SFT (hours) | 23.4 | 7.0% | 18.1% | 18.1% | 7.1% | 14.2% | 25.6% | 25.5% |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Tardiness (hours) | 0.4 | -1.4% | -58.6% | -56.7% | -16.5% | -16.9% | -58.8% | -58.8% |
| | % Tardy Orders (pcs) | 4.9% | -27.7% | -54.4% | -52.2% | -24.7% | -41.1% | -51.6% | -51.7% |
| | SD Lateness (hours) | 11.3 | -2.9% | -7.3% | -6.7% | -6.4% | -7.0% | -7.6% | -7.6% |
| Breakdown Level 3 | GTT (hours) | 34.9 | 2.7% | 3.5% | 3.5% | 2.7% | 5.1% | 5.5% | 5.5% |
| | SFT (hours) | 31.4 | 7.1% | 15.1% | 15.1% | 7.0% | 12.2% | 17.3% | 17.3% |
| | Tardiness (hours) | 1.7 | -10.9% | -25.6% | -26.2% | -14.1% | -18.7% | -20.9% | -21.6% |
| | % Tardy Orders (pcs) | 10.6% | -10.0% | -1.8% | -1.9% | -10.7% | 2.6% | 2.5% | 2.5% |
| | SD Lateness (hours) | 14.9 | -3.6% | -5.8% | -5.9% | -5.3% | -5.7% | -6.1% | -6.2% |

*Table 10. Performances of all ORR methods at the three breakdown levels and 20% distortion*

To further analyze the behavior and performance of the ORR methods at each breakdown level, the degree of distortion on the processing time was varied within each of these levels. In the previous part, only a low distortion factor was for the analysis. For this section, a medium and a high distortion factor were included in addition to the one of 20%. These factors are of 40% and 80%. Since it was already proven from the previous analysis that SPT sequencing rule performs better, for the analysis in this section we considered only this rule. The analysis is done separately according to the aggregation of workload methodology. Therefore AB/S is compared to AL/S, and RB/S to RL/S.

Figure 11 shows the results for the considered parameters for methods AB/S and AL/S. Each plot displays the results of the three distortion factors for the three breakdown levels. Each breakdown level is represented by a different color. Gold is for the first level, black for the second level, and green for the third one. Within each breakdown level there are three distortion factors represented by different lines. The dashed line represents the distortion of 20%, the full line represents the one of 40%, and the dotted line represents the one of 80%. In addition, the cross marker represents AB and the circle marker represents AL. Looking at the breakdown levels and comparing the results between them, it is very distinguishable that the advantage of AB/S over AL/S diminishes considerably for the third level of breakdown, while this advantage is lower for the second level, and less for the first one. This is true also for the three distortion factors within each breakdown level.

The effect of the distortion factor within each breakdown level is quite interesting. As the degree of distortion increases, the pattern or distribution shifts to a higher value of the initial SFT. Increasing from 20% to 40% distortion induces a slight shift to an initial SFT of higher value, but increasing from 40% to 80% has a much greater shift.

Considering only the third breakdown level, for the lower range of SFT values, the results of the parameters standard deviation of lateness and percentage of tardy orders of AB/S and AL/F shows almost the same performance, depending on the distortion degree. These two parameters can be used as an indicator for the dispersion of orders' lateness (Land 2006). For the 20% distortion, these performances are the same; for the 80% distortion, the performances are very close but interestingly for the 40% one, there is a higher difference between them. The impact under the three distortions factors are the same for the other two parameters, GTT and tardiness.

The distortion factors of 20% and 40% on the first and second level of breakdown have no great difference for both methods. In the case of the 80% factor, the pattern of each parameter moves to the upper-right side which shows a worsening in performances. However, the maximum value in each parameter, thus the worse performance, is almost maintained among the three distortion factors. This is most easily seen for the AL/S method which keeps almost the same maximum value for all parameters for the three distortion factors between the first and second breakdown level. For the third level, those values differ depending on the parameter. On the other hand, the situation is almost the same for AB/S but on the first breakdown level for the 80% distortion, the maximum value for all parameters is higher than for the other two distortion factors.

For both methods AB/S and specially for AL/S, when analyzing the results on the parameter GTT, we can see the initial maximum value of GTT for all distortion for each breakdown levels are almost maintained when the distortion increases while the minimum initial value of SFT is considerably increased. This suggests us that the impact of the degree of distortion is almost entirely translated onto the delays happening in the shop floor, so increasing the shop floor time. However, since the gross throughput time remains quite the same, it means that the average time an order stays in the pre-shop pool in reduced to maintain an overall gross throughput time. Therefore, requiring higher WIP to meet this requirement, and so having a negative impact.

Overall, the effect of the distortion factor can be compared to the effect of the breakdown level but at a lower scale, the 80% distortion factor has a greater impact on the performances as it has the third breakdown level. Another interesting point to mention is that in the case of the AL/S, the range of results values of the different parameters (the maximum, minimum and all the values within them) decreases firstly, as the breakdown level increases; and secondly, as the distortion level increases in each breakdown level. On the contrary, for the case of AB/S, the range of the results values of the parameters decreases as the breakdown level increases. However, we cannot assure the same situation for the distortion level within each breakdown level since it is not clear.

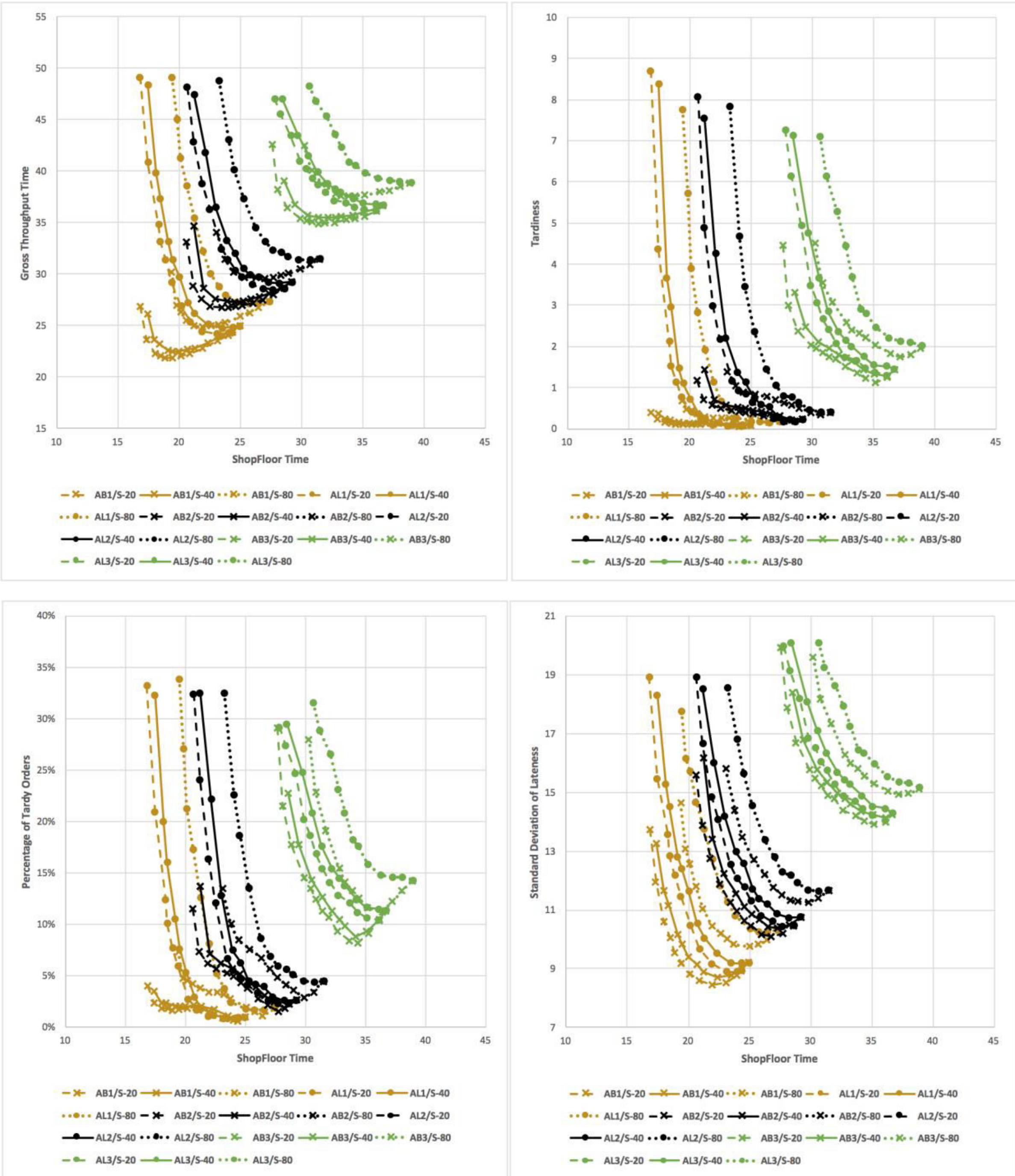
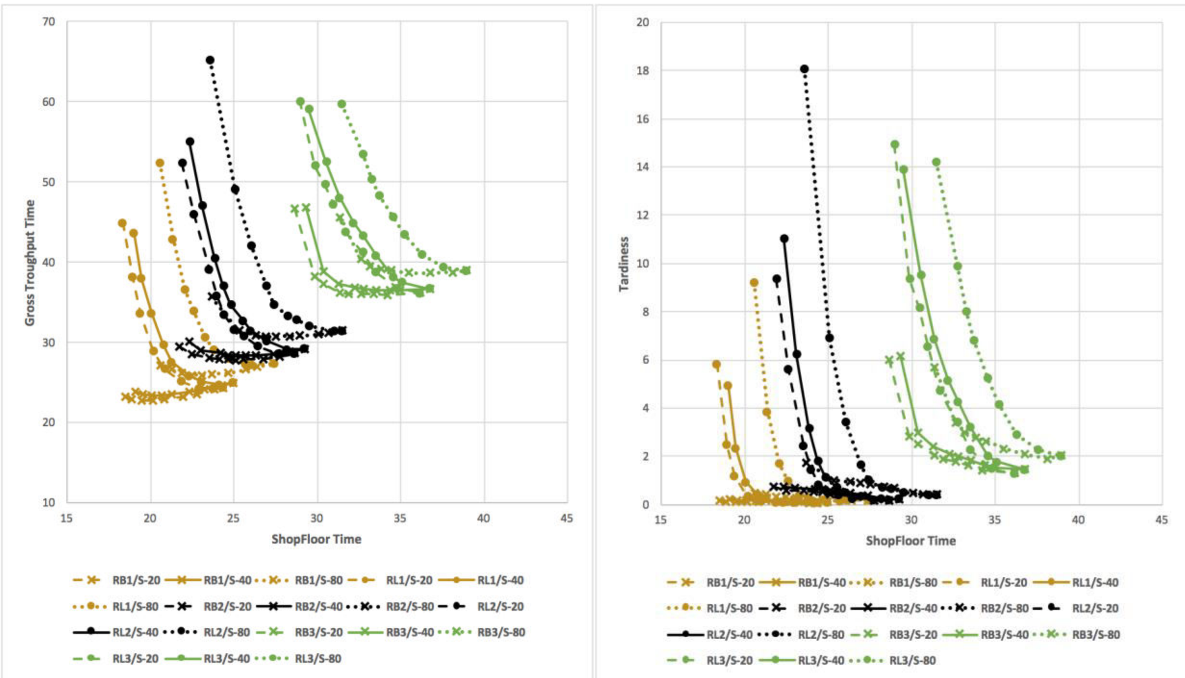



*Figure 11. Performances of ORR methods with aggregation of workload at all breakdown levels and all distortion levels*

Figure 12 shows the results for the considered parameters for methods RB/S and RL/S. In the same way, each breakdown level is represented by a different color. Gold is for the first level, black for the second level, and green for the third one. Within each breakdown level there are three distortion factors represented by different lines. The dashed line represents the distortion of 20%, the full line represents the one of 40%, and the dotted line represents the one of 80%. In addition, the cross marker represents RB and the circle marker represents RL. As in the case of AB/S vs AL/S, here also we can see that the advantage of RB over RL at all the parameters diminishes considerably at the breakdown level three. However, we cannot ensure anything for the first and second levels. In fact, it seems that the advantage of RB over RL is higher on the second level than on the first one.

When analyzing the results on the parameter GTT, we can see the initial maximum value of GTT increases as the distortion increases within each breakdown levels in the same way that the minimum initial value of SFT also increased as distortion increases. This as a difference from AB/S vs AL/S, tells us that not most of the delay on processing an order (gross throughput time) is burdened by delays on the shop floor time and so on increasing WIP (Fernandes and Carmo Silva 2011), but also part of this delay is translated into extended waiting periods in the pre-shop pool.



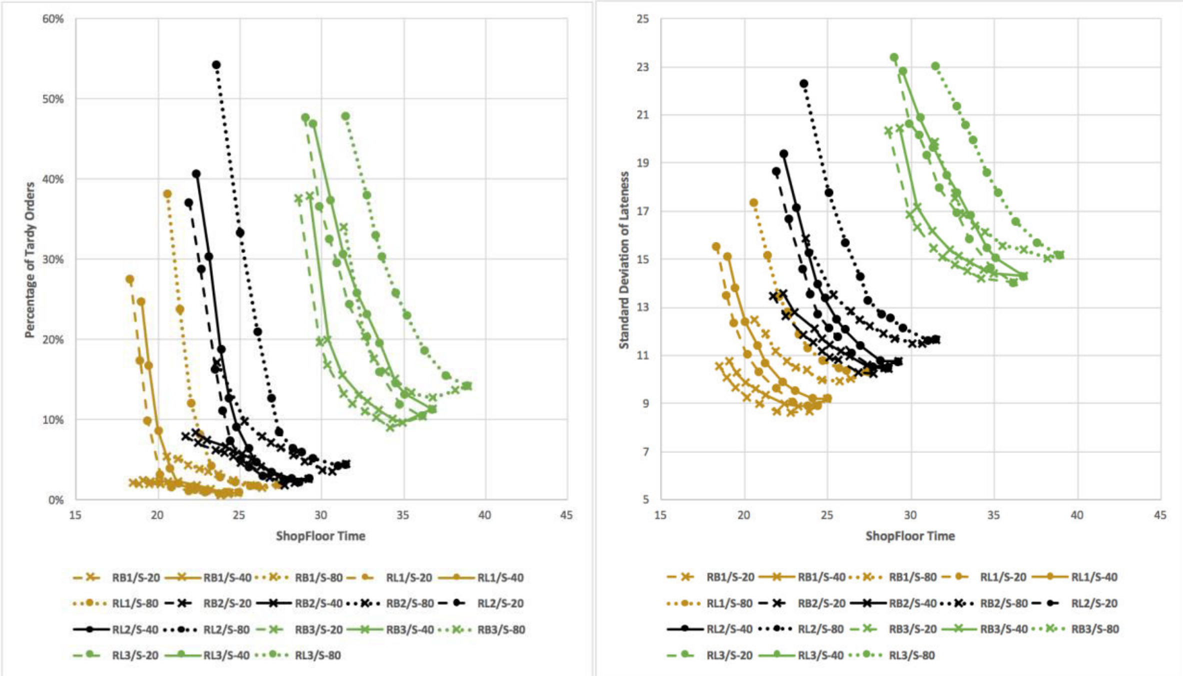



*Figure 12. Performances of ORR methods with released workload at all breakdown levels and all distortion levels*

### 4.1.4 Performances of the ORR methods at all scenarios

The performance results of all ORR methods under the three distortion factors and at the three different levels of breakdown are displayed in Table 11. In (a) shows the results for the first breakdown level, (b) for the second level, and (c) for the third level. For all the degrees of distortion and at the three breakdown levels, AB/S has better performance regarding GTT and SFT parameters but it is not the case for the other parameters. For the parameters GTT and SFT, the second best performing method in all cases is the RB/S which shows us the great advantage of having SPT as the sequencing rule. For the first and second level of breakdown and at all the distortion factors, the parameters Tardiness and Percentage of Tardy Orders don't have a single better performing method but instead it appears that are better performed by all methods with Limiting release rule independently of the sequencing rule used and having only small differences between them. These methods are AL/F, AL/S, RL/F, and RL/S. The results of these methods are statistically insignificant so they could be treated as equal. For the third level of breakdown the situation is different. These two parameters are not performed better by all Limiting methods but by a specific method. Tardiness is better performed by RL/S at all distortion factors and Percentage of Tardy Orders is better performed by AB/F with FCFS at all the distortion factors. The Standard Deviation of Lateness parameter shows a strong influence by the breakdown level but not so for the distortion degree since the best performing method at this parameter is the same for all distortion factors but is different depending on the breakdown level.

