Bottleneck shifting in production lines: Impact of variability, new detection method and control strategies

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BOTTLENECK SHIFTING IN PRODUCTION LINES
IMPACT OF VARIABILITY, NEW DETECTION METHOD AND CONTROL STRATEGIES

A Thesis by

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Submitted to the Department of Industrial and Manufacturing Engineering
and the faculty of the Graduate School of
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The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science with a major in Industrial Engineering.

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ABSTRACT

One of the main causes for degrade in the performance of a production line is bottleneck machine. To improve system performance, bottleneck (BN) is one of the critical factors that need to be addressed. Most of the researchers focus on long term bottlenecks in the system. From other researches, it is evident that detection and elimination of short term BNs is more efficient than long term BNs. Till now, there is no generic method to identify bottlenecks in production lines with and without buffer. Proposed inactive duration method for identification of BNs detects both short term and long term bottlenecks.

In production lines, bottlenecks can be classified into buffer bottlenecks and machine bottlenecks. Machine BNs are mainly due to variability in the system. There is always strong relationship between variability and machine BN. Due to dynamic nature of manufacturing lines, there will be frequent shifting of BN between different machines. In this research, BN characteristics are proposed to analyze the critical nature of BN and BN shifting. In production lines with buffer, buffer bottlenecks are eliminated by placing optimal buffer size before each machine. This thesis presents a two step heuristic procedure for optimal buffer size determination. Case studies were conducted for both production lines with optimal buffer and without buffer. Results from case studies proved that increase in variability increases BN time and BN shifting between different machines.

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CHAPTER 1

INTRODUCTION

1.1 Problem Background

Production line is a flow line manufacturing system, in which the workplace is divided into number of productive units called workstations arranged in a serial manner (Boysen, Fliedner & Scholl, 2007). Each product undergoes sequential value added activities at each workstation in a process sequence. Thus, raw material is converted into final product after a several number of value added operations at each workstation. Production line can be viewed as mass production of standard products and low volume manufacturing of made to order products. The production rate is a major factor which determines the efficiency of the production system. Often, reduction in production rate is significant. It is quite common to have performance at the level of 60% to 70% of system capacity, for machining operations in a large volume production system. This is often due to machines which have high utilization, which in turn blocks or impedes other machines. The machine which impedes the system performance is called as a bottleneck machine (Kuo, Lim, & Meerkov, 1996). Therefore, an important problem in improving the system performance is bottleneck identification and scheduling strategies that reduce the impact of the bottleneck machine.

1.2 Definition of Bottlenecks

Bottleneck machine is a machine which impedes the system output and throughput (Lawrence, & Buss, 1995). There are different definitions for bottlenecks in literature. Some of these definitions are listed below.

- Longest queue length in a system (Lawrence, & Buss, 1995)

- Lowest isolated production rate in a system (Kuo, Lim, & Meerkov, 1996)
- Upstream buffer with high work-in-process (WIP) inventory (Kuo, Lim, & Meerkov, 1996)
- High ratio of sensitivity (Kuo, Lim, & Meerkov, 1996). Sensitivity ratio is defined as ratio of sensitivity of production system"s performance to its isolated production rate (Kuo, Lim, & Meerkov, 1996)
- High utilization in a system (Law & Kelton, 2000)
- Lowest blockage and starvation time of all the machines in a system (Kuo, Lim, & Meerkov, 1996, Li, Chang, & Ni, 2008)

Li, Chang, and Ni, (2008) analyzed these definitions by developing a case study with three machines and two buffers in a serial production line. The case study showed that each definition resulted in the identification of a different machine as a bottleneck. This shows that there is no single universally accepted definition for a bottleneck machine (Lawrence, & Buss, 1995).

1.3 Types of Bottlenecks

Bottlenecks can be classified based on the duration of bottleneck machines in the system. Bottlenecks can be classified as short term bottlenecks and long term bottlenecks. Short term (momentary) bottleneck machines are machines which impede the system performance for the short duration of time. Long term bottleneck machines are machines which impede the system performance for long duration of time. Long term bottleneck is a machine which has high bottleneck time and dominates all other machines in the system throughout the analysis duration. Momentary bottleneck machines are machines which impede the performance of the system at that instant.

Momentary bottlenecks can be classified into sole bottleneck, shifting bottlenecks (Roser, Nakano, and Tanaka, 2002) and multiple bottlenecks. If the bottleneck is a single independent bottleneck machine in the system at any instant, then the machine is called as sole or momentary bottleneck machine. If the bottleneck is shifting between two or more machines in the system at any instant, then those machines are termed as shifting momentary bottleneck machines. If two or more independent bottleneck machines simultaneously exist in the system at any instant, then those machines are termed as multiple bottleneck machines.