***(a)***

| Performances at Breakdown Level 1 | | ORR Method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **AB/F** | **AB/S** | **RB/F** | **RB/S** | **AL/F** | **AL/S** | **RL/F** | **RL/S** |
| 20% Distortion | GTT (hours) | 23.11 | 21.81 | 24.04 | 22.77 | 25.25 | 24.17 | 25.25 | 24.13 |
| | SFT (hours) | 20.17 | 18.84 | 20.87 | 19.45 | 25.25 | 23.09 | 25.25 | 23.16 |
| | Tardiness (hours) | 0.10 | 0.11 | 0.10 | 0.13 | 0.08 | 0.07 | 0.08 | 0.08 |
| | % Tardy O. (pcs) | 1.32% | 1.72% | 1.42% | 1.96% | 0.85% | 0.78% | 0.85% | 0.87% |
| | SD Lateness (hours) | 8.98 | 9.54 | 9.06 | 9.66 | 8.86 | 8.90 | 8.86 | 8.95 |
| 40% Distortion | GTT (hours) | 23.75 | 22.45 | 24.69 | 23.38 | 25.89 | 24.74 | 25.89 | 24.82 |
| | SFT (hours) | 21.30 | 19.98 | 21.27 | 20.05 | 25.89 | 23.50 | 25.89 | 24.37 |
| | Tardiness (hours) | 0.12 | 0.12 | 0.14 | 0.16 | 0.09 | 0.08 | 0.09 | 0.09 |
| | % Tardy O. (pcs) | 1.78% | 2.15% | 0.95% | 2.24% | 0.95% | 0.81% | 0.95% | 0.90% |
| | SD Lateness (hours) | 8.99 | 9.40 | 9.41 | 9.88 | 9.16 | 9.18 | 9.16 | 9.20 |
| 80% Distortion | GTT (hours) | 26.24 | 24.86 | 27.30 | 25.86 | 28.37 | 27.15 | 28.41 | 27.21 |
| | SFT (hours) | 23.25 | 21.92 | 24.98 | 22.57 | 26.32 | 25.74 | 28.40 | 26.36 |
| | Tardiness (hours) | 0.24 | 0.26 | 0.23 | 0.30 | 0.18 | 0.16 | 0.18 | 0.16 |
| | % Tardy O. (pcs) | 3.01% | 3.35% | 2.59% | 3.50% | 1.81% | 1.65% | 1.92% | 1.75% |
| | SD Lateness (hours) | 10.10 | 10.46 | 10.00 | 10.73 | 10.22 | 10.26 | 10.31 | 10.33 |

***(b)***

| Performances at Breakdown Level 2 | | ORR Method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **AB/F** | **AB/S** | **RB/F** | **RB/S** | **AL/F** | **AL/S** | **RL/F** | **RL/S** |
| 20% Distortion | GTT (hours) | 27.88 | 26.77 | 28.84 | 27.79 | 29.42 | 28.52 | 29.41 | 28.54 |
| | SFT (hours) | 25.10 | 23.43 | 26.74 | 25.08 | 29.42 | 27.66 | 29.41 | 27.68 |
| | Tardiness (hours) | 0.37 | 0.44 | 0.36 | 0.43 | 0.18 | 0.18 | 0.18 | 0.19 |
| | % Tardy O. (pcs) | 3.68% | 4.89% | 2.88% | 3.54% | 2.37% | 2.23% | 2.36% | 2.34% |
| | SD Lateness (hours) | 10.54 | 11.26 | 10.47 | 10.93 | 10.40 | 10.44 | 10.40 | 10.50 |
| 40% Distortion | GTT (hours) | 28.40 | 27.31 | 29.41 | 28.43 | 30.04 | 29.11 | 30.05 | 29.14 |
| | SFT (hours) | 25.83 | 24.53 | 27.36 | 25.83 | 30.04 | 28.16 | 30.04 | 28.29 |
| | Tardiness (hours) | 0.42 | 0.49 | 0.42 | 0.53 | 0.23 | 0.23 | 0.23 | 0.24 |
| | % Tardy O. (pcs) | 3.91% | 4.43% | 2.98% | 4.93% | 2.74% | 2.54% | 2.75% | 2.74% |
| | SD Lateness (hours) | 10.70 | 11.11 | 10.69 | 11.11 | 10.68 | 10.73 | 10.69 | 10.78 |
| 80% Distortion | GTT (hours) | 30.71 | 29.53 | 31.85 | 30.69 | 32.43 | 31.36 | 32.43 | 31.47 |
| | SFT (hours) | 27.72 | 26.96 | 29.81 | 27.65 | 32.42 | 29.78 | 32.42 | 31.46 |
| | Tardiness (hours) | 0.67 | 0.70 | 0.64 | 0.83 | 0.43 | 0.46 | 0.43 | 0.41 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| % Tardy O. (pcs) | 5.34% | 4.81% | 4.00% | 5.60% | 4.85% | 4.46% | 4.84% | 4.46% |
| SD Lateness (hours) | 11.56 | 11.76 | 11.54 | 12.08 | 11.61 | 11.69 | 11.61 | 11.66 |

***(c)***

| Performances at Breakdown Level 3 | | ORR Method | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **AB/F** | **AB/S** | **RB/F** | **RB/S** | **AL/F** | **AL/S** | **RL/F** | **RL/S** |
| 20% Distortion | GTT (hours) | 35.86 | 34.93 | 36.71 | 35.87 | 36.85 | 36.14 | 36.86 | 36.14 |
| | SFT (hours) | 33.57 | 31.37 | 35.19 | 33.58 | 36.80 | 36.09 | 36.79 | 36.09 |
| | Tardiness (hours) | 1.49 | 1.74 | 1.41 | 1.55 | 1.38 | 1.29 | 1.36 | 1.28 |
| | % Tardy O. (pcs) | 9.50% | 10.64% | 10.92% | 9.57% | 10.90% | 10.45% | 10.90% | 10.43% |
| | SD Lateness (hours) | 14.11 | 14.90 | 14.06 | 14.36 | 14.00 | 14.04 | 13.98 | 14.02 |
| 40% Distortion | GTT (hours) | 36.47 | 35.47 | 37.24 | 36.46 | 37.44 | 36.71 | 37.44 | 36.71 |
| | SFT (hours) | 33.24 | 32.16 | 36.12 | 35.02 | 37.44 | 36.71 | 37.43 | 36.71 |
| | Tardiness (hours) | 1.79 | 1.81 | 1.47 | 1.50 | 1.54 | 1.46 | 1.54 | 1.46 |
| | % Tardy O. (pcs) | 11.43% | 11.26% | 10.53% | 9.61% | 11.70% | 11.30% | 11.70% | 11.30% |
| | SD Lateness (hours) | 14.62 | 14.97 | 14.16 | 14.36 | 14.22 | 14.29 | 14.22 | 14.29 |
| 80% Distortion | GTT (hours) | 38.65 | 37.57 | 39.54 | 38.61 | 39.74 | 38.93 | 39.75 | 38.92 |
| | SFT (hours) | 35.17 | 33.25 | 38.11 | 36.27 | 39.73 | 38.92 | 39.73 | 38.91 |
| | Tardiness (hours) | 2.26 | 2.41 | 2.02 | 2.13 | 2.10 | 2.03 | 2.11 | 2.02 |
| | % Tardy O. (pcs) | 13.28% | 13.28% | 13.61% | 12.49% | 14.81% | 14.22% | 14.81% | 14.22% |
| | SD Lateness (hours) | 15.31 | 15.98 | 15.03 | 15.40 | 15.05 | 15.16 | 15.06 | 15.15 |

*Table 11. Performances of all ORR methods at all breakdown levels ((a) for level 1, (b) for level 2, (c) for level 3), and all distortion levels*

Because the aggregation of workload is proven to outperform the released workload methodology, another comparison to be done is the one between AB and AL in which AL is taken to be as a reference to see how much better performs AB compared to it. This means that the comparison is done for the Balancing and the Limiting release rule while having the other variabilities the same. Therefore, since SPT is the best sequencing rule, it was chosen for the comparison of the mentioned release rules. Table 12 shows the performances of AB/S and AL/S for each breakdown level at three different shop floor times and considering all distortion levels at each of these shop floor times.

***(a)***

| **Breakdown Level 1** | | **AB/S** | | | | | | **AL/S** | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **20%** | **Δ** | **40%** | **Δ** | **80%** | **Δ** | **20%** | **Δ** | **40%** | **Δ** | **80%** | **Δ** |
| **SFT: 19.5** | GTT | 21.87 | - | 22.50 | 3% | 28.83 | 32% | 28.65 | 31% | 32.04 | 46% | 49.09 | 124% |
| | Tardiness | 0.11 | - | 0.14 | 32% | 0.59 | 437% | 0.65 | 495% | 1.21 | 1014% | 7.75 | 7009% |
| | % Tardy O. | 1.6% | - | 2.1% | 30% | 6.2% | 294% | 4.9% | 209% | 8.7% | 451% | 33.9% | 2042% |

| | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | SD Lateness | 9.18 | - | 9.82 | 7% | 14.01 | 53% | 11.22 | 22% | 12.54 | 37% | 17.74 | 93% |
| **SFT: 21.3** | GTT | 22.52 | - | 22.82 | 1% | 24.98 | 11% | 25.01 | 11% | 26.17 | 16% | 34.27 | 52% |
| | Tardiness | 0.11 | - | 0.13 | 16% | 0.29 | 156% | 0.20 | 77% | 0.24 | 116% | 1.63 | 1344% |
| | % Tardy O. | 1.8% | - | 2.0% | 10% | 3.8% | 109% | 1.5% | -16% | 5.3% | 195% | 12.6% | 601% |
| | SD Lateness | 8.51 | - | 8.89 | 4% | 11.05 | 30% | 9.57 | 12% | 10.05 | 18% | 13.72 | 61% |
| **SFT: 23.5** | GTT | 23.79 | - | 23.99 | 1% | 25.28 | 6% | 24.25 | 2% | 24.74 | 4% | 28.44 | 20% |
| | Tardiness | 0.07 | - | 0.11 | 54% | 0.26 | 257% | 0.07 | -8% | 0.08 | 13% | 0.37 | 402% |
| | % Tardy O. | 0.6% | - | 1.1% | 69% | 2.9% | 363% | 0.80% | 27% | 0.81% | 30% | 3.2% | 404% |
| | SD Lateness | 8.66 | - | 8.79 | 1% | 9.93 | 15% | 8.93 | 3% | 9.18 | 6% | 11.07 | 28% |

***(b)***

| Breakdown Level 2 | | AB/S | | | | | | AL/S | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **20%** | **Δ** | **40%** | **Δ** | **80%** | **Δ** | **20%** | **Δ** | **40%** | **Δ** | **80%** | **Δ** |
| **SFT: 24.0** | GTT | 26.76 | - | 27.38 | 2% | 30.86 | 15% | 31.06 | 16% | 33.20 | 24% | 43.03 | 61% |
| | Tardiness | 0.41 | - | 0.52 | 28% | 0.98 | 141% | 0.90 | 120% | 1.30 | 217% | 4.68 | 1046% |
| | % Tardy O. | 4.8% | - | 5.7% | 19% | 9.5% | 98% | 5.3% | 11% | 7.5% | 56% | 22.5% | 372% |
| | SD Lateness | 10.90 | - | 11.44 | 5% | 14.09 | 29% | 11.99 | 10% | 12.84 | 18% | 16.80 | 54% |
| **SFT: 26.3** | GTT | 27.31 | - | 27.68 | 1% | 29.62 | 8% | 28.78 | 5% | 29.68 | 9% | 34.30 | 26% |
| | Tardiness | 0.29 | - | 0.38 | 31% | 0.78 | 169% | 0.28 | -3% | 0.50 | 73% | 1.38 | 377% |
| | % Tardy O. | 2.5% | - | 4.4% | 76% | 6.7% | 167% | 3.0% | 19% | 3.9% | 54% | 8.6% | 240% |
| | SD Lateness | 10.13 | - | 10.50 | 4% | 12.21 | 21% | 10.75 | 6% | 11.17 | 10% | 13.40 | 32% |
| **SFT: 28.6** | GTT | 28.60 | - | 28.83 | 1% | 29.93 | 5% | 28.60 | 0% | 29.12 | 2% | 31.82 | 11% |
| | Tardiness | 0.18 | - | 0.19 | 6% | 0.53 | 192% | 0.18 | 0% | 0.23 | 24% | 0.64 | 250% |
| | % Tardy O. | 2.3% | - | 2.1% | -10% | 3.8% | 69% | 2.6% | 15% | 2.5% | 11% | 5.4% | 140% |
| | SD Lateness | 10.46 | - | 10.57 | 1% | 11.29 | 8% | 10.46 | 0% | 10.70 | 2% | 12.04 | 15% |

***(c)***

| **Breakdown Level 3** | | AB/S | | | | | | AL/S | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | **20%** | **Δ** | **40%** | **Δ** | **80%** | **Δ** | **20%** | **Δ** | **40%** | **Δ** | **80%** | **Δ** |
| **SFT: 30.8** | GTT | 35.04 | - | 35.68 | 2% | 40.07 | 14% | 39.28 | 12% | 40.99 | 17% | 47.44 | 35% |
| | Tardiness | 1.85 | - | 2.08 | 12% | 3.53 | 91% | 2.69 | 45% | 3.29 | 77% | 6.51 | 251% |
| | % Tardy O. | 13.4% | - | 13.8% | 3% | 22.9% | 70% | 16.6% | 24% | 19.7% | 47% | 30.2% | 125% |
| | SD Lateness | 15.21 | - | 15.63 | 3% | 18.16 | 19% | 16.11 | 6% | 16.72 | 10% | 19.60 | 29% |
| **SFT: 33.0** | GTT | 35.08 | - | 35.51 | 1% | 37.71 | 8% | 37.06 | 6% | 38.05 | 8% | 42.61 | 21% |
| | Tardiness | 1.48 | - | 1.66 | 12% | 2.51 | 70% | 1.71 | 16% | 2.07 | 41% | 3.81 | 158% |
| | % Tardy O. | 11.3% | - | 10.0% | -11% | 14.9% | 32% | 15.4% | 37% | 14.2% | 26% | 21.3% | 89% |
| | SD Lateness | 14.33 | - | 14.65 | 2% | 16.17 | 13% | 14.80 | 3% | 15.34 | 7% | 17.33 | 21% |
| **SFT: 36.0** | GTT | 36.03 | - | 36.32 | 1% | 37.93 | 5% | 36.14 | 0% | 36.76 | 2% | 39.33 | 9% |
| | Tardiness | 1.22 | - | 1.27 | 4% | 1.91 | 56% | 1.29 | 6% | 1.48 | 21% | 2.20 | 80% |
| | % Tardy O. | 10.4% | - | 10.5% | 1% | 11.3% | 9% | 12.1% | 16% | 12.4% | 20% | 14.8% | 43% |
| | SD Lateness | 13.99 | - | 14.13 | 1% | 15.14 | 8% | 14.04 | 0% | 14.39 | 3% | 15.55 | 11% |

*Table 12. Performances of AB/S and AL/S at all breakdown levels ((a) for level 1, (b) for level 2, (c) for level 3), and at all distortion levels*

The gross throughput time is the parameter considered as the performance indicator as it was already described thus the lowest value of this parameter is sought. Table 12 shows what it was already noticed from the graphs which is that as increasing the breakdown levels, the advantage of AB over AL decreases.

#### 4.1.5 Robustness Analysis

Considering the results of each ORR method separately at each scenario doesn't give us information about their performances when variances occur and so under different scenarios. Therefore, there is the need to measure the degree of variation on the results for all the parameters of each ORR method considering the three distortion factors at each breakdown level. And then also measuring the variation on the parameters among all the three breakdown levels. For this purpose, the Robustness Index is used and which indicates the variability or fluctuation on results of different scenarios. Therefore, lower values on the indexes are desired since it shows less fluctuation on results of different scenarios and more stability.

Table 13 shows the Robustness indexes at each distortion level separately but evaluating the variation and stability on results among the three breakdown levels. The best performances, which are the lowest values, are in bold. As already known AB/S has a better performance (which is obtained at a single shop floor value) in all scenarios but the performance of this method along the different shop floor time values doesn't show the strongest stability as it can be seen from the table. AB/S is not the most robust in neither the GTT parameter nor the SFT one. Instead AB/F appears to be the most robust in terms of SFT for all the three distortion levels. In the same way, RB/S is the most robust for the GTT parameter and for all the three distortion levels.
Looking at the other three parameters, percentage of tardy orders, tardiness and standard deviation of lateness, there is single method which is the most robust thus the more stable on these parameters. This method is the AB/S. this is interesting because this method doesn't have a better performance than the other methods on these parameters when see the results of each scenario independently, Table 11; but it is the one that has the more stability on the performance of the parameters along the different shop floor time values. The results are in consistency with the study

of Cigolini and Portioli (2002) which shows that the Balancing method is the most robust against changes in the environmental factors.

***(a)***

| Robustness Analysis | | Gross Throughput Time | | | Shop Floor Time | | |
|---|---|---|---|---|---|---|---|
| Distortion Factor | | **20%** | **40%** | **80%** | **20%** | **40%** | **80%** |
| **ORR method** | AB/F | 4.25 | 3.35 | 2.23 | **11.60** | **10.27** | **12.41** |
| | AB/S | 2.10 | 2.26 | 2.69 | 16.01 | 14.92 | 16.10 |
| | AL/F | 28.61 | 28.19 | 26.70 | 19.85 | 19.91 | 18.80 |
| | AL/S | 20.02 | 19.53 | 18.40 | 16.51 | 16.22 | 15.75 |
| | RB/F | 20.85 | 17.82 | 19.93 | 12.00 | 12.02 | 14.40 |
| | RB/S | **-0.51** | **-1.32** | **-2.64** | 12.78 | 13.47 | 12.86 |
| | RL/F | 39.06 | 38.62 | 37.88 | 19.89 | 19.95 | 20.26 |
| | RL/S | 32.16 | 31.78 | 30.58 | 16.56 | 17.07 | 17.66 |

***(b)***

| Robustness Analysis | | Tardiness | | | Percentage of Tardy Orders | | | Standard Deviation of Lateness | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Distortion Factor | | **20%** | **40%** | **80%** | **20%** | **40%** | **80%** | **20%** | **40%** | **80%** |
| **ORR method** | AB/F | -26.93 | -26.45 | -24.52 | -54.64 | -52.65 | -59.62 | -7.04 | -6.58 | -22.97 |
| | AB/S | **-29.95** | **-30.21** | **-24.98** | **-67.83** | **-80.72** | **-68.36** | **-8.80** | **-18.37** | **-24.64** |
| | AL/F | 15.93 | 15.57 | 14.63 | -25.60 | -25.78 | -26.47 | 17.43 | 16.71 | 14.52 |
| | AL/S | 2.75 | 2.48 | 3.80 | -35.75 | -35.55 | -35.84 | 10.80 | 10.20 | 9.14 |
| | RB/F | -0.71 | -2.46 | 2.52 | -34.16 | -35.20 | -31.61 | 14.12 | 12.58 | 13.77 |
| | RB/S | -23.11 | -20.46 | -17.53 | -54.01 | -50.62 | -54.05 | -5.91 | -7.30 | -9.93 |
| | RL/F | 29.50 | 28.96 | 29.02 | -16.12 | -16.29 | -16.30 | 24.56 | 24.01 | 23.34 |
| | RL/S | 18.66 | 17.89 | 17.54 | -22.91 | -23.05 | -23.59 | 18.91 | 18.44 | 17.12 |

*Table 13. Robusteness analysis of all ORR methods at each distortion level*

In addition to situations in which different levels of breakdown occur within a same certain period, it is very probable to find in real world also the probability for a shop floor to undergo not only a unique distortion level but different levels. Therefore, analyzing the Robustness of the ORR methods including also the three distortion levels will give us results for more realistic situations. Table 14 shows the Robustness Indexes considering the three breakdown levels as well as the three distortion levels. The most robust method at each parameter is the same as in the previous robustness analysis, Table 13. RB/S is most robust regarding GTT, AB/F is more robust regarding

SFT, and AB/ S is the most robust for the other three parameters: percentage of tardy orders, tardiness and standard deviation of lateness. From this we can conclude that independently of whether a shop floor may suffer different degrees of distortion or having an accurate estimated degree, the methods showing the more stability on their performances are the same so they are not affected by the different levels of distortion but only on the breakdown levels.

| **Overall Robustness Analysis** | | **Parameter** | | | | |
|---|---|---|---|---|---|---|
| | | **GTT** | **SFT** | **Tardiness** | **% Tardy Orders** | **SD Lateness** |
| **ORR method** | AB/F | 9.83 | **34.27** | -77.91 | -166.91 | -36.59 |
| | AB/S | 7.06 | 47.03 | **-85.14** | **-216.91** | **-51.82** |
| | AL/F | 83.50 | 58.56 | 46.13 | -77.84 | 48.66 |
| | AL/S | 57.95 | 48.48 | 9.02 | -107.14 | 30.14 |
| | RB/F | 58.60 | 38.43 | -0.64 | -100.97 | 40.47 |
| | RB/S | **-4.46** | 39.11 | -61.10 | -158.68 | -23.13 |
| | RL/F | 115.57 | 60.10 | 87.48 | -48.71 | 71.91 |
| | RL/S | 94.52 | 51.30 | 54.10 | -69.55 | 54.47 |

*Table 14. Overall Robustness analysis of all ORR methods*

The results of the robustness analysis serve as a reference or guidance for knowing the most suitable ORR method depending on the characteristics of the shop floor so there is no one best method suited for all situations. The selection of the method should be also done regarding the parameters which are considered the most important. As it was already mentioned the degree of distortion doesn't have an impact on which method is the most robust on a certain parameter thus the same method is the most robust under a single distortion level or under all three levels. The RB/S method appears to be the most stable on the GTT parameter but when looking only at performances at each scenario individually, this method is the second best performing and the AB/S is the best one. Therefore, if the breakdown in the shop floor is not certain and all three types of breakdown are probable to occur, the RB/S method could be the chosen one, but if the degree of breakdown is predictable and quite accurate then AB/S is the best option since this method yields better performing values. This could be the case of the production of high value products since it may allow to have some machine idle time and overall delays on completion but it may not be wanted to have higher WIP. On the other hand, if the parameters tardiness, tardy orders and standard deviation of lateness are more important and relevant, then AB/S should be the suitable method in the case that the breakdown level is uncertain since it is the more stable method on these parameters. And in the same way, when the level of breakdown is predictable then the values of Table 14 should be used as guidance to select an appropriate method.