1.4 Bottleneck Identification Methods

Just as different bottleneck definitions, there are multiple methods of bottleneck identification such as, machine utilization method (Law, & Kelton, 2000), queue length analysis method (Lawrence & Buss, 1995), and active duration method (Roser, Nakano, & Tanaka, 2002). In the machine utilization method (Law & Kelton, 2000), machine with largest utilization is considered to be the bottleneck machine. This method identifies the bottleneck machine by determining the highest utilized machine by calculating average time that each machine spends as a bottleneck. This method is unsuitable for the detection and analysis of momentary bottlenecks, since the bottleneck is determined after the production run is completed.

Kuo, Lim, and Meerkov (1996) proposed three definitions for bottleneck identification. The first definition states that the machine with lowest isolated production rate in a system is bottleneck. In the second definition, the machine with the highest sensitivity ratio becomes the bottleneck. Both these definitions identify only long term bottlenecks. Hence, momentary bottlenecks cannot be detected using these two definitions. The third definition states that the machine with the highest Work-in-Process (WIP) inventory in its downstream buffer becomes bottleneck. This method becomes ineffective for production lines with constrained buffers or with no buffers in the system.

In the queue length analysis method (Lawrence & Buss, 1995), queue length or waiting time of different machines were used to determine the bottleneck. This method may not be suitable for systems with different queue sizes or the systems with no upstream and downstream buffer (aircraft manufacturing industry). Roser, Nakano and Tanaka (2002) proposed active duration method for identifying bottleneck shifting. The machine with largest uninterrupted active time at that instant is identified as bottleneck machine. They proposed the bottleneck control strategy for production lines with buffer. Based upon the inactivity of the machine, buffer spaces were increased or parts have been supplied for buffers. Therefore, buffer size determination is an important tool to mitigate bottleneck in production lines with buffer.

1.5 Buffer Size Determination

There are many proposed methodologies for solving buffer size determination problems and buffer allocation problem (BAP). Most of the methods are based on throughput maximization methods and Work in Process (WIP) minimization methods. So (1997) determined optimal buffer allocation by minimizing WIP for a buffer space constraint problem in a balanced and unbalanced assembly lines. Powell, and Pyke (1998) found optimal buffer location with minimal WIP in stochastic unbalanced assembly lines. This method does not address optimal buffer size determination.

Gershwin, and Schor (2000) determined buffer space allocation through primal and dual problem based on production rate maximization and buffer space minimization. Jeong, and Kim (2000) determined buffer location and buffer sizes in assembly systems by cost minimization and throughput maximization problem. Papadopoulos, and Vidalis (2001) proposed a heuristic procedure and sectioning algorithm for BAP in unreliable unbalanced production lines. Hillier, and Hillier (2006) proposed cost model based on throughput maximization and buffer space reduction for BAP.

Sabuncuoglu, Erel, and Gocgun (2006) developed throughput maximization heuristic for BAP in serial production lines. They analyzed BAP with single bottleneck lines and two bottleneck lines. This method does not address more number of BN machines, BN shifting and causes for BN machines. Nahas, Ait-Kadi, and Nourelfath (2006) proposed a local search heuristic to maximize throughput for BAP in unreliable lines. Qudeiri, Yamamoto, Ramli, and Jamali (2008) determined buffer capacity and work station capacity in Serial – Parallel Production lines (S-PPL) by genetic algorithm approach. Nahavandi (2009) proposed buffering strategy based on maximizing throughput and minimizing lead time by Critical WIP loops II in unbalanced flow lines.

Cochran, Kokangul, and Khaniyev (2009) proposed a mathematical random walk approach to determine optimal buffer size and initial stock levels. Vergara and Kim (2009) proposed a heuristic to find optimal buffer sizes for serial production line. This method addressed starved machines, but failed to address the blocked machines while allocating buffer spaces. Battini, Persona, and Regattieri (2009) conducted comprehensive research on buffer size determination and classified buffer allocation problem based on different criteria such as topic of the problem (buffer location and buffer size determination), objective of the problem (throughput maximization, WIP inventory minimization, service level maximization, operations cost minimization, idle time minimization), assumptions (reliable lines, unreliable lines, balanced lines, unbalanced lines) and solution methodology of the problem (mathematical model, heuristic procedure, simulation models, artificial intelligent techniques).

Source of bottleneck time include starvation time and blocking time. To find an optimal buffer, these sources should be addressed. Previous researches on buffer size determination do not address all these sources of bottleneck and bottleneck shifting.

1.6 Shifting of Bottlenecks

A bottleneck machine in the system has the largest effect in terms of slowing down the processing of the entire manufacturing system (Roser, Nakano, & Tanaka, 2002). There may be a single dominant bottleneck machine (average bottleneck machine) or two or more bottleneck machines for the entire system (average bottleneck machine) causing more production delays than any other machine in the system. Bottleneck machines are not static but rather shift between different machines (Lawrence, & Buss, 1994, Moss, & Yu, 1999). Thus, in most situations, different machines act as bottlenecks and cause production delays at different instants. The machine which impedes another machine becomes the momentary bottleneck at that instant. In other instance, some other machine may become the bottleneck, thus resulting in the bottleneck shifting between different machines in the production system (Lawrence, & Buss, 1995).

1.7 Impact of Variability on Bottleneck Shifting

The bottleneck shifting may be due to variability in the system and sequence of random events (Roser, Nakano, & Tanaka, 2002). There are many reasons that cause variability (Hopp, & Spearman, 1996) as follows: (a) random outages, (b) difference in operator, machine, material, (c) setup times, (d) operator unavailability, (e) recycle. Due to random variations in the processing times of machines, there may be shifting in the bottlenecks between two or three machines in the system. According to Goldratt and Cox (1992), production disturbances may lead to one or more production bottlenecks in a system. Therefore it is more critical to identify and analyze the impact of variability on bottleneck shifting, to control bottlenecking effect in production lines.

1.8 Goal of Thesis

The objectives of this research are as follows,

- Method for identification of BN and BN shifting
- Measures to capture bottleneck characteristics
- Method for buffer size determination
- Analysis on shifting of bottlenecks with impact of variability in
    - ✓ Production lines with no buffer
    - ✓ Production lines with buffer

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter reviews the literature in the field of bottleneck detection and bottleneck shifting. Section 2.1 discusses about characteristics of production lines. Section 2.2 discusses about relationship between bottlenecks and production lines. Section 2.3 discusses about different types of bottlenecks in manufacturing scenario. Section 2.4 researches on different methods of bottleneck identification as specified in the literature. Section 2.5 discusses about importance of buffer size and different methods of buffer size determination. Section 2.6 discusses about shifting of bottlenecks between different machines. Section 2.7 discusses about impact of variability in bottleneck shifting. Section 2.8 represents the summary of chapter 2.

2.2 Production Lines

Production line is a manufacturing system in which the final product is fabricated from raw materials through different value added activities at each workstation. (Boysen, Fliedner, & Scholl, 2007). It is arranged with a serial network of workstations placed in a process sequence. Production process is divided into number of small undividable units of work called tasks. Each task is assigned to different workstations in a production line. The tasks performed in the workstation may vary from a complex assembly to a simple surface polishing.

There are technical or departmental requirement for the sequence to be followed in an assembly. Production process consists of a network of merging and concurrent flows. Consecutive operation cannot be selected arbitrarily in an assembly. The relationship between each product in a sequence of the assembly is considered with the precedence constraint. The important characteristics of production lines are as follows (1) number of stations is small compared to the number of tasks (2) station times are large (3) number of tasks assigned to a single station is large (3) high variability in task times. High variability is due to (a) parts not available (b) worker experience or learning effect (c) worker not available.

2.3 Bottlenecks in Production Lines

Production rate may be a major factor to affect efficiency of the production system. In a real manufacturing scenario, reduction in production rate is quite common. In large volume manufacturing, performance may be at the level of 60% to 70% of system capacity for machining operations (Chiang, Kuo, & Meerkov, 2001). The machine which impedes the system performance is called as a bottleneck machine (Kuo, Lim, & Meerkov, 1996, Chiang, Kuo, & Meerkov, 2001). Bottleneck machine is a machine which slows down the system output and throughput (Lawrence, & Buss, 1995). The definition of bottleneck is not universally accepted (Lawrence, & Buss, 1995).

There are different definitions for bottlenecks specified in the literature, (a) bottleneck machine is defined as a machine having longest queue length in a system (Lawrence, & Buss, 1995), (b) machine with the lowest isolated production rate in a system will be bottleneck machine (Kuo, Lim, & Meerkov, 1996), (c) machine with highest WIP in its upstream buffer is bottleneck machine (Kuo, Lim, & Meerkov, 1996), (d) machine with lowest blockage and starvation time of all the machines in a system will be the bottleneck machine (Kuo, Lim, & Meerkov, 1996, Li, Chang, & Ni, 2008), (e) "Bottleneck machine is a machine having high ratio of sensitivity, where as sensitivity ratio is defined as ratio of sensitivity of production system"s performance to its isolated production rate" (Kuo, Li, & Meerkov, 1996), (f) machine with high utilization in a system is called bottleneck machine (Law, & Kelton, 2000), (g) Roser, Nakano, and Tanaka (2002) proposed bottleneck machine as machine with highest active duration.