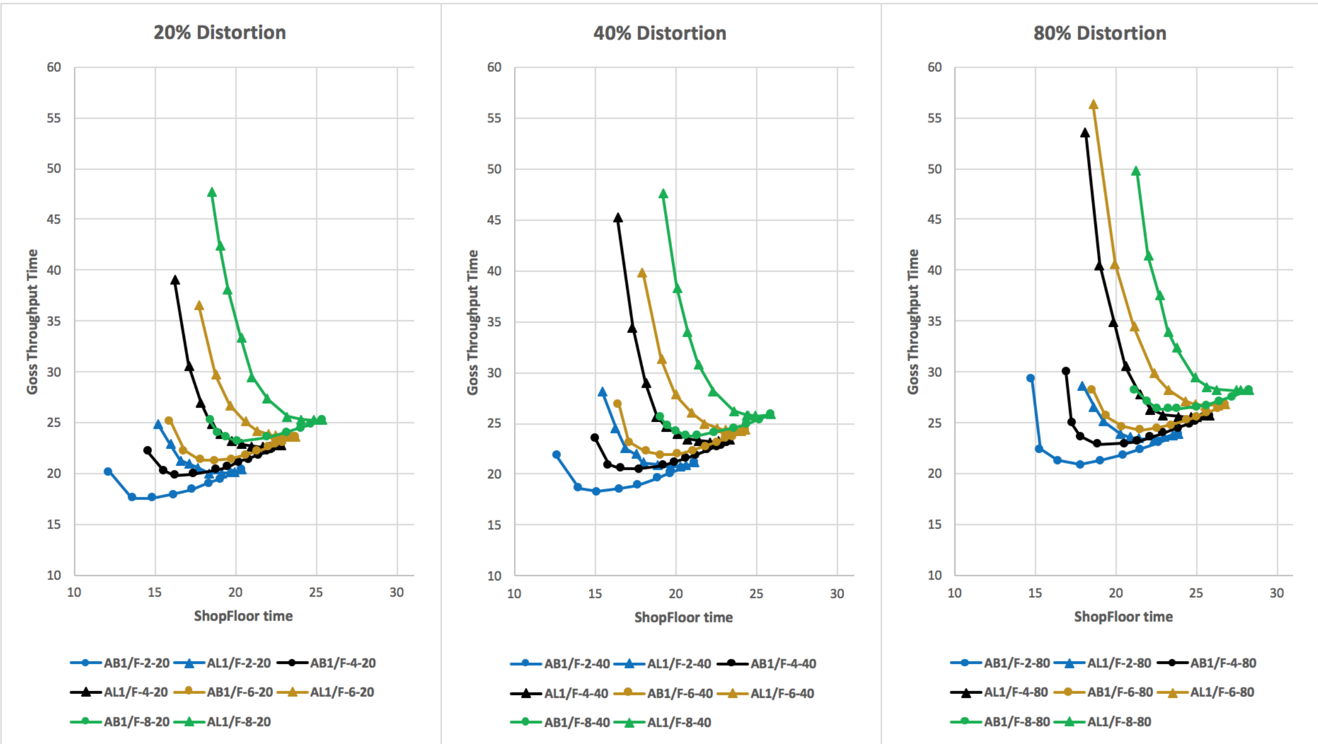
Overall, since the characteristics of the shop floor are different, the products produced are different, the row material used are different, the core parameters or indicators which are the most important are different, and as many other features may be different, the selection of the ORR method should be carried out regarding those features as well as the importance of the parameters on the company. Therefore, the results given in this thesis may serve as a guidance and reference for such purpose.

## 4.2 Analysis of Order Release Frequency

### 4.2.1 ORR methods' performances at the different order release frequencies

This second section of the thesis analyses the effect of having other frequencies of order release to the shop floor. In the previous section, the whole study was done having this frequency fixed to be every eight hours and because the daily working time is also eight hours, it was said that the release was done once a day at the beginning. Other three order release frequencies were introduced, they are the releases at every six, four and two hours. The more frequent the release of orders is done, the more approximated to the continuous order release (Fernandes and Carmo Silva 2011). For this purpose, we considered only four ORR methods which are AB/F that is compared to AL/F and AB/S compared to AL/F. Furthermore, this analysis was done also to study the effects of the three distortion levels on the different order release frequencies thus enclosing the tests at the first breakdown level. Figure 14 shows the results of the methods regarding the GTT since it is the indicator for their performance. In all the graphs, the blue lines represent the order release frequency of two hours, the black lines represent the frequencies of four hours, the gold lines represent the frequencies of six hours, and the green lines represent the frequencies of eight hours. In addition, the circle mark represents the balancing method and the triangle mark, the limiting method.

*(a)*




*(b)*

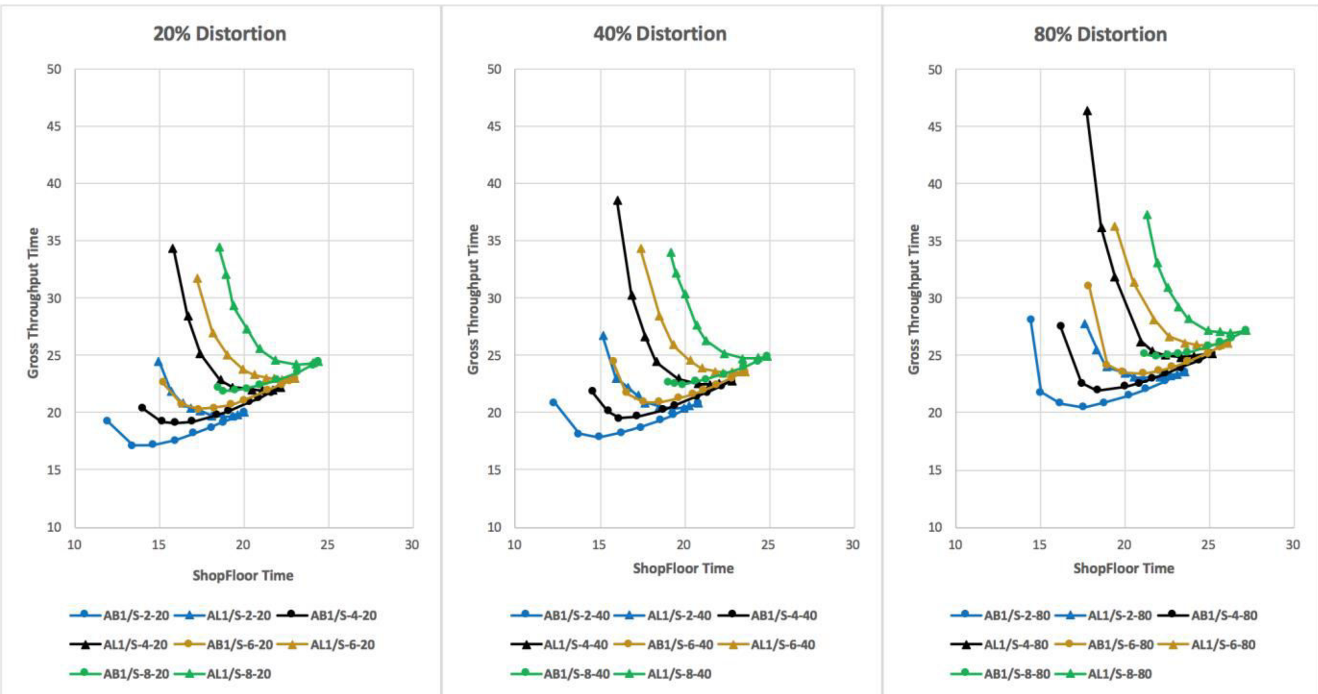



*Figure 13. Performances of ORR methods with aggregation of workload ((a) for FCFS, (b) for SPT) at the four order release frequencies*

Within the same distortion level, increasing the frequency of the order release has a positive impact because the performance distribution shifts to lower the down-left side of the graph meaning to lower values of GTT and to lower values of SFT therefore resulting in better performance. The reduction on SFT means a better control on WIP which could be especially important when the manufacturing system can have a very high product mix (Olaitan et. al 2017). The more frequent the release of order is done, the lower the resulting GTT, and so a better performance is reached. This result is in accordance with the statement of Fernades and Carmo Silva (2011) who indicates that a continuous order release is expected to shorten the delivery times. Quite the same trend is seen for both cases of sequencing rule, in (a) and (b) of Figure 14.

### 4.2.2 Balancing and Limiting performance comparison

The best performance is taken to be the point in which the value of the GTT is the lowest. For each distortion level, the best performances are identified for the four frequencies of order release. Table 15 represents the performances of the methods for all the parameters. As it was already noticed from Figure 13 the GTT and the SFT improves (their value decreases) as the frequencies of release increases. As the order release is more frequent, the more approximated it is to the continuous order release (Fernandes and Carmo Silva 2011). Though the likeliness of the complexity and costs related to the continuous order release to be a barrier for its implementation (Bergamaschi 1997), its benefits will require it to be implemented as a strategy for workload control in the future (Stevenson and Silva 2008). Furthermore, the other three parameters considered for the analysis also have an improvement which is not as much as GTT and SFT but that can be noticed only when comparing the initial frequency of eight hours to the frequencies of two and four hours.

***(a)***

| Best Performances | | AB/F | | | | AL/F | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **2H** | **4H** | **6H** | **8H** | **2H** | **4H** | **6H** | **8H** |
| 20% | GTT | 17.57 | 19.81 | 21.29 | 23.17 | 19.99 | 22.57 | 23.62 | 25.23 |
| | SFT | 14.79 | 16.21 | 18.71 | 20.06 | 18.32 | 21.62 | 23.43 | 24.82 |
| | Tardiness | 0.00 | 0.03 | 0.14 | 0.07 | 0.01 | 0.02 | 0.07 | 0.06 |
| | % Tardy Orders | 0.2% | 0.5% | 1.9% | 1.3% | 0.0% | 0.3% | 1.1% | 0.8% |
| | SD Lateness | 8.13 | 9.04 | 8.72 | 9.02 | 7.47 | 8.07 | 8.60 | 8.67 |
| 40% | GTT | 18.26 | 20.52 | 21.88 | 23.78 | 20.72 | 23.18 | 24.28 | 25.76 |
| | SFT | 15.09 | 17.66 | 19.05 | 21.25 | 19.61 | 22.10 | 24.05 | 24.91 |
| | Tardiness | 0.01 | 0.03 | 0.19 | 0.07 | 0.01 | 0.02 | 0.09 | 0.05 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | % Tardy Orders | 0.3% | 0.6% | 2.3% | 1.5% | 0.1% | 0.3% | 1.3% | 0.7% |
| | SD Lateness | 8.60 | 8.70 | 9.05 | 8.90 | 7.82 | 8.26 | 8.89 | 8.81 |
| 80% | GTT | 20.88 | 22.91 | 24.30 | 26.34 | 23.36 | 25.57 | 26.69 | 28.17 |
| | SFT | 17.78 | 18.81 | 21.51 | 23.75 | 22.33 | 24.65 | 25.54 | 27.43 |
| | Tardiness | 0.06 | 0.04 | 0.26 | 0.17 | 0.02 | 0.02 | 0.16 | 0.11 |
| | % Tardy Orders | 1.2% | 1.2% | 3.6% | 3.1% | 0.5% | 0.6% | 1.7% | 1.7% |
| | SD Lateness | 9.38 | 9.90 | 9.76 | 9.81 | 9.10 | 9.09 | 9.84 | 9.83 |

***(b)***

| Best Performances | | AB/S | | | | AL/S | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **2H** | **4H** | **6H** | **8H** | **2H** | **4H** | **6H** | **8H** |
| 20% | GTT | 17.15 | 19.09 | 20.32 | 21.88 | 19.64 | 21.92 | 22.93 | 24.22 |
| | SFT | 13.38 | 15.91 | 17.30 | 18.81 | 18.78 | 21.07 | 22.23 | 23.11 |
| | Tardiness | 0.00 | 0.03 | 0.18 | 0.07 | 0.01 | 0.02 | 0.07 | 0.05 |
| | % Tardy Orders | 0.2% | 0.6% | 2.3% | 1.6% | 0.0% | 0.3% | 1.0% | 0.8% |
| | SD Lateness | 9.05 | 9.14 | 9.45 | 9.54 | 7.46 | 8.08 | 8.58 | 8.78 |
| 40% | GTT | 17.88 | 19.53 | 20.94 | 22.48 | 20.29 | 22.46 | 23.47 | 24.69 |
| | SFT | 14.94 | 16.12 | 18.53 | 19.92 | 19.29 | 21.51 | 22.28 | 23.43 |
| | Tardiness | 0.01 | 0.02 | 0.17 | 0.08 | 0.01 | 0.01 | 0.08 | 0.05 |
| | % Tardy Orders | 0.4% | 0.6% | 2.5% | 2.0% | 0.0% | 0.3% | 1.2% | 0.8% |
| | SD Lateness | 8.65 | 9.34 | 9.15 | 9.39 | 7.77 | 8.16 | 8.79 | 9.00 |
| 80% | GTT | 20.48 | 21.96 | 23.46 | 24.89 | 23.05 | 24.84 | 25.86 | 26.93 |
| | SFT | 17.54 | 18.36 | 21.05 | 21.85 | 21.09 | 23.29 | 24.79 | 26.23 |
| | Tardiness | 0.05 | 0.05 | 0.29 | 0.20 | 0.02 | 0.02 | 0.14 | 0.10 |
| | % Tardy Orders | 1.23% | 1.27% | 3.56% | 3.49% | 0.58% | 0.53% | 1.70% | 1.64% |
| | SD Lateness | 9.38 | 9.89 | 9.95 | 10.36 | 9.02 | 9.02 | 9.79 | 9.82 |

*Table 15. Performances of ORR methods with aggregation of workload ((a) for FCFS, (b) for SPT) at the four order release frequencies*

The first section of the thesis was done having a frequency of order release of eight hours so the performance achieved for the ORR methods at this release frequency are as the reference from which the methods' performances at the other frequencies can be compared and analyzed. Therefore, the objective is to see what is the degree of improvement on the GTT parameter because it is the performance indicator (Land 2006), when applying more frequent order releases. Table 16 shows the improvement of GTT for the order release frequencies of two, four and six hours when compared to the one of eight hours. Each method is compared to itself, therefore the results of GTT for AB method at the order release frequencies of two, four and six hours; are compared to the results of AB method at the frequency of eight hours. The same logic is applied for AL method. The numbers displayed on the table are the reduction of the value of GTT at the frequency comparisons described. This reduction is also represented in percentage of the value at the eight hours' frequency release. The reduction of the GTT is higher on the Balancing method (AB) than the Limiting one (AL) on terms of absolute value and of percentage in all cases, for each order release frequency when compared to the one of eight hours and at the different distortion levels. Thus, the GTT value reductions is highlighted in green in the table for method AB. The reduction of the GTT is higher for AB than AL for both sequencing rules, FCFS and SPT. In other words, this means that when comparing the results at a frequency of two hours to the one of eight hours, when comparing the results at a frequency of four hours to the one of eight hours, and when comparing the results at a frequency of six hours to the one of eight hours, the improvement of GTT in each case is higher for AB/F than AL/F and is higher for AB/S than AL/S.