2.4 Types of Bottlenecks

Bottlenecks can be classified based on the duration of bottleneck machines in the system. They are short term bottlenecks and long term bottlenecks. Short term bottleneck machines are the machines which impede the system performance for the short duration of time. Long term bottleneck machines are the machines which impede the system performance for long duration of time. Large term bottleneck is a machine which has high bottleneck time and dominates all other machines in the system throughout the duration of analysis.

Momentary bottlenecks can be classified into sole, shifting bottlenecks (Roser, Nakano, & Tanaka, 2002) and multiple bottlenecks. If the bottleneck is a single independent bottleneck machine in the system at that instant, then the machine is called as sole momentary bottleneck machine. If the bottleneck is shifting between two or more machines in the system at that instant, then those machines are termed as shifting momentary bottleneck machines. If two or more independent bottleneck machines simultaneously exist in the system at that instant, then those machines are termed as multiple bottleneck machines.

2.5 Bottleneck Identification Methods

In the queue length analysis method, queue length or waiting time of different machines were analyzed. The machine which has the highest queue length at that instant becomes the bottleneck machine (Lawrence, & Buss, 1994). This method detects momentary bottlenecks, but not suitable for systems with different batch sizes or systems with no upstream and downstream buffer (aircraft manufacturing industry) in a production line.

Kuo, Lim, and Meerkov (1996) proposed four definitions (definitions (b), (c), (d) & (e)) for identification of bottleneck machines. By first definition (b), machine with the highest isolated production rate become bottleneck machine. This definition does not capture momentary bottleneck detection. In addition, this method does not focus on bottleneck shifting. By second definition (c), machine with high WIP in its upstream buffer become bottleneck machine. This method detects momentary bottlenecks at that instant, but this method is suitable only for production lines with buffer.

By third definition (d), machine with largest sensitivity ratio becomes bottleneck machine. Chang, Ni, Bandyopadhyay, Biller, and Xiao (2007) analyzed this method and this method detects momentary bottlenecks. They proposed four steps to mitigate short term bottleneck machines in the system, (1) increase in mean time before failure (MTBF) to increase station reliability, (2) decrease in mean time to repair (MTTR) to increase maintenance efficiency (3) increase in engineered job per hour (4) increase in the size of upstream and downstream buffer of the bottleneck machine.

Case studies conducted proved that short term bottleneck policy improves production by 11% and in contrast, long term bottleneck policy improves production by 6%. This method proved the importance of short term bottleneck identification and mitigation (Figure 2.1).

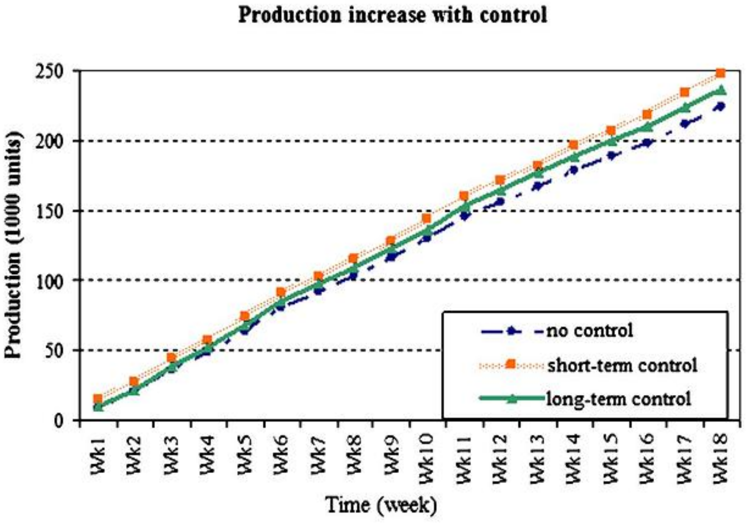


Figure 2.1. Comparison between short term and long term bottlenecks (Chang, Ni, Bandyopadhyay, Biller, & Xiao, 2007)

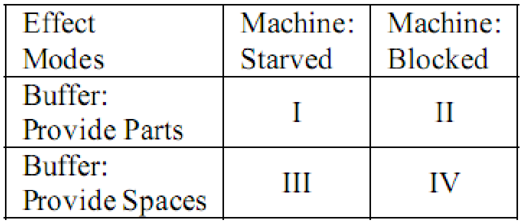
This method focus on production lines without buffer and this method does not help to detect bottlenecks at instant. Since, collection of online data for detection of bottleneck machines may be complicated for real time analysis.