***(a)***

| | | **GTT reduction compared to 8H** | | | | | |
|---|---|---|---|---|---|---|---|
| Frequency of release | | **2H** | | **4H** | | **6H** | |
| **In absolute value** | | **AB/F** | **AL/F** | **AB/F** | **AL/F** | **AB/F** | **AL/F** |
| Distortion Level | 20% | 5.59 | 5.24 | 3.36 | 2.66 | 1.87 | 1.61 |
| | 40% | 5.52 | 5.04 | 3.26 | 2.58 | 1.91 | 1.48 |
| | 80% | 5.45 | 4.81 | 3.43 | 2.60 | 2.04 | 1.48 |
| **In percentage** | | **AB/F** | **AL/F** | **AB/F** | **AL/F** | **AB/F** | **AL/F** |
| Distortion Level | 20% | 24.2% | 20.8% | 14.5% | 10.5% | 8.1% | 6.4% |
| | 40% | 23.2% | 19.6% | 13.7% | 10.0% | 8.0% | 5.7% |
| | 80% | 20.7% | 17.1% | 13.0% | 9.2% | 7.7% | 5.3% |

***(b)***

| | | **GTT reduction compared to 8H** | | | | | |
|---|---|---|---|---|---|---|---|
| Frequency of release | | **2H** | | **4H** | | **6H** | |
| **In absolute value** | | **AB/S** | **AL/S** | **AB/S** | **AL/S** | **AB/S** | **AL/S** |
| Distortion Level | 20% | 4.73 | 4.58 | 2.79 | 2.29 | 1.56 | 1.29 |
| | 40% | 4.60 | 4.41 | 2.95 | 2.24 | 1.54 | 1.23 |
| | 80% | 4.40 | 3.89 | 2.92 | 2.09 | 1.43 | 1.07 |
| **In percentage** | | **AB/S** | **AL/S** | **AB/S** | **AL/S** | **AB/S** | **AL/S** |
| Distortion Level | 20% | 21.6% | 18.9% | 12.7% | 9.5% | 7.1% | 5.3% |
| | 40% | 20.5% | 17.8% | 13.1% | 9.1% | 6.9% | 5.0% |
| | 80% | 17.7% | 14.4% | 11.7% | 7.8% | 5.7% | 4.0% |

*Table 16. Reduction of GTT values in the scenarios of two, four and six hours order release frequency compared to the eight hours order release frequency*

On the other hand, the effects of the distortion level on the GTT on each method for the different cases of order release frequencies, were analyzed. In this case, the results in table 16 are compared not vertically but horizontally. In the same manner than the previous comparison, each method's result is compared to itself. It was shown that the GTT improves as the frequency of order release increases. However, regarding the level of distortion, this improvement on the GTT in terms of percentage decreases as the distortion level increases. To have a clearer picture, the reduction of GTT in percentage when comparing the frequencies of order release, is represented in table 17. There is a greater positive impact from increasing the frequency of order release when the distortion level is low. As the distortion level increases, this benefit from a more frequent order release, decreases. For instance, for method AB/F, at 20% distortion, the GTT is reduced by an initial 8.1% and up to 24.2%. However, for the same method at 80% distortion, the GTT is reduced by an initial 7.7% and up to only 20.7%. In the same way, all the other methods have a lower GTT reduction when the distortion level is higher. Thus, in other words, the reduction of the GTT which comes from increasing the order release frequency (from 8 hours' release frequency to 6, 4 or 2 hours) in the case of 20% distortion is higher than the ones of 40% and 80% distortion; and on the 40% is higher than on the 80% distortion.

| | **2H vs 8H** | **4H vs 8H** | **6H vs 8H** | **2H vs 8H** | **4H vs 8H** | **6H vs 8H** |
|---|---|---|---|---|---|---|
| | **AB/F** | | | **AL/F** | | |
| **20% distortion** | 24.2% | 14.5% | 8.1% | 20.8% | 10.5% | 6.4% |
| **40% distortion** | 23.2% | 13.7% | 8.0% | 19.6% | 10.0% | 5.7% |
| **80% distortion** | 20.7% | 13.0% | 7.7% | 17.1% | 9.2% | 5.3% |
| | **AB/S** | | | **AL/S** | | |
| **20% distortion** | 21.6% | 12.7% | 7.1% | 18.9% | 9.5% | 5.3% |
| **40% distortion** | 20.5% | 13.1% | 6.9% | 17.8% | 9.1% | 5.0% |
| **80% distortion** | 17.7% | 11.7% | 5.7% | 14.4% | 7.8% | 4.0% |

*Table 17. GTT reduction as percentage when increasing the frequency of order release at the different distortion levels*

# 5 Conclusions

The increasing competition in the industry pushed the companies to seek ways to improve productivity and efficiency. Such is the case of Make-to-Order companies which started following the example of implementations on Make-to- Stock companies already being adopted like the lean techniques. Due to the inherent characteristics of MTO companies, the appropriate implementations sought to improve productivity obeys the need for the required capacity to deal with the demand of customized production and the capability to face uneven and fluctuating demand. Therefore, there have been a continuously increasing interest on ORR methodologies as an approach to control the workload on the shop through the customer orders which is crucial for production planning and to support decisions. Some recent studies focus on card-based systems for workload control such is the case of COBACABANA which is a system that focuses on load balancing and it was proved to improve the performance of flow shops characterized with a high processing time variability (Thurer 2015). Another card-based system is POLCA and serves as a decision support system for production control developed for a quick manufacturing response (Fernandes et al. 2017, Braglia et al. 2017, Olaitan et al. 2017).

Its common in the MTO industry to find diverse types of disturbances that affect the production in the shop thus the different criterias of the ORR methodologies are investigated under those circumstances to study their effectiveness. The outcomes also depend on the configuration of the shop and the system. In this thesis, the analysis was based on a pure flow shop in which all orders follow a defined process flow; and the disturbances considered for the analysis are specifically ones affecting the shop floor. These disturbances are the machine breakdown, characterized by its frequency of failure and by its severity, and the degree of distortion affecting the shop. In addition, the order release mechanism used was the periodic (discrete) approach and which was widely used by different authors (Cigolini and Portioli 2002, Oosterman et al. 2000, Henrich et al. 2007, Land 2006).

The objective of the thesis is to analyze the performances of the ORR methods under the described disturbances. The studied ORR methods are in total eight and they differ in their methodologies regarding three criteria: the aggregation of workload measure, the release of orders to the shop by workload control, and the sequencing of orders in the pre-shop pool. The results of the thesis confirmed what is was demonstrated by Portioli and Tantardini (2012) that for the workload control, the Balancing methodology outperforms the Limiting one. The results also prove the advantage of implementing the short-process-time criteria rather than the first-come-first-served one for the sequencing rule. Though the two sequencing rules used on this study are quite simple, other studies suggest that the sequencing rule should also include balancing considerations such as the one developed to balance loads only when there are many urgent jobs (Thurer & Stevenson 2014).

## 5.1 Answer to the Research questions

I. *Under the diverse levels of breakdown and distortion, what ORR method is the best performing one? And which methods are the most robust and stable in their results at different scenarios?*

This study focused on the analysis of the ORR methods in a shop floor characterized to have a pure flow process and machine (station) processing time modeled by the lognormal distribution and a simple FCFS dispatching rule. Other papers analyze the effectiveness of using the operation due-dates of the orders as the criteria for the sequencing in the workstations (Lödding 2017). The model of our shop floor undergoes two types of disturbances: machine breakdown and distortion. Five parameters were used to analyze their performances in the different scenarios and identify the best performing method. Regarding the parameters gross throughput time (GTT) and shop floor time (SFT), the AB/S method reaches the best performing point in each and all disturbance scenarios individually. The second best performing method in these two parameters is not only one but two, AB/F and RB/S, depending on the disturbance scenario. The performance results of these two methods are very close in all scenarios. This confirms the superiority of applying the Balancing Release approach since it is present in all these three best performing methods. On the other hand, for the other three parameters which are tardiness, percentage of tardy orders, and standard deviation of lateness, the Limiting Release approach seems to have a slight advantage that is not very significant over the Balancing approach. This slight advantage is present only when the breakdown and distortion levels are low. As those levels increase, the advantage of the Limiting approach on those parameters, disappears.

Even though AB/S performs better in each disturbance scenario regarding the GTT and SFT, when analyzed in situations of varying levels of disturbances, it is not the method being the most stable (robust) in its results. The most robust method on GTT is RB/S, and the method most robust on SFT is the AB/F. Once again, we can see the presence of the Balancing release approach on these methods. However, though AB/S is not the most robust method on GTT and SFT, it appears to be so for the other three parameters: tardiness, percentage of tardy orders and standard deviation lateness. These three most robust methods use the Balancing approach and the results is consistent with the study of Cigolini and Portioli (2002).

II. *How does the frequency of order release to the shop, affect the results of the ORR methods in terms of the performance indicators?*

The previous study was done having an order release frequency of eight hours, thus the whole study was carried out on a fixed release frequency. For the study of this section, this release frequency is not maintained constant but it is varied to see the impact on the performances of the ORR methods. In addition to the frequency of eight hours, other three frequencies were tested: release frequencies of six, four, and two hours. In this section, not all ORR methods were studied but only four of them, AB/F, AB/S, AL/F, and AL/S. The disturbance scenarios implemented were only of the distortion while doing all the experiments only on the low level of breakdown. The objectives were to compare the results of the Balancing and Limiting approaches and how they differ when the order release frequency varies, and how the distortion level affects these approaches. The results of the study show that all methods improve their performances as the order release frequency increases. Increasing the order release frequency makes the discrete release approach (the one of this thesis) to become closer to the continuous release approach and to the benefits of it (Fernandes and Carmo Silva 2011). The improvements are more notorious and significant in the GTT and SFT parameters which are the most relevant, while the improvements on the other parameters are of less impact. This means that as the frequency of order release increases, there is a reduction on the values of GTT and SFT for all methods. The reduction on SFT means a better control on WIP which could be especially important when the manufacturing system can have a very high product mix (Olaitan et. al 2017). Recent studies show a significant performance improvement for continuous order release in terms of mean tardiness and standard deviation of lateness by triggering the avoidance of starvation (Fernades & Thurer 2017)

The next step was to make a comparison between the performance improvement on each method, specifically between the Balancing and Limiting approaches. The analysis is done focusing only on the GTT since this parameter is the main performance indicator (Land 2006). The reduction of the GTT is higher on the Balancing method (AB) than the Limiting one (AL) on terms of absolute value and of percentage in all cases, for each order release frequency (2, 4 and 6 hours' frequency) when compared to the one of 8 hours and at the different distortion levels. The reduction of the GTT is higher for AB than AL for both sequencing rules, FCFS and SPT. On the other hand, a high degree of distortion diminishes the benefits of increasing the frequency of order release in all methods. This means that when increasing the frequency of order release, the improvement on the GTT (reduction of its value) decreases as the distortion level increases.

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# 7 Appendix

| Workload Norms (minutes) | FCFS AB (2 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Average Gross Throughput time (in hours)** | **Average Shop Floor time (in hours)** | **Average Output (in pieces)** | **Average Tardiness (in hours)** | **% Average Tardiness** | **Average No. of Tardy Orders (in pieces)** | **% Average No. of Tardy Orders** | **Average Lateness (in hours)** | **SD of Lateness** |
| 500 | 29.94 | 12.71 | 14.09 | 0.25 | 0.8% | 0.66 | 4.7% | -26.06 | 15.19 |
| 650 | 20.19 | 12.13 | 14.16 | 0.03 | 0.1% | 0.13 | 0.9% | -35.81 | 12.03 |
| 850 | 17.61 | 13.56 | 14.18 | 0.00 | 0.0% | 0.03 | 0.2% | -38.39 | 9.14 |
| 1000 | 17.57 | 14.79 | 14.18 | 0.00 | 0.0% | 0.03 | 0.2% | -38.43 | 8.13 |
| 1200 | 17.91 | 16.14 | 14.18 | 0.01 | 0.0% | 0.04 | 0.3% | -38.09 | 7.48 |
| 1400 | 18.45 | 17.24 | 14.18 | 0.01 | 0.1% | 0.06 | 0.4% | -37.55 | 7.30 |
| 1700 | 19.02 | 18.32 | 14.18 | 0.02 | 0.1% | 0.10 | 0.7% | -36.98 | 7.29 |
| 2000 | 19.48 | 19.07 | 14.18 | 0.03 | 0.2% | 0.08 | 0.6% | -36.52 | 7.42 |
| 2500 | 19.92 | 19.72 | 14.18 | 0.03 | 0.2% | 0.05 | 0.4% | -36.08 | 7.64 |
| 9000 | 20.35 | 20.35 | 14.18 | 0.00 | 0.0% | 0.00 | 0.0% | -35.65 | 7.85 |

| Workload Norms (minutes) | FCFS AB (2 Hours-40% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Average Gross Throughput time (in hours)** | **Average Shop Floor time (in hours)** | **Average Output (in pieces)** | **Average Tardiness (in hours)** | **% Average Tardiness** | **Average No. of Tardy Orders (in pieces)** | **% Average No. of Tardy Orders** | **Average Lateness (in hours)** | **SD of Lateness** |
| 500 | 32.59 | 13.54 | 14.09 | 0.42 | 1.3% | 0.94 | 6.7% | -23.41 | 15.34 |
| 650 | 21.85 | 12.62 | 14.15 | 0.07 | 0.3% | 0.23 | 1.6% | -34.15 | 12.75 |
| 850 | 18.67 | 13.94 | 14.17 | 0.01 | 0.1% | 0.08 | 0.6% | -37.33 | 9.86 |
| 1000 | 18.26 | 15.09 | 14.18 | 0.01 | 0.0% | 0.04 | 0.3% | -37.74 | 8.60 |
| 1200 | 18.54 | 16.50 | 14.18 | 0.01 | 0.1% | 0.06 | 0.4% | -37.46 | 7.93 |
| 1400 | 18.94 | 17.57 | 14.18 | 0.02 | 0.1% | 0.07 | 0.5% | -37.06 | 7.61 |
| 1700 | 19.63 | 18.83 | 14.18 | 0.03 | 0.1% | 0.12 | 0.8% | -36.37 | 7.60 |
| 2000 | 20.11 | 19.61 | 14.18 | 0.04 | 0.2% | 0.10 | 0.7% | -35.89 | 7.76 |
| 2500 | 20.60 | 20.37 | 14.18 | 0.04 | 0.2% | 0.06 | 0.5% | -35.40 | 7.98 |
| 9000 | 21.12 | 21.12 | 14.18 | 0.00 | 0.0% | 0.02 | 0.1% | -34.88 | 8.26 |

| Workload Norms (minutes) | FCFS AB (2 Hours-80% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Average Gross Throughput time (in hours)** | **Average Shop Floor time (in hours)** | **Average Output (in pieces)** | **Average Tardiness (in hours)** | **% Average Tardiness** | **Average No. of Tardy Orders (in pieces)** | **% Average No. of Tardy Orders** | **Average Lateness (in hours)** | **SD of Lateness** |
| 500 | 41.61 | 17.33 | 14.10 | 1.54 | 3.7% | 2.51 | 17.8% | -14.39 | 15.26 |
| 650 | 29.33 | 14.75 | 14.13 | 0.41 | 1.4% | 0.82 | 5.8% | -26.67 | 14.78 |
| 850 | 22.38 | 15.27 | 14.17 | 0.12 | 0.5% | 0.33 | 2.4% | -33.62 | 11.97 |
| 1000 | 21.26 | 16.35 | 14.17 | 0.07 | 0.3% | 0.23 | 1.6% | -34.74 | 10.60 |
| 1200 | 20.88 | 17.78 | 14.18 | 0.06 | 0.3% | 0.17 | 1.2% | -35.12 | 9.38 |
| 1400 | 21.27 | 19.06 | 14.18 | 0.06 | 0.3% | 0.19 | 1.4% | -34.73 | 9.02 |
| 1700 | 21.82 | 20.47 | 14.17 | 0.09 | 0.4% | 0.24 | 1.7% | -34.18 | 8.89 |
| 2000 | 22.37 | 21.52 | 14.17 | 0.10 | 0.4% | 0.19 | 1.4% | -33.63 | 8.91 |
| 2500 | 23.01 | 22.60 | 14.17 | 0.09 | 0.4% | 0.12 | 0.9% | -32.99 | 9.11 |
| 9000 | 23.87 | 23.87 | 14.17 | 0.04 | 0.2% | 0.14 | 1.0% | -32.13 | 9.57 |

| Workload Norms (minutes) | FCFS AL (2 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Average Gross Throughput time (in hours)** | **Average Shop Floor time (in hours)** | **Average Output (in pieces)** | **Average Tardiness (in hours)** | **% Average Tardiness** | **Average No. of Tardy Orders (in pieces)** | **% Average No. of Tardy Orders** | **Average Lateness (in hours)** | **SD of Lateness** |
| 600 | 125.99 | 10.66 | 13.24 | 72.37 | 57.4% | 11.33 | 85.5% | 69.99 | 53.99 |
| 800 | 44.04 | 13.18 | 13.93 | 6.19 | 14.1% | 4.19 | 30.1% | -11.96 | 18.82 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1000 | 24.86 | 15.14 | 14.13 | 0.35 | 1.4% | 0.50 | 3.5% | -31.14 | 10.22 |
| 1100 | 22.86 | 15.96 | 14.15 | 0.09 | 0.4% | 0.22 | 1.5% | -33.14 | 9.29 |
| 1200 | 21.30 | 16.56 | 14.16 | 0.04 | 0.2% | 0.10 | 0.7% | -34.70 | 8.51 |
| 1300 | 20.94 | 17.14 | 14.16 | 0.03 | 0.2% | 0.07 | 0.5% | -35.06 | 8.30 |
| 1400 | 20.58 | 17.61 | 14.17 | 0.02 | 0.1% | 0.05 | 0.4% | -35.42 | 8.06 |
| 1600 | 19.99 | 18.32 | 14.18 | 0.01 | 0.0% | 0.01 | 0.0% | -36.01 | 7.47 |
| 1900 | 20.04 | 19.11 | 14.18 | 0.01 | 0.0% | 0.00 | 0.0% | -35.96 | 7.53 |
| 2300 | 20.07 | 19.65 | 14.18 | 0.01 | 0.0% | 0.00 | 0.0% | -35.93 | 7.61 |
| 2700 | 20.19 | 19.92 | 14.18 | 0.00 | 0.0% | 0.00 | 0.0% | -35.81 | 7.70 |
| 9000 | 20.35 | 20.35 | 14.18 | 0.00 | 0.0% | 0.00 | 0.0% | -35.65 | 7.85 |

| Workload Norms (minutes) | FCFS AL (2 Hours-40% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 600 | 141.59 | 10.76 | 13.16 | 87.00 | 61.4% | 12.04 | 91.4% | 85.59 | 58.66 |
| 800 | 51.76 | 13.31 | 13.89 | 11.07 | 21.4% | 5.42 | 39.0% | -4.24 | 21.30 |
| 1000 | 28.19 | 15.39 | 14.11 | 0.76 | 2.7% | 0.96 | 6.8% | -27.81 | 11.39 |
| 1100 | 24.53 | 16.22 | 14.15 | 0.21 | 0.9% | 0.40 | 2.8% | -31.47 | 9.95 |
| 1200 | 22.53 | 16.86 | 14.16 | 0.06 | 0.3% | 0.15 | 1.1% | -33.47 | 8.95 |
| 1300 | 21.98 | 17.49 | 14.16 | 0.04 | 0.2% | 0.12 | 0.8% | -34.02 | 8.81 |
| 1400 | 21.14 | 17.95 | 14.17 | 0.02 | 0.1% | 0.05 | 0.3% | -34.86 | 8.18 |
| 1600 | 20.95 | 18.80 | 14.17 | 0.01 | 0.1% | 0.02 | 0.2% | -35.05 | 8.02 |
| 1900 | 20.72 | 19.61 | 14.18 | 0.01 | 0.0% | 0.01 | 0.1% | -35.28 | 7.82 |
| 2300 | 20.81 | 20.27 | 14.18 | 0.01 | 0.0% | 0.00 | 0.0% | -35.19 | 7.99 |
| 2700 | 20.87 | 20.56 | 14.18 | 0.00 | 0.0% | 0.00 | 0.0% | -35.13 | 8.06 |
| 9000 | 21.12 | 21.12 | 14.18 | 0.00 | 0.0% | 0.02 | 0.1% | -34.88 | 8.26 |

| Workload Norms (minutes) | FCFS AL (2 Hours-80% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 600 | 213.86 | 11.14 | 12.78 | 158.39 | 74.1% | 12.44 | 97.3% | 157.86 | 79.58 |
| 800 | 85.81 | 13.79 | 13.65 | 36.04 | 42.0% | 9.52 | 69.7% | 29.81 | 33.79 |
| 1000 | 43.17 | 16.12 | 14.03 | 5.95 | 13.8% | 3.55 | 25.3% | -12.83 | 16.39 |
| 1200 | 28.67 | 17.90 | 14.13 | 0.64 | 2.2% | 0.86 | 6.1% | -27.33 | 11.30 |
| 1300 | 26.58 | 18.61 | 14.15 | 0.45 | 1.7% | 0.67 | 4.7% | -29.42 | 10.37 |
| 1400 | 25.14 | 19.23 | 14.15 | 0.21 | 0.8% | 0.34 | 2.4% | -30.86 | 9.88 |
| 1600 | 23.94 | 20.24 | 14.16 | 0.07 | 0.3% | 0.19 | 1.3% | -32.06 | 9.29 |
| 1750 | 23.56 | 20.83 | 14.16 | 0.03 | 0.1% | 0.09 | 0.6% | -32.44 | 9.08 |
| 1900 | 23.47 | 21.40 | 14.17 | 0.02 | 0.1% | 0.09 | 0.6% | -32.53 | 9.06 |
| 2300 | 23.36 | 22.33 | 14.17 | 0.02 | 0.1% | 0.07 | 0.5% | -32.64 | 9.10 |
| 2700 | 23.55 | 22.97 | 14.17 | 0.02 | 0.1% | 0.08 | 0.5% | -32.45 | 9.29 |
| 3300 | 23.77 | 23.48 | 14.17 | 0.03 | 0.1% | 0.11 | 0.8% | -32.23 | 9.49 |
| 9000 | 23.88 | 23.88 | 14.17 | 0.04 | 0.2% | 0.14 | 1.0% | -32.12 | 9.57 |

| Workload Norms (minutes) | FCFS AB (4 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 850 | 22.16 | 14.52 | 14.23 | 0.12 | 0.5% | 0.22 | 1.5% | -33.84 | 11.75 |
| 1000 | 20.31 | 15.51 | 14.24 | 0.03 | 0.2% | 0.10 | 0.7% | -35.69 | 9.88 |
| 1100 | 19.81 | 16.21 | 14.25 | 0.03 | 0.1% | 0.07 | 0.5% | -36.19 | 9.04 |
| 1250 | 19.95 | 17.36 | 14.26 | 0.04 | 0.2% | 0.10 | 0.7% | -36.05 | 8.43 |
| 1500 | 20.34 | 18.80 | 14.26 | 0.03 | 0.2% | 0.09 | 0.7% | -35.66 | 7.79 |
| 1650 | 20.65 | 19.49 | 14.27 | 0.02 | 0.1% | 0.11 | 0.8% | -35.35 | 7.65 |
| 1800 | 21.11 | 20.17 | 14.26 | 0.03 | 0.2% | 0.13 | 0.9% | -34.89 | 7.73 |
| 2000 | 21.41 | 20.75 | 14.26 | 0.04 | 0.2% | 0.12 | 0.8% | -34.59 | 7.69 |
| 2300 | 21.82 | 21.42 | 14.27 | 0.04 | 0.2% | 0.09 | 0.6% | -34.18 | 7.77 |
| 2700 | 22.14 | 21.92 | 14.27 | 0.04 | 0.2% | 0.06 | 0.4% | -33.86 | 7.90 |
| 3000 | 22.31 | 22.16 | 14.26 | 0.03 | 0.1% | 0.04 | 0.3% | -33.69 | 7.99 |
| 4000 | 22.58 | 22.53 | 14.26 | 0.02 | 0.1% | 0.04 | 0.3% | -33.42 | 8.12 |
| 9000 | 22.77 | 22.77 | 14.26 | 0.04 | 0.2% | 0.06 | 0.4% | -33.23 | 8.26 |

| Workload Norms (minutes) | FCFS AB (4 Hours-40% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 850 | 23.57 | 14.95 | 14.23 | 0.12 | 0.5% | 0.29 | 2.0% | -32.43 | 12.25 |
| 1000 | 20.96 | 15.79 | 14.24 | 0.04 | 0.2% | 0.13 | 0.9% | -35.04 | 10.22 |
| 1100 | 20.56 | 16.54 | 14.25 | 0.03 | 0.1% | 0.10 | 0.7% | -35.44 | 9.42 |
| 1250 | 20.52 | 17.66 | 14.26 | 0.03 | 0.1% | 0.09 | 0.6% | -35.48 | 8.70 |
| 1500 | 20.86 | 19.17 | 14.26 | 0.02 | 0.1% | 0.10 | 0.7% | -35.14 | 8.00 |
| 1650 | 21.18 | 19.89 | 14.27 | 0.02 | 0.1% | 0.12 | 0.8% | -34.82 | 7.86 |
| 1800 | 21.56 | 20.56 | 14.27 | 0.03 | 0.1% | 0.13 | 0.9% | -34.44 | 7.83 |
| 2000 | 21.93 | 21.21 | 14.27 | 0.04 | 0.2% | 0.13 | 0.9% | -34.07 | 7.84 |
| 2300 | 22.36 | 21.91 | 14.27 | 0.04 | 0.2% | 0.10 | 0.7% | -33.64 | 7.96 |
| 2700 | 22.73 | 22.48 | 14.27 | 0.04 | 0.2% | 0.07 | 0.5% | -33.27 | 8.08 |
| 3000 | 22.91 | 22.75 | 14.27 | 0.03 | 0.2% | 0.05 | 0.3% | -33.09 | 8.17 |
| 4000 | 23.17 | 23.12 | 14.26 | 0.02 | 0.1% | 0.04 | 0.3% | -32.83 | 8.31 |
| 9000 | 23.35 | 23.35 | 14.26 | 0.03 | 0.1% | 0.06 | 0.4% | -32.65 | 8.43 |

| Workload Norms (minutes) | FCFS AB (4 Hours-80% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 850 | 30.00 | 16.88 | 14.22 | 0.47 | 1.6% | 0.85 | 6.0% | -26.00 | 13.99 |
| 1000 | 25.01 | 17.23 | 14.24 | 0.17 | 0.7% | 0.39 | 2.7% | -30.99 | 12.21 |
| 1100 | 23.67 | 17.77 | 14.25 | 0.07 | 0.3% | 0.25 | 1.8% | -32.33 | 11.09 |
| 1250 | 22.91 | 18.81 | 14.26 | 0.04 | 0.2% | 0.17 | 1.2% | -33.09 | 9.90 |
| 1500 | 22.93 | 20.47 | 14.26 | 0.04 | 0.2% | 0.17 | 1.2% | -33.07 | 9.00 |
| 1650 | 23.17 | 21.31 | 14.27 | 0.05 | 0.2% | 0.21 | 1.5% | -32.83 | 8.77 |
| 1800 | 23.59 | 22.11 | 14.27 | 0.07 | 0.3% | 0.25 | 1.7% | -32.41 | 8.76 |
| 2000 | 24.01 | 22.91 | 14.27 | 0.08 | 0.3% | 0.23 | 1.6% | -31.99 | 8.75 |
| 2300 | 24.52 | 23.83 | 14.27 | 0.09 | 0.3% | 0.17 | 1.2% | -31.48 | 8.80 |
| 2700 | 24.93 | 24.55 | 14.27 | 0.07 | 0.3% | 0.11 | 0.8% | -31.07 | 8.91 |
| 3000 | 25.15 | 24.89 | 14.27 | 0.06 | 0.2% | 0.08 | 0.6% | -30.85 | 8.97 |
| 4000 | 25.54 | 25.46 | 14.27 | 0.03 | 0.1% | 0.05 | 0.4% | -30.46 | 9.15 |
| 9000 | 25.77 | 25.77 | 14.27 | 0.04 | 0.2% | 0.10 | 0.7% | -30.23 | 9.30 |

| Workload Norms (minutes) | FCFS AL (4 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1000 | 54.11 | 15.14 | 13.97 | 11.75 | 21.7% | 5.57 | 39.8% | -1.89 | 18.83 |
| 1100 | 39.02 | 16.19 | 14.13 | 3.02 | 7.7% | 2.60 | 18.4% | -16.98 | 13.44 |
| 1200 | 30.60 | 17.07 | 14.18 | 0.75 | 2.5% | 1.04 | 7.3% | -25.40 | 11.17 |
| 1300 | 26.95 | 17.85 | 14.22 | 0.16 | 0.6% | 0.38 | 2.7% | -29.05 | 9.91 |
| 1400 | 24.86 | 18.50 | 14.24 | 0.06 | 0.3% | 0.14 | 1.0% | -31.14 | 9.04 |
| 1500 | 23.85 | 19.07 | 14.24 | 0.04 | 0.2% | 0.09 | 0.6% | -32.15 | 8.64 |
| 1650 | 23.20 | 19.77 | 14.25 | 0.02 | 0.1% | 0.05 | 0.3% | -32.80 | 8.31 |
| 1800 | 22.90 | 20.36 | 14.25 | 0.02 | 0.1% | 0.04 | 0.3% | -33.10 | 8.27 |
| 2000 | 22.66 | 20.97 | 14.26 | 0.03 | 0.1% | 0.05 | 0.4% | -33.34 | 8.14 |
| 2300 | 22.57 | 21.62 | 14.26 | 0.02 | 0.1% | 0.04 | 0.3% | -33.43 | 8.07 |
| 2700 | 22.63 | 22.13 | 14.26 | 0.03 | 0.1% | 0.05 | 0.3% | -33.37 | 8.14 |
| 3000 | 22.71 | 22.38 | 14.26 | 0.03 | 0.1% | 0.05 | 0.3% | -33.29 | 8.21 |
| 9000 | 22.77 | 22.77 | 14.26 | 0.04 | 0.2% | 0.06 | 0.4% | -33.23 | 8.26 |

| Workload Norms (minutes) | FCFS AL (4 Hours-40% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1000 | 60.63 | 15.29 | 13.95 | 14.96 | 24.7% | 6.81 | 48.9% | 4.63 | 19.98 |
| 1100 | 45.23 | 16.38 | 14.08 | 6.40 | 14.2% | 3.85 | 27.3% | -10.77 | 14.94 |
| 1200 | 34.39 | 17.28 | 14.17 | 1.76 | 5.1% | 1.57 | 11.0% | -21.61 | 11.87 |
| 1300 | 28.93 | 18.10 | 14.22 | 0.47 | 1.6% | 0.66 | 4.6% | -27.07 | 10.13 |
| 1400 | 25.69 | 18.77 | 14.24 | 0.05 | 0.2% | 0.12 | 0.9% | -30.31 | 9.26 |
| 1500 | 24.71 | 19.34 | 14.24 | 0.03 | 0.1% | 0.09 | 0.6% | -31.29 | 8.89 |
| 1650 | 23.89 | 20.11 | 14.25 | 0.03 | 0.1% | 0.09 | 0.6% | -32.11 | 8.64 |
| 1800 | 23.43 | 20.70 | 14.25 | 0.02 | 0.1% | 0.05 | 0.3% | -32.57 | 8.34 |
| 2000 | 23.31 | 21.38 | 14.26 | 0.02 | 0.1% | 0.05 | 0.3% | -32.69 | 8.30 |
| 2300 | 23.18 | 22.10 | 14.26 | 0.02 | 0.1% | 0.05 | 0.3% | -32.82 | 8.26 |
| 2700 | 23.21 | 22.65 | 14.26 | 0.02 | 0.1% | 0.05 | 0.4% | -32.79 | 8.29 |
| 3000 | 23.26 | 22.90 | 14.26 | 0.02 | 0.1% | 0.05 | 0.3% | -32.74 | 8.34 |
| 9000 | 23.35 | 23.35 | 14.26 | 0.03 | 0.1% | 0.06 | 0.4% | -32.65 | 8.43 |

| Workload Norms (minutes) | FCFS AL (4 Hours-80% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1000 | 93.35 | 15.72 | 13.74 | 41.70 | 44.7% | 10.69 | 77.8% | 37.35 | 29.86 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1100 | 70.52 | 16.94 | 13.94 | 21.46 | 30.4% | 8.78 | 63.0% | 14.52 | 20.69 |
| 1200 | 53.51 | 18.06 | 14.08 | 10.33 | 19.3% | 5.44 | 38.7% | -2.49 | 16.41 |
| 1300 | 40.48 | 18.97 | 14.17 | 3.81 | 9.4% | 2.67 | 18.8% | -15.52 | 13.07 |
| 1400 | 34.92 | 19.84 | 14.21 | 1.67 | 4.8% | 1.67 | 11.7% | -21.08 | 11.34 |
| 1500 | 30.57 | 20.56 | 14.23 | 0.67 | 2.2% | 0.92 | 6.5% | -25.43 | 10.58 |
| 1650 | 27.83 | 21.44 | 14.24 | 0.18 | 0.7% | 0.44 | 3.1% | -28.17 | 9.73 |
| 1800 | 26.27 | 22.09 | 14.25 | 0.06 | 0.2% | 0.16 | 1.2% | -29.73 | 9.36 |
| 2000 | 25.73 | 22.92 | 14.26 | 0.02 | 0.1% | 0.10 | 0.7% | -30.27 | 9.11 |
| 2300 | 25.61 | 23.85 | 14.26 | 0.03 | 0.1% | 0.09 | 0.6% | -30.39 | 9.07 |
| 2700 | 25.57 | 24.65 | 14.27 | 0.02 | 0.1% | 0.09 | 0.6% | -30.43 | 9.09 |
| 3000 | 25.61 | 25.02 | 14.27 | 0.03 | 0.1% | 0.09 | 0.6% | -30.39 | 9.14 |
| 9000 | 25.77 | 25.77 | 14.27 | 0.04 | 0.2% | 0.10 | 0.7% | -30.23 | 9.30 |

| Workload Norms (minutes) | FCFS AB (6 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 950 | 25.16 | 15.92 | 14.12 | 0.45 | 1.8% | 0.63 | 4.5% | -30.84 | 13.02 |
| 1100 | 22.23 | 16.79 | 14.16 | 0.26 | 1.2% | 0.32 | 2.3% | -33.77 | 10.79 |
| 1250 | 21.38 | 17.77 | 14.16 | 0.20 | 0.9% | 0.29 | 2.0% | -34.62 | 9.43 |
| 1400 | 21.29 | 18.71 | 14.17 | 0.14 | 0.7% | 0.28 | 1.9% | -34.71 | 8.72 |
| 1600 | 21.42 | 19.72 | 14.17 | 0.12 | 0.5% | 0.27 | 1.9% | -34.58 | 8.18 |
| 1800 | 21.84 | 20.62 | 14.17 | 0.12 | 0.5% | 0.23 | 1.6% | -34.16 | 8.05 |
| 2000 | 22.20 | 21.31 | 14.17 | 0.11 | 0.5% | 0.19 | 1.4% | -33.80 | 8.09 |
| 2300 | 22.62 | 22.03 | 14.17 | 0.10 | 0.5% | 0.15 | 1.0% | -33.38 | 8.17 |
| 2600 | 22.86 | 22.46 | 14.17 | 0.10 | 0.4% | 0.11 | 0.8% | -33.14 | 8.23 |
| 3000 | 23.10 | 22.87 | 14.17 | 0.08 | 0.3% | 0.08 | 0.6% | -32.90 | 8.33 |
| 4000 | 23.44 | 23.39 | 14.17 | 0.06 | 0.3% | 0.13 | 0.9% | -32.56 | 8.51 |
| 5000 | 23.61 | 23.59 | 14.17 | 0.07 | 0.3% | 0.15 | 1.1% | -32.39 | 8.60 |
| 12000 | 23.67 | 23.67 | 14.17 | 0.07 | 0.3% | 0.15 | 1.0% | -32.33 | 8.64 |

| Workload Norms (minutes) | FCFS AB (6 Hours-40% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 950 | 26.90 | 16.40 | 14.13 | 0.59 | 2.2% | 0.80 | 5.7% | -29.10 | 13.87 |
| 1100 | 23.17 | 17.05 | 14.16 | 0.29 | 1.3% | 0.36 | 2.5% | -32.83 | 11.34 |
| 1250 | 22.24 | 18.11 | 14.17 | 0.25 | 1.1% | 0.34 | 2.4% | -33.76 | 10.03 |
| 1400 | 21.88 | 19.05 | 14.17 | 0.19 | 0.8% | 0.33 | 2.3% | -34.12 | 9.05 |
| 1600 | 21.94 | 20.09 | 14.18 | 0.14 | 0.7% | 0.31 | 2.2% | -34.06 | 8.42 |
| 1800 | 22.34 | 21.01 | 14.18 | 0.13 | 0.6% | 0.26 | 1.8% | -33.66 | 8.30 |
| 2000 | 22.77 | 21.79 | 14.18 | 0.14 | 0.6% | 0.22 | 1.6% | -33.23 | 8.37 |
| 2300 | 23.16 | 22.53 | 14.17 | 0.12 | 0.5% | 0.16 | 1.1% | -32.84 | 8.38 |
| 2600 | 23.47 | 23.04 | 14.18 | 0.11 | 0.5% | 0.13 | 0.9% | -32.53 | 8.51 |
| 3000 | 23.71 | 23.46 | 14.18 | 0.09 | 0.4% | 0.09 | 0.7% | -32.29 | 8.56 |
| 4000 | 24.04 | 23.98 | 14.18 | 0.07 | 0.3% | 0.16 | 1.1% | -31.96 | 8.74 |
| 5000 | 24.23 | 24.22 | 14.18 | 0.09 | 0.4% | 0.18 | 1.3% | -31.77 | 8.86 |
| 12000 | 24.30 | 24.30 | 14.18 | 0.09 | 0.4% | 0.18 | 1.2% | -31.70 | 8.89 |