By fourth definition (e), bottleneck machine is a machine which has lowest blockage and starvation time among all machines in the production line (Li, Chang & Ni, 2008). This method does not detect shifting bottlenecks in the system. Law, and Kelton (2000) defined bottleneck machine as the machine with high utilization among all machines in the system. This method does not detect momentary bottlenecks and bottleneck shifting in the system. Since, collection of online data for detection of bottleneck machine was complicated and not useful for real time problem analysis.

Roser, Nakano, and Tanaka (2002) proposed a bottleneck identification method called active duration method. The status of each machine can be classified into active and inactive states. Active state is the state in which the machine is processing a part. Inactive state is the state in which the machine waits for a new part, blocked by successive machine and failure time of the machine. The machine with largest uninterrupted active time at that instant becomes the bottleneck machine. If there are two or machines with high uninterrupted active duration at same point of time, then those machines are called shifting bottlenecks.

Roser, Nakano, and Tanaka (2003) proposed a bottleneck mitigation method for production lines with buffer. Active duration method (Roser, Nakano & Tanaka, 2002) was used to detect bottlenecks. In production lines with buffer, bottleneck can be mitigated either by providing optimal buffer spaces before machine or by providing parts to the buffer as shown in Table 2.1. According to the inactive state of each machine, buffer can be provided with parts or spaces to mitigate bottlenecks and bottleneck shifting. This shows that buffer size determination is the important tool to mitigate bottlenecks in production lines with buffer.

Table 2.1 Bottleneck mitigation approach for production lines with buffer (Roser, Nakano, & Tanaka, 2002)



Effect Modes	Machine: Starved	Machine: Blocked
Buffer: Provide Parts	I	II
Buffer: Provide Spaces	III	IV

2.6 Buffer Size Determination

So (1997) determined optimal buffer allocation by minimizing work in process inventory for a given total number of buffer spaces (buffer space constraint) in a balanced and unbalanced assembly lines. Mathematical formulation was formulated using classical system of finite queues in series. Key insight from the study showed that slowest processes should be allocated in the starting end of assembly line to have optimal tradeoff between average WIP and throughput in an unbalanced assembly line. Powell and Pyke (1998) determined optimal buffer location with minimal work in process inventory. This method considered unbalanced assembly lines with probabilistic processing times. This method does not address optimal buffer size determination.

Gershwin and Schor (2000) proposed buffer space allocation algorithm and analyzed it with primal and dual problem. Primal problem involved with minimization of buffer space with respect to production rate constraint and dual problem involved with maximization of production rate with respect to buffer space constraint. The solution of dual problem was determined by gradient method and by using the dual solution primal problem was solved. Qualitative properties such as continuity, monotonicity, concavity have been discussed. Continuity is referred as the phenomenon of change in system efficiency due to change in buffer capacity. Monotonicity is referred as the phenomenon of increase in production rate as the buffer capacity increases. Concavity is referred as the phenomenon of decrease in production rate increase as the buffer capacity increases.

Jeong and Kim (2000) proposed a solution methodology for determining buffer location machines and calculating buffer sizes in assembly systems. Cost minimization was done to determine buffer size and to have preferred system throughput. Figure 2.2 shows throughput rates for different buffer capacities for a 4 station assembly system.

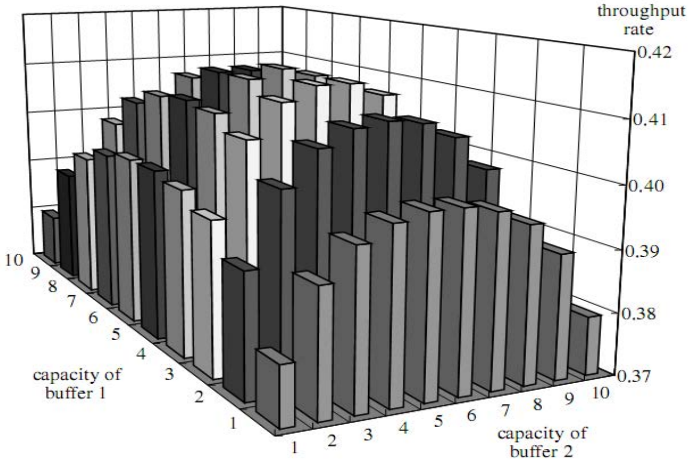


Figure 2.2. Throughput rates for different buffer sizes (Jeong & Kim, 2000)

Papadopoulos and Vidalis (2001) developed a heuristic procedure for buffer allocation problem (BAP) in unreliable unbalanced production lines. The solution of BAP in unreliable unbalanced line was solved using sectioning algorithm and found initial buffer allocation. Initial solution was used to fast convergence of optimal solution for BAP. Hillier and Hillier (2006) developed a cost based model for BAP and workload allocation problem. The model was based on tradeoff between cost per unit throughput and cost per unit buffer space. The buffer allocation storage bowl phenomenon was analyzed that more buffer spaces were allocated close to centre of the production line than closer to its ends.

Sabuncuoglu, Erel and Gocgun (2006) developed a heuristic to maximize throughput by allocating optimal buffers in a serial production lines. They analyzed optimal buffer allocation cases with single bottleneck lines and multiple bottleneck lines. The maximum number of bottleneck machines considered in case studies were about two. But, real case scenario involves with shifting and multiple bottlenecks more than two machines. The different characteristics of bottlenecks and buffers have been analyzed as follows:

1) If bottleneck has high severity, then it draws more buffers towards itself.
2) In case of multiple asymmetric bottlenecks, machine which is nearer to the centre of production line draws more buffers than in ends.

Nahas, Ait-Kadi, and Nourelfath (2006) developed a local search heuristic for BAP in unreliable lines to maximize throughput. This paper mainly focuses on degraded ceiling metaheuristic solution methodology. Qudeiri, Yamamoto, Ramli, and Jamali (2008) developed genetic algorithm approach for determining buffer capacity and work station capacity in Serial – Parallel Production lines (S-PPL). Near optimal solution was found with maximizing production efficiency and by optimizing three factors such as buffer size between two machines, number of machines in the workstation, and type of each machine.

Nahavandi (2009) developed Critical WIP loops II mechanism for increasing throughput and decreasing lead time in unbalanced flow lines. This mechanism determines the right time of releasing the raw material to the line. Buffering strategy used was globally flexible mechanism. This mechanism has no limit over the buffer size of machines in the centre of the line and end machines have limited buffer space. This method was compared with theory of constraints and

CONWIP model. Simulation software Visual Slam II has been used for determining throughput and lead time.

Battini, Persona, and Regattieri (2009) conducted comprehensive literature research on buffer size determination (Table 2.2) and proposed a methodology for buffer size determination.

Table 2.2 BAP classification (Battini, Persona, & Regattieri, 2009)

Criteria	**Classification**
Topic	1) Optimal buffers size 2) Optimal buffers location
Objectives	1) Maximize net present value 2) Minimize total operation costs 3) Minimize number of stations 4) Maximize throughput 5) Minimize average idle times 6) Minimize cycle time 7) Minimize WIP / total buffer spaces 8) Maximize Service level
Assumptions	1) Reliable lines 2) Unreliable lines
Methodology	1) Mathematical model 2) Heuristic procedure 3) Artificial intelligent techniques 4) Simulation models

Cochran, Kokangul, and Khaniyev (2009) determined optimal buffer size and initial stock levels using mathematical random walk approach. This paper does not discuss the relationship between bottlenecks and buffers. This method considered stochastic processing times with breakdown and repair times. Vergara and Kim (2009) proposed a new methodology to find optimal buffer sizes for serial production line by considering starving machines. This method proved to be better than genetic algorithm approach. This method failed to address the blocked machines while allocating buffer spaces.

The literature review for BAP has been classified based on different criteria such as topic, objective, assumptions and methodology. The proposed methodology analyzes the relationship between availability of machine and buffer size.

Previous research work on buffer size determination does not address all causes for bottleneck machines (blocking and starving) and shifting of bottleneck from one machine to another in production line. Due to high variability in processing times, shifting of bottlenecks may be a common phenomenon. Therefore, it is necessary to include starvation, blockage and bottleneck shifting while determining buffer size.

2.7 Shifting of Bottlenecks

A bottleneck machine in the system has largest effect to slow down the processing of the entire system (Roser, Nakano & Tanaka, 2002). There may be a single bottleneck machine for the entire system throughout the cycle, causing production delays than any other machine in the system. But in reality, different machines will cause production delays at different instants. The machine which impedes the system performance at that instant becomes momentary bottleneck at that instant. After some time period, another machine may impede the system performance, thus the bottleneck shifted from that former machine to latter. This is called shifting of bottlenecks between different machines in the production system (Lawrence & Buss, 1994).