| Workload Norms (minutes) | FCFS AB (6 Hours-80% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 950 | 34.44 | 18.68 | 14.10 | 1.56 | 4.5% | 1.90 | 13.5% | -21.56 | 15.97 |
| 1100 | 28.23 | 18.49 | 14.15 | 0.67 | 2.4% | 0.99 | 7.0% | -27.77 | 13.64 |
| 1250 | 25.65 | 19.37 | 14.17 | 0.44 | 1.7% | 0.66 | 4.7% | -30.35 | 11.95 |
| 1400 | 24.61 | 20.36 | 14.18 | 0.35 | 1.4% | 0.58 | 4.1% | -31.39 | 10.73 |
| 1600 | 24.30 | 21.51 | 14.18 | 0.26 | 1.1% | 0.51 | 3.6% | -31.70 | 9.76 |
| 1800 | 24.51 | 22.57 | 14.18 | 0.25 | 1.0% | 0.43 | 3.0% | -31.49 | 9.44 |
| 2000 | 24.77 | 23.39 | 14.18 | 0.22 | 0.9% | 0.34 | 2.4% | -31.23 | 9.28 |
| 2300 | 25.29 | 24.37 | 14.18 | 0.20 | 0.8% | 0.26 | 1.9% | -30.71 | 9.36 |
| 2600 | 25.60 | 25.01 | 14.18 | 0.18 | 0.7% | 0.21 | 1.5% | -30.40 | 9.42 |
| 3000 | 25.93 | 25.57 | 14.18 | 0.15 | 0.6% | 0.18 | 1.3% | -30.07 | 9.56 |
| 4000 | 26.45 | 26.35 | 14.19 | 0.15 | 0.6% | 0.24 | 1.7% | -29.55 | 9.82 |
| 5000 | 26.64 | 26.61 | 14.19 | 0.17 | 0.7% | 0.26 | 1.8% | -29.36 | 9.92 |
| 12000 | 26.79 | 26.79 | 14.19 | 0.17 | 0.6% | 0.27 | 1.9% | -29.21 | 9.97 |

| Workload Norms (minutes) | FCFS AL (6 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1300 | 36.57 | 17.70 | 14.05 | 3.67 | 10.0% | 1.97 | 14.0% | -19.43 | 14.42 |
| 1450 | 29.73 | 18.77 | 14.11 | 1.48 | 5.0% | 1.13 | 8.0% | -26.27 | 11.70 |
| 1600 | 26.71 | 19.64 | 14.14 | 0.63 | 2.4% | 0.65 | 4.6% | -29.29 | 10.08 |
| 1800 | 25.07 | 20.60 | 14.16 | 0.38 | 1.5% | 0.40 | 2.8% | -30.93 | 9.35 |
| 2000 | 24.22 | 21.30 | 14.16 | 0.13 | 0.5% | 0.24 | 1.7% | -31.78 | 8.83 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 2300 | 23.86 | 22.01 | 14.17 | 0.10 | 0.4% | 0.18 | 1.3% | -32.14 | 8.63 |
| 2600 | 23.70 | 22.44 | 14.17 | 0.08 | 0.3% | 0.17 | 1.2% | -32.30 | 8.55 |
| 3000 | 23.68 | 22.93 | 14.17 | 0.07 | 0.3% | 0.15 | 1.1% | -32.32 | 8.60 |
| 4000 | 23.62 | 23.43 | 14.17 | 0.07 | 0.3% | 0.15 | 1.1% | -32.38 | 8.60 |
| 12000 | 23.67 | 23.67 | 14.17 | 0.07 | 0.3% | 0.15 | 1.0% | -32.33 | 8.64 |

| **Workload Norms (minutes)** | **FCFS AL (6 Hours-40% distortion)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Average Gross Throughput time (in hours)** | **Average Shop Floor time (in hours)** | **Average Output (in pieces)** | **Average Tardiness (in hours)** | **% Average Tardiness** | **Average No. of Tardy Orders (in pieces)** | **% Average No. of Tardy Orders** | **Average Lateness (in hours)** | **SD of Lateness** |
| 1300 | 39.82 | 17.90 | 14.02 | 4.39 | 11.0% | 2.55 | 18.2% | -16.18 | 15.23 |
| 1450 | 31.27 | 19.10 | 14.11 | 1.36 | 4.4% | 1.26 | 8.9% | -24.73 | 12.09 |
| 1600 | 27.81 | 19.96 | 14.15 | 0.71 | 2.6% | 0.72 | 5.1% | -28.19 | 10.63 |
| 1800 | 25.99 | 20.96 | 14.16 | 0.38 | 1.4% | 0.41 | 2.9% | -30.01 | 9.81 |
| 2000 | 24.95 | 21.74 | 14.17 | 0.16 | 0.6% | 0.26 | 1.9% | -31.05 | 9.11 |
| 2300 | 24.52 | 22.52 | 14.17 | 0.12 | 0.5% | 0.20 | 1.4% | -31.48 | 8.90 |
| 2600 | 24.33 | 23.01 | 14.18 | 0.09 | 0.4% | 0.17 | 1.2% | -31.67 | 8.81 |
| 3000 | 24.29 | 23.50 | 14.18 | 0.09 | 0.4% | 0.17 | 1.2% | -31.71 | 8.85 |
| 4000 | 24.28 | 24.05 | 14.18 | 0.09 | 0.4% | 0.19 | 1.3% | -31.72 | 8.89 |
| 12000 | 24.30 | 24.30 | 14.18 | 0.09 | 0.4% | 0.18 | 1.2% | -31.70 | 8.89 |

| **Workload Norms (minutes)** | **FCFS AL (6 Hours-80% distortion)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Average Gross Throughput time (in hours)** | **Average Shop Floor time (in hours)** | **Average Output (in pieces)** | **Average Tardiness (in hours)** | **% Average Tardiness** | **Average No. of Tardy Orders (in pieces)** | **% Average No. of Tardy Orders** | **Average Lateness (in hours)** | **SD of Lateness** |
| 1300 | 56.36 | 18.54 | 13.90 | 12.58 | 22.3% | 5.54 | 39.9% | 0.36 | 19.09 |
| 1450 | 40.55 | 19.94 | 14.05 | 4.51 | 11.1% | 2.81 | 20.0% | -15.45 | 15.25 |
| 1600 | 34.45 | 21.12 | 14.12 | 2.05 | 6.0% | 1.74 | 12.3% | -21.55 | 13.14 |
| 1800 | 29.82 | 22.34 | 14.16 | 0.66 | 2.2% | 0.75 | 5.3% | -26.18 | 11.21 |
| 2000 | 28.27 | 23.23 | 14.17 | 0.43 | 1.5% | 0.48 | 3.4% | -27.73 | 10.59 |
| 2300 | 27.13 | 24.25 | 14.18 | 0.19 | 0.7% | 0.30 | 2.1% | -28.87 | 9.91 |
| 2600 | 26.78 | 24.93 | 14.18 | 0.16 | 0.6% | 0.25 | 1.7% | -29.22 | 9.80 |
| 3000 | 26.69 | 25.54 | 14.19 | 0.16 | 0.6% | 0.24 | 1.7% | -29.31 | 9.84 |
| 4000 | 26.73 | 26.32 | 14.19 | 0.17 | 0.6% | 0.27 | 1.9% | -29.27 | 9.96 |
| 12000 | 26.79 | 26.79 | 14.19 | 0.17 | 0.6% | 0.27 | 1.9% | -29.21 | 9.97 |

| **Workload Norms (minutes)** | **FCFS AB (8 Hours-20% distortion)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Average Gross Throughput time (in hours)** | **Average Shop Floor time (in hours)** | **Average Output (in pieces)** | **Average Tardiness (in hours)** | **% Average Tardiness** | **Average No. of Tardy Orders (in pieces)** | **% Average No. of Tardy Orders** | **Average Lateness (in hours)** | **SD of Lateness** |
| 1200 | 25.23 | 18.40 | 14.13 | 0.22 | 0.9% | 0.35 | 2.5% | -30.77 | 11.24 |
| 1280 | 24.04 | 18.82 | 14.14 | 0.13 | 0.5% | 0.27 | 1.9% | -31.96 | 10.33 |
| 1360 | 23.64 | 19.35 | 14.14 | 0.10 | 0.4% | 0.23 | 1.7% | -32.36 | 9.72 |
| 1480 | 23.17 | 20.06 | 14.14 | 0.07 | 0.3% | 0.18 | 1.3% | -32.83 | 9.02 |
| 1816 | 23.59 | 21.96 | 14.15 | 0.07 | 0.3% | 0.22 | 1.6% | -32.41 | 8.45 |
| 2150 | 24.05 | 23.18 | 14.14 | 0.08 | 0.3% | 0.19 | 1.4% | -31.95 | 8.30 |
| 2502 | 24.47 | 24.00 | 14.14 | 0.06 | 0.3% | 0.12 | 0.9% | -31.53 | 8.36 |
| 3000 | 24.84 | 24.63 | 14.14 | 0.05 | 0.2% | 0.07 | 0.5% | -31.16 | 8.49 |
| 9000 | 25.33 | 25.33 | 14.14 | 0.06 | 0.2% | 0.12 | 0.9% | -30.67 | 8.72 |

| **Workload Norms (minutes)** | **FCFS AB (8 Hours-40% distortion)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Average Gross Throughput time (in hours)** | **Average Shop Floor time (in hours)** | **Average Output (in pieces)** | **Average Tardiness (in hours)** | **% Average Tardiness** | **Average No. of Tardy Orders (in pieces)** | **% Average No. of Tardy Orders** | **Average Lateness (in hours)** | **SD of Lateness** |
| 1240 | 25.66 | 18.98 | 14.13 | 0.24 | 0.9% | 0.37 | 2.6% | -30.34 | 11.43 |
| 1320 | 24.74 | 19.45 | 14.13 | 0.17 | 0.7% | 0.31 | 2.2% | -31.26 | 10.57 |
| 1404 | 24.25 | 19.94 | 14.14 | 0.12 | 0.5% | 0.27 | 1.9% | -31.75 | 9.90 |
| 1515 | 23.81 | 20.61 | 14.14 | 0.09 | 0.4% | 0.24 | 1.7% | -32.19 | 9.29 |
| 1625 | 23.78 | 21.25 | 14.14 | 0.07 | 0.3% | 0.21 | 1.5% | -32.22 | 8.90 |
| 1819 | 24.12 | 22.35 | 14.14 | 0.08 | 0.3% | 0.25 | 1.8% | -31.88 | 8.66 |
| 2160 | 24.52 | 23.59 | 14.14 | 0.09 | 0.4% | 0.21 | 1.5% | -31.48 | 8.47 |
| 2460 | 24.90 | 24.36 | 14.14 | 0.07 | 0.3% | 0.14 | 1.0% | -31.10 | 8.51 |
| 3000 | 25.35 | 25.13 | 14.14 | 0.06 | 0.2% | 0.08 | 0.6% | -30.65 | 8.67 |
| 9000 | 25.86 | 25.86 | 14.14 | 0.06 | 0.2% | 0.13 | 1.0% | -30.14 | 8.90 |

| **Workload Norms** | **FCFS AB (8 Hours-80% distortion)** |
|---|---|

| (minutes) | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
|---|---|---|---|---|---|---|---|---|---|
| 1370 | 28.27 | 21.16 | 14.14 | 0.44 | 1.5% | 0.69 | 4.9% | -27.73 | 12.08 |
| 1495 | 27.16 | 21.90 | 14.15 | 0.31 | 1.1% | 0.57 | 4.0% | -28.84 | 11.18 |
| 1615 | 26.40 | 22.57 | 14.14 | 0.18 | 0.7% | 0.44 | 3.1% | -29.60 | 10.37 |
| 1715 | 26.35 | 23.21 | 14.14 | 0.17 | 0.7% | 0.43 | 3.1% | -29.65 | 9.99 |
| 1820 | 26.34 | 23.75 | 14.14 | 0.17 | 0.7% | 0.45 | 3.1% | -29.66 | 9.81 |
| 2100 | 26.55 | 24.99 | 14.14 | 0.16 | 0.6% | 0.36 | 2.5% | -29.45 | 9.46 |
| 2270 | 26.74 | 25.62 | 14.14 | 0.15 | 0.6% | 0.29 | 2.0% | -29.26 | 9.33 |
| 2535 | 27.13 | 26.39 | 14.14 | 0.15 | 0.6% | 0.24 | 1.7% | -28.87 | 9.47 |
| 3000 | 27.56 | 27.21 | 14.14 | 0.12 | 0.4% | 0.16 | 1.1% | -28.44 | 9.58 |
| 9000 | 28.25 | 28.25 | 14.14 | 0.13 | 0.5% | 0.27 | 1.9% | -27.75 | 9.90 |

| Workload Norms (minutes) | FCFS AL (8 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1420 | 47.72 | 18.50 | 13.97 | 6.66 | 14.0% | 4.52 | 32.4% | -8.28 | 15.83 |
| 1470 | 42.37 | 19.01 | 14.02 | 4.17 | 9.8% | 3.29 | 23.4% | -13.63 | 14.28 |
| 1532 | 38.02 | 19.51 | 14.05 | 2.51 | 6.6% | 2.29 | 16.3% | -17.98 | 13.14 |
| 1640 | 33.29 | 20.32 | 14.08 | 1.32 | 4.0% | 1.27 | 9.0% | -22.71 | 11.83 |
| 1750 | 29.52 | 20.97 | 14.10 | 0.55 | 1.9% | 0.64 | 4.6% | -26.48 | 10.58 |
| 1934 | 27.32 | 21.94 | 14.13 | 0.26 | 1.0% | 0.31 | 2.2% | -28.68 | 9.72 |
| 2284 | 25.61 | 23.18 | 14.14 | 0.08 | 0.3% | 0.15 | 1.0% | -30.39 | 8.84 |
| 2639 | 25.34 | 24.01 | 14.14 | 0.06 | 0.2% | 0.11 | 0.8% | -30.66 | 8.68 |
| 3500 | 25.23 | 24.82 | 14.14 | 0.06 | 0.2% | 0.11 | 0.8% | -30.77 | 8.67 |
| 12000 | 25.33 | 25.33 | 14.14 | 0.06 | 0.2% | 0.12 | 0.9% | -30.67 | 8.72 |

| Workload Norms (minutes) | FCFS AL (8 Hours-40% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1470 | 47.53 | 19.15 | 13.99 | 6.52 | 13.7% | 4.47 | 31.9% | -8.47 | 15.50 |
| 1570 | 38.32 | 20.03 | 14.06 | 2.52 | 6.6% | 2.19 | 15.6% | -17.68 | 13.37 |
| 1665 | 33.96 | 20.72 | 14.09 | 1.32 | 3.9% | 1.34 | 9.5% | -22.04 | 12.08 |
| 1770 | 30.78 | 21.35 | 14.10 | 0.78 | 2.5% | 0.83 | 5.9% | -25.22 | 11.10 |
| 1944 | 28.15 | 22.26 | 14.13 | 0.32 | 1.1% | 0.39 | 2.8% | -27.85 | 10.10 |
| 2280 | 26.21 | 23.54 | 14.14 | 0.08 | 0.3% | 0.17 | 1.2% | -29.79 | 9.04 |
| 2611 | 25.83 | 24.34 | 14.14 | 0.05 | 0.2% | 0.11 | 0.8% | -30.17 | 8.83 |
| 2690 | 25.78 | 24.46 | 14.14 | 0.05 | 0.2% | 0.11 | 0.7% | -30.22 | 8.79 |
| 3000 | 25.76 | 24.91 | 14.14 | 0.05 | 0.2% | 0.10 | 0.7% | -30.24 | 8.81 |
| 9000 | 25.86 | 25.86 | 14.14 | 0.06 | 0.2% | 0.13 | 1.0% | -30.14 | 8.90 |

| Workload Norms (minutes) | FCFS AL (8 Hours-80% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1620 | 49.86 | 21.25 | 14.02 | 7.60 | 15.3% | 4.85 | 34.6% | -6.14 | 15.96 |
| 1710 | 41.44 | 21.97 | 14.08 | 3.41 | 8.2% | 2.92 | 20.8% | -14.56 | 14.20 |
| 1810 | 37.54 | 22.68 | 14.10 | 2.34 | 6.2% | 2.07 | 14.7% | -18.46 | 13.48 |
| 1900 | 33.98 | 23.23 | 14.12 | 1.21 | 3.6% | 1.28 | 9.1% | -22.02 | 12.43 |
| 2000 | 32.37 | 23.74 | 14.13 | 0.90 | 2.8% | 1.03 | 7.3% | -23.63 | 11.89 |
| 2254 | 29.43 | 24.90 | 14.14 | 0.23 | 0.8% | 0.42 | 3.0% | -26.57 | 10.50 |
| 2470 | 28.56 | 25.64 | 14.14 | 0.15 | 0.5% | 0.31 | 2.2% | -27.44 | 10.07 |
| 2693 | 28.22 | 26.25 | 14.14 | 0.11 | 0.4% | 0.25 | 1.7% | -27.78 | 9.86 |
| 3500 | 28.17 | 27.43 | 14.14 | 0.11 | 0.4% | 0.24 | 1.7% | -27.83 | 9.83 |
| 4000 | 28.19 | 27.74 | 14.14 | 0.11 | 0.4% | 0.25 | 1.8% | -27.81 | 9.85 |
| 9000 | 28.25 | 28.25 | 14.14 | 0.13 | 0.5% | 0.27 | 1.9% | -27.75 | 9.90 |

| Workload Norms (minutes) | SPT AB (2 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 650 | 19.30 | 11.88 | 14.16 | 0.01 | 0.1% | 0.07 | 0.5% | -36.70 | 11.83 |
| 850 | 17.15 | 13.38 | 14.18 | 0.00 | 0.0% | 0.03 | 0.2% | -38.85 | 9.05 |
| 1000 | 17.20 | 14.60 | 14.18 | 0.00 | 0.0% | 0.03 | 0.2% | -38.80 | 8.15 |
| 1200 | 17.59 | 15.93 | 14.18 | 0.01 | 0.0% | 0.04 | 0.3% | -38.41 | 7.51 |
| 1400 | 18.17 | 17.02 | 14.18 | 0.01 | 0.1% | 0.07 | 0.5% | -37.83 | 7.37 |
| 1700 | 18.73 | 18.07 | 14.18 | 0.03 | 0.1% | 0.10 | 0.7% | -37.27 | 7.31 |
| 2000 | 19.17 | 18.77 | 14.18 | 0.03 | 0.2% | 0.08 | 0.6% | -36.83 | 7.45 |
| 2500 | 19.58 | 19.39 | 14.18 | 0.03 | 0.2% | 0.05 | 0.4% | -36.42 | 7.64 |
| 9000 | 20.02 | 20.02 | 14.18 | 0.00 | 0.0% | 0.00 | 0.0% | -35.98 | 7.84 |

| Workload Norms (minutes) | SPT AB (2 Hours-40% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 650 | 20.85 | 12.30 | 14.16 | 0.04 | 0.2% | 0.16 | 1.2% | -35.15 | 12.59 |
| 850 | 18.12 | 13.74 | 14.18 | 0.01 | 0.1% | 0.05 | 0.4% | -37.88 | 9.77 |
| 1000 | 17.88 | 14.94 | 14.18 | 0.01 | 0.1% | 0.06 | 0.4% | -38.12 | 8.65 |
| 1200 | 18.24 | 16.31 | 14.18 | 0.02 | 0.1% | 0.07 | 0.5% | -37.76 | 8.00 |
| 1400 | 18.71 | 17.40 | 14.18 | 0.02 | 0.1% | 0.09 | 0.6% | -37.29 | 7.72 |
| 1700 | 19.35 | 18.58 | 14.18 | 0.04 | 0.2% | 0.13 | 0.9% | -36.65 | 7.69 |
| 2000 | 19.81 | 19.33 | 14.18 | 0.04 | 0.2% | 0.10 | 0.7% | -36.19 | 7.79 |
| 2500 | 20.31 | 20.08 | 14.17 | 0.05 | 0.2% | 0.07 | 0.5% | -35.69 | 8.02 |
| 9000 | 20.79 | 20.79 | 14.17 | 0.00 | 0.0% | 0.02 | 0.1% | -35.21 | 8.25 |

| Workload Norms (minutes) | SPT AB (2 Hours-80% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 650 | 28.06 | 14.43 | 14.13 | 0.40 | 1.4% | 0.77 | 5.4% | -27.94 | 14.81 |
| 850 | 21.77 | 15.00 | 14.16 | 0.08 | 0.4% | 0.26 | 1.8% | -34.23 | 11.93 |
| 1000 | 20.82 | 16.16 | 14.18 | 0.06 | 0.3% | 0.19 | 1.4% | -35.18 | 10.58 |
| 1200 | 20.48 | 17.54 | 14.18 | 0.05 | 0.3% | 0.17 | 1.2% | -35.52 | 9.38 |
| 1400 | 20.89 | 18.80 | 14.18 | 0.06 | 0.3% | 0.21 | 1.5% | -35.11 | 9.04 |
| 1700 | 21.49 | 20.20 | 14.18 | 0.09 | 0.4% | 0.24 | 1.7% | -34.51 | 8.85 |
| 2000 | 22.06 | 21.25 | 14.18 | 0.11 | 0.5% | 0.20 | 1.4% | -33.94 | 8.92 |
| 2500 | 22.74 | 22.35 | 14.17 | 0.09 | 0.4% | 0.12 | 0.9% | -33.26 | 9.15 |
| 9000 | 23.58 | 23.58 | 14.17 | 0.04 | 0.2% | 0.14 | 1.0% | -32.42 | 9.56 |

| Workload Norms (minutes) | SPT AL (2 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1000 | 24.50 | 14.93 | 14.14 | 0.42 | 1.7% | 0.59 | 4.2% | -31.50 | 10.19 |
| 1100 | 21.88 | 15.68 | 14.16 | 0.04 | 0.2% | 0.11 | 0.8% | -34.12 | 9.10 |
| 1200 | 20.83 | 16.35 | 14.16 | 0.03 | 0.1% | 0.06 | 0.4% | -35.17 | 8.42 |
| 1300 | 20.36 | 16.84 | 14.16 | 0.02 | 0.1% | 0.03 | 0.2% | -35.64 | 8.25 |
| 1400 | 20.16 | 17.35 | 14.17 | 0.02 | 0.1% | 0.03 | 0.2% | -35.84 | 7.99 |
| 1600 | 19.71 | 18.07 | 14.18 | 0.01 | 0.0% | 0.01 | 0.0% | -36.29 | 7.51 |
| 1900 | 19.64 | 18.78 | 14.18 | 0.01 | 0.0% | 0.00 | 0.0% | -36.36 | 7.46 |
| 2300 | 19.70 | 19.30 | 14.18 | 0.01 | 0.0% | 0.00 | 0.0% | -36.30 | 7.56 |
| 2700 | 19.85 | 19.61 | 14.18 | 0.00 | 0.0% | 0.00 | 0.0% | -36.15 | 7.70 |
| 9000 | 20.02 | 20.02 | 14.18 | 0.00 | 0.0% | 0.00 | 0.0% | -35.98 | 7.84 |

| Workload Norms (minutes) | SPT AL (2 Hours-40% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1000 | 26.73 | 15.18 | 14.11 | 0.48 | 1.8% | 0.77 | 5.5% | -29.27 | 11.04 |
| 1100 | 22.99 | 15.93 | 14.15 | 0.11 | 0.5% | 0.24 | 1.7% | -33.01 | 9.39 |
| 1200 | 22.16 | 16.68 | 14.16 | 0.06 | 0.3% | 0.15 | 1.1% | -33.84 | 8.98 |
| 1300 | 21.47 | 17.24 | 14.16 | 0.04 | 0.2% | 0.10 | 0.7% | -34.53 | 8.79 |
| 1400 | 20.87 | 17.68 | 14.16 | 0.03 | 0.1% | 0.06 | 0.4% | -35.13 | 8.32 |
| 1600 | 20.50 | 18.51 | 14.17 | 0.01 | 0.0% | 0.02 | 0.1% | -35.50 | 7.94 |
| 1900 | 20.29 | 19.29 | 14.17 | 0.01 | 0.0% | 0.00 | 0.0% | -35.71 | 7.77 |
| 2300 | 20.43 | 19.93 | 14.17 | 0.01 | 0.0% | 0.00 | 0.0% | -35.57 | 7.92 |
| 2700 | 20.59 | 20.29 | 14.17 | 0.00 | 0.0% | 0.00 | 0.0% | -35.41 | 8.13 |
| 9000 | 20.79 | 20.79 | 14.17 | 0.00 | 0.0% | 0.02 | 0.1% | -35.21 | 8.25 |

| Workload Norms (minutes) | SPT AL (2 Hours-80% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1200 | 27.79 | 17.64 | 14.13 | 0.63 | 2.3% | 0.84 | 6.0% | -28.21 | 11.33 |
| 1300 | 25.52 | 18.33 | 14.15 | 0.23 | 0.9% | 0.46 | 3.3% | -30.48 | 10.16 |
| 1400 | 23.99 | 18.91 | 14.16 | 0.10 | 0.4% | 0.23 | 1.7% | -32.01 | 9.64 |
| 1600 | 23.51 | 19.99 | 14.17 | 0.06 | 0.3% | 0.16 | 1.1% | -32.49 | 9.29 |
| 1750 | 23.10 | 20.55 | 14.17 | 0.02 | 0.1% | 0.07 | 0.5% | -32.90 | 9.10 |
| 1900 | 23.05 | 21.09 | 14.17 | 0.02 | 0.1% | 0.08 | 0.6% | -32.95 | 9.02 |
| 2300 | 23.15 | 22.11 | 14.17 | 0.02 | 0.1% | 0.08 | 0.6% | -32.85 | 9.11 |
| 2700 | 23.24 | 22.66 | 14.17 | 0.02 | 0.1% | 0.07 | 0.5% | -32.76 | 9.29 |
| 3300 | 23.37 | 23.09 | 14.17 | 0.03 | 0.1% | 0.09 | 0.6% | -32.63 | 9.43 |
| 9000 | 23.56 | 23.56 | 14.17 | 0.03 | 0.1% | 0.13 | 0.9% | -32.44 | 9.55 |

| Workload Norms | SPT AB (4 Hours-20% distortion) |
|---|---|

| (minutes) | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
|---|---|---|---|---|---|---|---|---|---|
| 850 | 20.34 | 14.00 | 14.24 | 0.03 | 0.2% | 0.12 | 0.9% | -35.66 | 11.39 |
| 1000 | 19.23 | 15.13 | 14.25 | 0.03 | 0.2% | 0.09 | 0.6% | -36.77 | 9.83 |
| 1100 | 19.09 | 15.91 | 14.25 | 0.03 | 0.2% | 0.09 | 0.6% | -36.91 | 9.14 |
| 1250 | 19.20 | 16.93 | 14.26 | 0.03 | 0.2% | 0.09 | 0.6% | -36.80 | 8.44 |
| 1500 | 19.78 | 18.38 | 14.26 | 0.03 | 0.2% | 0.12 | 0.9% | -36.22 | 7.90 |
| 1650 | 20.15 | 19.07 | 14.26 | 0.03 | 0.2% | 0.15 | 1.0% | -35.85 | 7.76 |
| 2000 | 20.89 | 20.29 | 14.26 | 0.04 | 0.2% | 0.12 | 0.8% | -35.11 | 7.76 |
| 2300 | 21.25 | 20.88 | 14.26 | 0.04 | 0.2% | 0.09 | 0.6% | -34.75 | 7.78 |
| 3000 | 21.75 | 21.61 | 14.26 | 0.04 | 0.2% | 0.04 | 0.3% | -34.25 | 8.03 |
| 9000 | 22.18 | 22.18 | 14.26 | 0.04 | 0.2% | 0.06 | 0.4% | -33.82 | 8.26 |

| Workload Norms (minutes) | SPT AB (4 Hours-40% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 850 | 21.83 | 14.54 | 14.24 | 0.10 | 0.4% | 0.25 | 1.7% | -34.17 | 12.10 |
| 1000 | 20.12 | 15.48 | 14.25 | 0.03 | 0.1% | 0.10 | 0.7% | -35.88 | 10.31 |
| 1100 | 19.53 | 16.12 | 14.25 | 0.02 | 0.1% | 0.08 | 0.6% | -36.47 | 9.34 |
| 1250 | 19.67 | 17.22 | 14.26 | 0.03 | 0.1% | 0.09 | 0.6% | -36.33 | 8.65 |
| 1500 | 20.26 | 18.73 | 14.26 | 0.03 | 0.2% | 0.14 | 1.0% | -35.74 | 8.08 |
| 1650 | 20.63 | 19.44 | 14.26 | 0.04 | 0.2% | 0.17 | 1.2% | -35.37 | 8.01 |
| 2000 | 21.41 | 20.74 | 14.26 | 0.05 | 0.2% | 0.14 | 0.9% | -34.59 | 7.94 |
| 2300 | 21.78 | 21.37 | 14.27 | 0.05 | 0.2% | 0.10 | 0.7% | -34.22 | 7.96 |
| 3000 | 22.35 | 22.20 | 14.26 | 0.04 | 0.2% | 0.05 | 0.3% | -33.65 | 8.21 |
| 9000 | 22.78 | 22.78 | 14.26 | 0.04 | 0.2% | 0.06 | 0.4% | -33.22 | 8.44 |

| Workload Norms (minutes) | SPT AB (4 Hours-80% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 850 | 27.51 | 16.22 | 14.22 | 0.37 | 1.3% | 0.70 | 4.9% | -28.49 | 13.92 |
| 1100 | 22.60 | 17.43 | 14.24 | 0.06 | 0.3% | 0.21 | 1.5% | -33.40 | 11.01 |
| 1250 | 21.96 | 18.36 | 14.26 | 0.05 | 0.2% | 0.18 | 1.3% | -34.04 | 9.89 |
| 1500 | 22.27 | 20.04 | 14.26 | 0.06 | 0.3% | 0.25 | 1.7% | -33.73 | 9.17 |
| 1650 | 22.56 | 20.85 | 14.26 | 0.06 | 0.3% | 0.25 | 1.7% | -33.44 | 8.86 |
| 1800 | 22.97 | 21.60 | 14.26 | 0.09 | 0.4% | 0.26 | 1.8% | -33.03 | 8.84 |
| 2000 | 23.41 | 22.40 | 14.26 | 0.10 | 0.4% | 0.23 | 1.6% | -32.59 | 8.82 |
| 2300 | 23.91 | 23.29 | 14.27 | 0.09 | 0.4% | 0.16 | 1.1% | -32.09 | 8.84 |
| 3000 | 24.59 | 24.35 | 14.27 | 0.07 | 0.3% | 0.08 | 0.6% | -31.41 | 9.04 |
| 9000 | 25.16 | 25.16 | 14.26 | 0.04 | 0.2% | 0.09 | 0.7% | -30.84 | 9.30 |

| Workload Norms (minutes) | SPT AL (4 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1000 | 46.80 | 14.81 | 14.04 | 7.44 | 15.9% | 4.33 | 30.9% | -9.20 | 16.51 |
| 1100 | 34.37 | 15.80 | 14.16 | 1.58 | 4.6% | 1.77 | 12.5% | -21.63 | 12.19 |
| 1200 | 28.42 | 16.65 | 14.19 | 0.57 | 2.0% | 0.71 | 5.0% | -27.58 | 10.84 |
| 1300 | 25.13 | 17.41 | 14.22 | 0.10 | 0.4% | 0.30 | 2.1% | -30.87 | 9.46 |
| 1500 | 22.84 | 18.60 | 14.24 | 0.04 | 0.2% | 0.09 | 0.6% | -33.16 | 8.67 |
| 1650 | 22.23 | 19.29 | 14.25 | 0.01 | 0.0% | 0.03 | 0.2% | -33.77 | 8.23 |
| 2000 | 22.00 | 20.47 | 14.26 | 0.02 | 0.1% | 0.04 | 0.3% | -34.00 | 8.11 |
| 2300 | 21.92 | 21.07 | 14.26 | 0.02 | 0.1% | 0.04 | 0.3% | -34.08 | 8.08 |
| 3000 | 22.00 | 21.69 | 14.26 | 0.02 | 0.1% | 0.04 | 0.3% | -34.00 | 8.13 |
| 9000 | 22.18 | 22.18 | 14.26 | 0.04 | 0.2% | 0.06 | 0.4% | -33.82 | 8.26 |

| Workload Norms (minutes) | SPT AL (4 Hours-40% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1000 | 52.99 | 14.97 | 14.00 | 10.73 | 20.2% | 5.22 | 37.3% | -3.01 | 18.04 |
| 1100 | 38.52 | 16.03 | 14.14 | 3.33 | 8.6% | 2.55 | 18.0% | -17.48 | 13.15 |
| 1200 | 30.27 | 16.88 | 14.19 | 0.75 | 2.5% | 0.96 | 6.7% | -25.73 | 11.33 |
| 1300 | 26.56 | 17.66 | 14.21 | 0.17 | 0.7% | 0.45 | 3.1% | -29.44 | 9.76 |
| 1400 | 24.42 | 18.31 | 14.24 | 0.04 | 0.2% | 0.10 | 0.7% | -31.58 | 9.29 |
| 1650 | 22.96 | 19.63 | 14.25 | 0.01 | 0.1% | 0.04 | 0.3% | -33.04 | 8.53 |
| 2000 | 22.48 | 20.84 | 14.26 | 0.01 | 0.1% | 0.04 | 0.3% | -33.52 | 8.21 |
| 2300 | 22.46 | 21.51 | 14.26 | 0.01 | 0.1% | 0.04 | 0.3% | -33.54 | 8.16 |
| 2700 | 22.57 | 22.06 | 14.26 | 0.01 | 0.1% | 0.04 | 0.3% | -33.43 | 8.27 |
| 9000 | 22.78 | 22.78 | 14.26 | 0.04 | 0.2% | 0.06 | 0.4% | -33.22 | 8.44 |

| Workload Norms | SPT AL (4 Hours-80% distortion) |
|---|---|

| (minutes) | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
|---|---|---|---|---|---|---|---|---|---|
| 1100 | 59.13 | 16.63 | 14.02 | 13.41 | 22.7% | 6.63 | 47.3% | 3.13 | 18.29 |
| 1200 | 46.38 | 17.74 | 14.12 | 6.90 | 14.9% | 3.85 | 27.2% | -9.62 | 15.05 |
| 1300 | 36.20 | 18.60 | 14.19 | 2.35 | 6.5% | 1.90 | 13.4% | -19.80 | 12.26 |
| 1400 | 31.84 | 19.41 | 14.22 | 0.95 | 3.0% | 1.06 | 7.5% | -24.16 | 11.37 |
| 1650 | 26.21 | 20.93 | 14.25 | 0.06 | 0.2% | 0.21 | 1.4% | -29.79 | 9.64 |
| 1800 | 25.37 | 21.63 | 14.26 | 0.05 | 0.2% | 0.14 | 1.0% | -30.63 | 9.45 |
| 2000 | 25.01 | 22.42 | 14.26 | 0.02 | 0.1% | 0.08 | 0.6% | -30.99 | 9.12 |
| 2300 | 24.84 | 23.29 | 14.26 | 0.02 | 0.1% | 0.08 | 0.5% | -31.16 | 9.02 |
| 2700 | 24.98 | 24.10 | 14.27 | 0.02 | 0.1% | 0.08 | 0.6% | -31.02 | 9.14 |
| 9000 | 25.16 | 25.16 | 14.26 | 0.04 | 0.2% | 0.09 | 0.7% | -30.84 | 9.30 |