Roser, Nakano, and Tanaka (2002) compared bottleneck analysis by active duration method and queue length analysis method. By active duration method shifting bottleneck period have been analyzed unlike queue length method. Although queue length method focused momentary bottleneck detection, it fails to address on shifting bottleneck period.

Bottleneck machines are not static but shift between different machines (Lawrence and Buss 1994, Moss and Yu 1999). Shifting of bottlenecks may occur due to two conditions (Roser, Nakano & Tanaka, 2002), they are (a) if overlapping of longest active periods (bottleneck periods) of two machines, then shifting of bottlenecks occur between those two machines during the overlapping period, (b) if two or more machines have same longest uninterrupted active duration at that instant, then there may be shifting of bottlenecks between those machines at that instant (multiple bottlenecks).

2.8 Impact of Variability in Bottleneck Shifting

Chang, Ni, Bandyopadhyay, Biller and Xiao explained that bottleneck is one of the reasons causing production variability and fluctuations. Variability is the vital characteristic of any process performance. Variability of the system can be classified into three types such as low, medium and high variability. Hopp & Spearman, (1996) defined levels of variability using the coefficient of variation (C_v) of the system.

There are many reasons that affect variability (Hopp et al. 1996), as follows: (a) random outages, (b) difference in operator, machine, material, (c) setup times, (d) operator unavailability, (e) recycle. Production bottlenecks in a system may be due to production disturbances (Goldratt, 1984). Therefore, it is more critical to identify and analyze the impact of variability on bottleneck shifting.

2.9 Research motivation

Research works on this topic is not extensive. Moreover, most of the researches focus on average or dominant bottleneck machines in the system. Bottleneck shifting and momentary bottleneck identifications were considered by less number of researchers. Only very few researches have proposed a generic bottleneck identification method for both production lines with buffer and without buffer. Besides this, previous researches fail to address the effect of variability on momentary bottlenecks and bottleneck shifting between different machines.

Hence, this thesis has objectives as listed below.

- Method for identification of BN and BN shifting
- Measures to capture bottleneck characteristics
- Method for buffer size determination
- Analysis on shifting of bottlenecks with impact of variability in
  - ✓ Production lines with no buffer
  - ✓ Production lines with buffer

CHAPTER 3

BOTTLENECK METHODOLOGY FOR NO BUFFER CASES

3.1 Introduction

A bottleneck machine in the system slows down the processing of the complete production system (Roser, Nakano, & Tanaka, 2002) and impedes the system performance (Kuo, Lim, & Meerkov, 1996). One method of improving the system performance is to identify bottlenecks and mitigate its impact. This chapter describes the proposed inactive duration method for bottleneck detection and compares it with the active duration method for bottleneck detection proposed by Roser, Nakano, and Tanaka (2002). New measures to show bottleneck characteristics such as bottleneck shifting frequency, bottleneck time ratio, bottleneck ratio and bottleneck severity ratio are proposed. The bottleneck characteristics and the effect of variability on shifting of bottlenecks in production lines without buffer are detailed using case studies.

3.2 Bottleneck Detection

There are various types of bottleneck methods mentioned in the literature such as machine utilization method (Law, & Kelton 2000), queue length analysis method (Lawrence, & Buss, 1995) and sensitivity ratio method (Kuo, Lim, & Meerkov, 1996). These methods do not focus on the detection of momentary bottlenecks and shifting of bottlenecks between different machines. Some of the methods focus on the production lines with unlimited buffer (queue length analysis method). The first method for detecting momentary bottlenecks and bottleneck shifting in production lines was the active duration method (Roser, Nakano, & Tanaka, 2002).

3.2.1 Active Duration Method

The active duration method is based on tracking the duration of active machines and identifying the machine which has the longest active duration without interruption as bottleneck machine (Roser, Nakano, & Tanaka, 2002). To detect the momentary bottleneck, the status of each machine is identified. The status of each machine can be classified into active and inactive states. Active state is the state in which the machine is processing a part and inactive state includes waiting time, blocking time and failure time of the machine. The machine with longest active duration at any instant is considered as the momentary bottleneck at that instant. The machine with highest average bottleneck time among all bottleneck machines becomes the average bottleneck machine.