| Workload Norms (minutes) | SPT AB (6 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 950 | 22.64 | 15.22 | 14.15 | 0.32 | 1.4% | 0.45 | 3.2% | -33.36 | 12.69 |
| 1100 | 20.74 | 16.28 | 14.16 | 0.24 | 1.1% | 0.35 | 2.5% | -35.26 | 10.64 |
| 1250 | 20.32 | 17.30 | 14.17 | 0.18 | 0.9% | 0.33 | 2.3% | -35.68 | 9.45 |
| 1400 | 20.39 | 18.22 | 14.17 | 0.15 | 0.7% | 0.32 | 2.2% | -35.61 | 8.74 |
| 1600 | 20.72 | 19.23 | 14.17 | 0.14 | 0.7% | 0.28 | 2.0% | -35.28 | 8.29 |
| 1800 | 21.09 | 20.03 | 14.17 | 0.12 | 0.6% | 0.22 | 1.6% | -34.91 | 8.13 |
| 2300 | 21.93 | 21.39 | 14.17 | 0.12 | 0.6% | 0.15 | 1.0% | -34.07 | 8.27 |
| 3000 | 22.43 | 22.21 | 14.17 | 0.09 | 0.4% | 0.09 | 0.6% | -33.57 | 8.37 |
| 4000 | 22.78 | 22.73 | 14.17 | 0.06 | 0.3% | 0.13 | 0.9% | -33.22 | 8.53 |
| 12000 | 23.02 | 23.02 | 14.17 | 0.07 | 0.3% | 0.14 | 1.0% | -32.98 | 8.65 |

| Workload Norms (minutes) | SPT AB (6 Hours-40% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 950 | 24.42 | 15.77 | 14.14 | 0.49 | 2.0% | 0.69 | 4.9% | -31.58 | 13.54 |
| 1100 | 21.69 | 16.57 | 14.16 | 0.29 | 1.4% | 0.41 | 2.9% | -34.31 | 11.28 |
| 1250 | 20.95 | 17.61 | 14.17 | 0.22 | 1.1% | 0.37 | 2.6% | -35.05 | 9.89 |
| 1400 | 20.94 | 18.53 | 14.18 | 0.17 | 0.8% | 0.35 | 2.5% | -35.06 | 9.15 |
| 1600 | 21.25 | 19.65 | 14.18 | 0.17 | 0.8% | 0.30 | 2.1% | -34.75 | 8.54 |
| 1800 | 21.61 | 20.47 | 14.18 | 0.16 | 0.7% | 0.25 | 1.8% | -34.39 | 8.38 |
| 2000 | 21.93 | 21.10 | 14.18 | 0.13 | 0.6% | 0.19 | 1.4% | -34.07 | 8.35 |
| 2300 | 22.42 | 21.86 | 14.18 | 0.13 | 0.6% | 0.16 | 1.1% | -33.58 | 8.46 |
| 3000 | 23.01 | 22.79 | 14.18 | 0.09 | 0.4% | 0.09 | 0.6% | -32.99 | 8.60 |
| 12000 | 23.61 | 23.61 | 14.18 | 0.08 | 0.3% | 0.17 | 1.2% | -32.39 | 8.86 |

| Workload Norms (minutes) | SPT AB (6 Hours-80% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 950 | 31.01 | 17.84 | 14.12 | 1.23 | 4.0% | 1.54 | 10.9% | -24.99 | 16.09 |
| 1250 | 24.16 | 18.92 | 14.17 | 0.45 | 1.9% | 0.69 | 4.8% | -31.84 | 12.01 |
| 1400 | 23.54 | 19.87 | 14.17 | 0.37 | 1.6% | 0.62 | 4.4% | -32.46 | 10.78 |
| 1600 | 23.46 | 21.05 | 14.18 | 0.29 | 1.3% | 0.50 | 3.6% | -32.54 | 9.95 |
| 1800 | 23.65 | 21.99 | 14.18 | 0.23 | 1.0% | 0.37 | 2.6% | -32.35 | 9.52 |
| 2000 | 23.99 | 22.78 | 14.18 | 0.23 | 0.9% | 0.30 | 2.1% | -32.01 | 9.39 |
| 2300 | 24.45 | 23.66 | 14.18 | 0.19 | 0.8% | 0.23 | 1.6% | -31.55 | 9.41 |
| 3000 | 25.21 | 24.90 | 14.18 | 0.15 | 0.6% | 0.16 | 1.1% | -30.79 | 9.60 |
| 4000 | 25.74 | 25.65 | 14.18 | 0.14 | 0.5% | 0.22 | 1.5% | -30.26 | 9.82 |
| 12000 | 26.08 | 26.08 | 14.19 | 0.14 | 0.6% | 0.24 | 1.7% | -29.92 | 9.94 |

| Workload Norms (minutes) | SPT AL (6 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1300 | 31.67 | 17.21 | 14.08 | 2.14 | 6.8% | 1.45 | 10.3% | -24.33 | 12.90 |
| 1450 | 26.99 | 18.15 | 14.13 | 0.94 | 3.5% | 0.85 | 6.0% | -29.01 | 10.98 |
| 1600 | 25.01 | 19.02 | 14.15 | 0.53 | 2.1% | 0.53 | 3.7% | -30.99 | 9.93 |
| 1800 | 23.78 | 19.94 | 14.16 | 0.30 | 1.2% | 0.33 | 2.3% | -32.22 | 9.19 |
| 2000 | 23.33 | 20.61 | 14.17 | 0.19 | 0.8% | 0.24 | 1.7% | -32.67 | 8.89 |
| 2300 | 23.04 | 21.32 | 14.17 | 0.11 | 0.5% | 0.19 | 1.4% | -32.96 | 8.69 |
| 2600 | 22.96 | 21.81 | 14.17 | 0.08 | 0.3% | 0.15 | 1.1% | -33.04 | 8.61 |
| 3000 | 22.93 | 22.23 | 14.17 | 0.07 | 0.3% | 0.15 | 1.0% | -33.07 | 8.58 |
| 4000 | 22.97 | 22.77 | 14.17 | 0.07 | 0.3% | 0.14 | 1.0% | -33.03 | 8.64 |
| 12000 | 23.02 | 23.02 | 14.17 | 0.07 | 0.3% | 0.14 | 1.0% | -32.98 | 8.65 |

| Workload Norms | SPT AL (6 Hours-40% distortion) |
|---|---|

| (minutes) | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
|---|---|---|---|---|---|---|---|---|---|
| 1300 | 34.31 | 17.41 | 14.07 | 3.03 | 8.8% | 1.61 | 11.5% | -21.69 | 13.79 |
| 1450 | 28.42 | 18.50 | 14.14 | 1.08 | 3.8% | 0.91 | 6.4% | -27.58 | 11.48 |
| 1600 | 25.91 | 19.31 | 14.16 | 0.48 | 1.9% | 0.56 | 4.0% | -30.09 | 10.43 |
| 1800 | 24.57 | 20.31 | 14.17 | 0.32 | 1.3% | 0.34 | 2.4% | -31.43 | 9.51 |
| 2000 | 23.89 | 21.04 | 14.17 | 0.13 | 0.5% | 0.22 | 1.5% | -32.11 | 9.08 |
| 2300 | 23.59 | 21.81 | 14.17 | 0.12 | 0.5% | 0.18 | 1.3% | -32.41 | 8.88 |
| 2600 | 23.47 | 22.28 | 14.18 | 0.08 | 0.4% | 0.16 | 1.2% | -32.53 | 8.79 |
| 3000 | 23.52 | 22.78 | 14.18 | 0.09 | 0.4% | 0.16 | 1.1% | -32.48 | 8.83 |
| 4000 | 23.55 | 23.33 | 14.18 | 0.08 | 0.3% | 0.17 | 1.2% | -32.45 | 8.88 |
| 12000 | 23.61 | 23.61 | 14.18 | 0.08 | 0.3% | 0.17 | 1.2% | -32.39 | 8.86 |

| Workload Norms (minutes) | SPT AL (6 Hours-80% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1450 | 36.32 | 19.42 | 14.08 | 2.88 | 7.9% | 2.19 | 15.5% | -19.68 | 14.41 |
| 1600 | 31.39 | 20.53 | 14.14 | 1.20 | 3.8% | 1.18 | 8.4% | -24.61 | 12.57 |
| 1800 | 28.13 | 21.72 | 14.17 | 0.45 | 1.6% | 0.61 | 4.3% | -27.87 | 11.07 |
| 2000 | 26.67 | 22.59 | 14.18 | 0.20 | 0.8% | 0.33 | 2.3% | -29.33 | 10.15 |
| 2300 | 26.09 | 23.56 | 14.18 | 0.17 | 0.7% | 0.27 | 1.9% | -29.91 | 9.91 |
| 2600 | 25.92 | 24.26 | 14.18 | 0.15 | 0.6% | 0.24 | 1.7% | -30.08 | 9.80 |
| 3000 | 25.86 | 24.79 | 14.18 | 0.14 | 0.5% | 0.24 | 1.7% | -30.14 | 9.79 |
| 4000 | 26.00 | 25.62 | 14.18 | 0.15 | 0.6% | 0.26 | 1.8% | -30.00 | 9.96 |
| 12000 | 26.08 | 26.08 | 14.19 | 0.14 | 0.6% | 0.24 | 1.7% | -29.92 | 9.94 |

| Workload Norms (minutes) | SPT AB (8 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1335 | 22.23 | 18.48 | 14.14 | 0.11 | 0.5% | 0.28 | 2.0% | -33.77 | 10.12 |
| 1400 | 21.88 | 18.81 | 14.14 | 0.07 | 0.3% | 0.23 | 1.6% | -34.12 | 9.54 |
| 1493 | 21.97 | 19.44 | 14.15 | 0.08 | 0.4% | 0.25 | 1.8% | -34.03 | 9.23 |
| 1610 | 22.14 | 20.14 | 14.15 | 0.08 | 0.4% | 0.26 | 1.9% | -33.86 | 8.88 |
| 1770 | 22.42 | 20.91 | 14.15 | 0.09 | 0.4% | 0.28 | 2.0% | -33.58 | 8.67 |
| 2040 | 22.87 | 21.97 | 14.14 | 0.10 | 0.4% | 0.21 | 1.5% | -33.13 | 8.42 |
| 2543 | 23.54 | 23.17 | 14.14 | 0.07 | 0.3% | 0.11 | 0.8% | -32.46 | 8.46 |
| 3500 | 24.14 | 24.06 | 14.14 | 0.06 | 0.2% | 0.10 | 0.7% | -31.86 | 8.67 |
| 9000 | 24.41 | 24.41 | 14.14 | 0.06 | 0.3% | 0.14 | 1.0% | -31.59 | 8.81 |

| Workload Norms (minutes) | SPT AB (8 Hours-40% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1385 | 22.68 | 19.03 | 14.14 | 0.11 | 0.5% | 0.31 | 2.2% | -33.32 | 10.16 |
| 1440 | 22.56 | 19.42 | 14.14 | 0.10 | 0.4% | 0.30 | 2.1% | -33.44 | 9.75 |
| 1531 | 22.48 | 19.92 | 14.15 | 0.08 | 0.4% | 0.29 | 2.0% | -33.52 | 9.39 |
| 1650 | 22.74 | 20.66 | 14.15 | 0.10 | 0.4% | 0.31 | 2.2% | -33.26 | 9.11 |
| 1776 | 22.88 | 21.27 | 14.14 | 0.09 | 0.4% | 0.29 | 2.0% | -33.12 | 8.89 |
| 2045 | 23.34 | 22.34 | 14.14 | 0.11 | 0.5% | 0.24 | 1.7% | -32.66 | 8.65 |
| 2509 | 23.96 | 23.53 | 14.14 | 0.09 | 0.4% | 0.13 | 0.9% | -32.04 | 8.65 |
| 3220 | 24.47 | 24.32 | 14.14 | 0.06 | 0.2% | 0.07 | 0.5% | -31.53 | 8.78 |
| 9000 | 24.88 | 24.88 | 14.14 | 0.06 | 0.2% | 0.14 | 1.0% | -31.12 | 8.98 |

| Workload Norms (minutes) | SPT AB (8 Hours-80% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |
| 1510 | 25.16 | 21.16 | 14.15 | 0.25 | 1.0% | 0.58 | 4.1% | -30.84 | 11.01 |
| 1630 | 24.89 | 21.85 | 14.15 | 0.20 | 0.8% | 0.49 | 3.5% | -31.11 | 10.36 |
| 1753 | 25.08 | 22.57 | 14.15 | 0.22 | 0.9% | 0.50 | 3.5% | -30.92 | 10.12 |
| 1870 | 25.17 | 23.18 | 14.15 | 0.21 | 0.8% | 0.46 | 3.2% | -30.83 | 9.92 |
| 2000 | 25.25 | 23.66 | 14.15 | 0.20 | 0.8% | 0.39 | 2.8% | -30.75 | 9.67 |
| 2352 | 25.79 | 24.93 | 14.15 | 0.18 | 0.7% | 0.26 | 1.8% | -30.21 | 9.56 |
| 2670 | 26.15 | 25.63 | 14.14 | 0.16 | 0.6% | 0.19 | 1.3% | -29.85 | 9.56 |
| 3200 | 26.56 | 26.31 | 14.14 | 0.12 | 0.4% | 0.13 | 0.9% | -29.44 | 9.67 |
| 9000 | 27.15 | 27.15 | 14.14 | 0.13 | 0.5% | 0.28 | 2.0% | -28.85 | 9.90 |

| Workload Norms (minutes) | SPT AL (8 Hours-20% distortion) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Average Gross Throughput time (in hours) | Average Shop Floor time (in hours) | Average Output (in pieces) | Average Tardiness (in hours) | % Average Tardiness | Average No. of Tardy Orders (in pieces) | % Average No. of Tardy Orders | Average Lateness (in hours) | SD of Lateness |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1490 | 34.41 | 18.50 | 14.06 | 1.73 | 5.0% | 1.64 | 11.7% | -21.59 | 12.93 |
| 1540 | 32.03 | 18.93 | 14.08 | 1.25 | 3.9% | 1.18 | 8.4% | -23.97 | 12.33 |
| 1615 | 29.32 | 19.37 | 14.10 | 0.78 | 2.7% | 0.84 | 6.0% | -26.68 | 11.53 |
| 1740 | 27.29 | 20.17 | 14.11 | 0.44 | 1.6% | 0.48 | 3.4% | -28.71 | 10.53 |
| 1892 | 25.60 | 20.89 | 14.13 | 0.20 | 0.8% | 0.26 | 1.8% | -30.40 | 9.73 |
| 2160 | 24.56 | 21.88 | 14.14 | 0.09 | 0.4% | 0.16 | 1.1% | -31.44 | 9.15 |
| 2677 | 24.22 | 23.11 | 14.14 | 0.05 | 0.2% | 0.11 | 0.8% | -31.78 | 8.78 |
| 4000 | 24.33 | 24.11 | 14.14 | 0.06 | 0.2% | 0.11 | 0.8% | -31.67 | 8.80 |
| 9000 | 24.41 | 24.41 | 14.14 | 0.06 | 0.3% | 0.14 | 1.0% | -31.59 | 8.81 |

| **Workload Norms (minutes)** | **SPT AL (8 Hours-40% distortion)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Average Gross Throughput time (in hours)** | **Average Shop Floor time (in hours)** | **Average Output (in pieces)** | **Average Tardiness (in hours)** | **% Average Tardiness** | **Average No. of Tardy Orders (in pieces)** | **% Average No. of Tardy Orders** | **Average Lateness (in hours)** | **SD of Lateness** |
| 1540 | 33.98 | 19.16 | 14.08 | 1.62 | 4.8% | 1.62 | 11.5% | -22.02 | 12.57 |
| 1590 | 32.21 | 19.48 | 14.09 | 1.37 | 4.3% | 1.22 | 8.7% | -23.79 | 12.50 |
| 1665 | 30.33 | 20.01 | 14.10 | 0.90 | 3.0% | 0.96 | 6.8% | -25.67 | 11.83 |
| 1800 | 27.62 | 20.70 | 14.12 | 0.41 | 1.5% | 0.54 | 3.8% | -28.38 | 10.63 |
| 1909 | 26.33 | 21.25 | 14.13 | 0.24 | 0.9% | 0.32 | 2.3% | -29.67 | 9.97 |
| 2175 | 25.15 | 22.33 | 14.13 | 0.10 | 0.4% | 0.18 | 1.3% | -30.85 | 9.39 |
| 2665 | 24.69 | 23.43 | 14.14 | 0.05 | 0.2% | 0.11 | 0.8% | -31.31 | 9.00 |
| 3500 | 24.78 | 24.32 | 14.14 | 0.05 | 0.2% | 0.12 | 0.9% | -31.22 | 9.02 |
| 9000 | 24.88 | 24.88 | 14.14 | 0.06 | 0.2% | 0.14 | 1.0% | -31.12 | 8.98 |

| **Workload Norms (minutes)** | **SPT AL (8 Hours-80% distortion)** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Average Gross Throughput time (in hours)** | **Average Shop Floor time (in hours)** | **Average Output (in pieces)** | **Average Tardiness (in hours)** | **% Average Tardiness** | **Average No. of Tardy Orders (in pieces)** | **% Average No. of Tardy Orders** | **Average Lateness (in hours)** | **SD of Lateness** |
| 1705 | 37.32 | 21.28 | 14.10 | 2.60 | 7.0% | 2.15 | 15.2% | -18.68 | 13.99 |
| 1820 | 33.09 | 21.89 | 14.11 | 1.51 | 4.6% | 1.40 | 9.9% | -22.91 | 12.85 |
| 1927 | 30.92 | 22.53 | 14.13 | 0.90 | 2.9% | 1.04 | 7.4% | -25.08 | 12.03 |
| 2060 | 29.27 | 23.19 | 14.14 | 0.50 | 1.7% | 0.72 | 5.1% | -26.73 | 11.40 |
| 2190 | 28.21 | 23.74 | 14.14 | 0.22 | 0.8% | 0.39 | 2.7% | -27.79 | 10.73 |
| 2553 | 27.16 | 24.91 | 14.14 | 0.13 | 0.5% | 0.27 | 1.9% | -28.84 | 10.15 |
| 2880 | 27.05 | 25.65 | 14.14 | 0.11 | 0.4% | 0.24 | 1.7% | -28.95 | 9.94 |
| 3500 | 26.93 | 26.23 | 14.14 | 0.10 | 0.4% | 0.23 | 1.6% | -29.07 | 9.82 |
| 9000 | 27.15 | 27.15 | 14.14 | 0.13 | 0.5% | 0.28 | 2.0% | -28.85 | 9.90 |