The flow chart for the active duration is shown in Figure 3.1. This method of identification assumes that any machine that is active for longest time will be classified as a bottleneck machine, even if that machine is not lowering the system performance or impeding other machines in the system. This method of identification is in contrast to bottleneck definition that a bottleneck machine is one that slows down the processing of the complete production system (Roser, Nakano, & Tanaka, 2002) or impedes the system performance (Kuo, Lim, & Meerkov, 1996).

Bottleneck can be classified broadly into momentary BN and long term bottleneck and momentary bottlenecks can be further classified into sole, shifting bottlenecks and multiple bottlenecks (Roser, Nakano, & Tanaka, 2002, termed it as shifting BNs). If the bottleneck is a single independent bottleneck machine in the system at that instance, then the machine is called as sole momentary bottleneck machine. If the bottleneck is shifting between two or more machines in the system at that instance, then those machines are termed as shifting momentary bottleneck machines. If two or more independent bottleneck machines simultaneously exist in the system at that instance, then those machines are termed as multiple bottleneck machines.

According to Roser, Nakano, and Tanaka (2002), there are two conditions for shifting of bottlenecks; (a) if there is an overlapping of longest active periods (bottleneck periods) of two machines, then there may be shifting of bottlenecks between those two machines during the overlapping period, (b) if two or more machines have same longest uninterrupted active duration at that instant, then there may be shifting of bottlenecks between those machines. According to Roser, Multiple BN machines are considered as shifting BN machines.

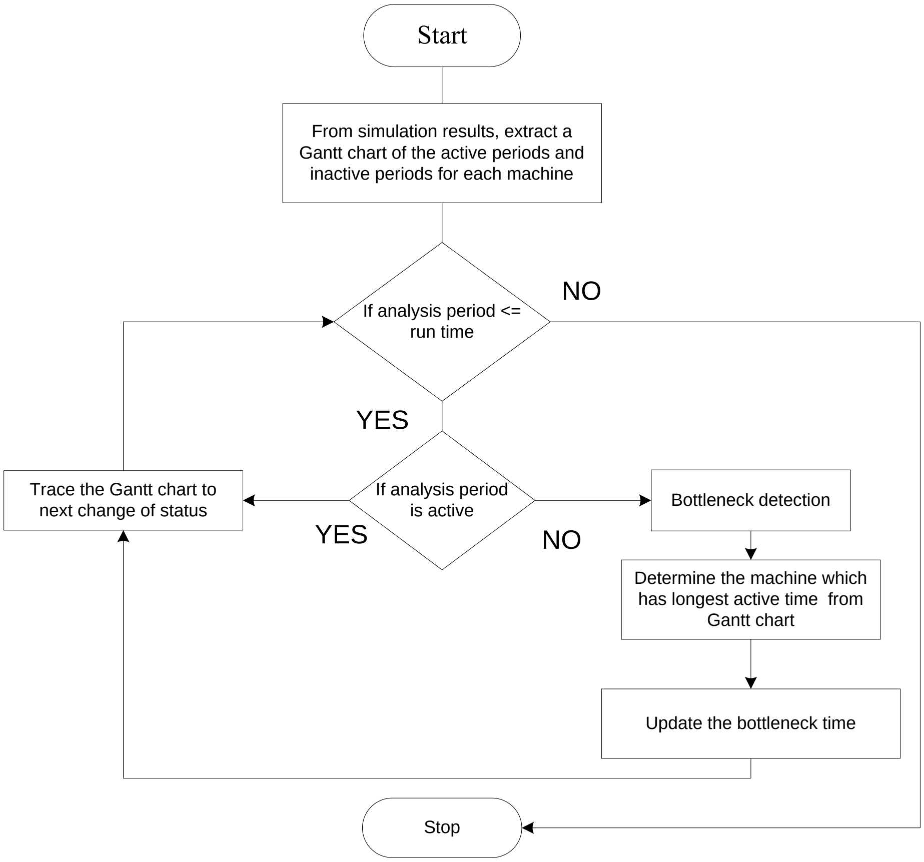


Figure 3.1. Flowchart of active duration method

Consider a flow shop line with three machines in series as shown in Figure 3.2. Machines A, B and C has processing times of 20 minutes, 10 minutes and 6 minutes respectively (Table

3.1). A processing-time chart for the processing of parts on machines with active and inactive states is shown in Figure 3.3.

Since Machine A and Machine C have same longest active duration for the first six minutes, both Machine A and Machine C become shifting bottlenecks for first six minutes. Then Machine C was interrupted for the next 14 minutes. Therefore, Machine A becomes the sole bottleneck machine for the next 54 minutes, because of its longest active duration among all other machines in the system.

Table 3.1. Processing Time of Each Machine

Machine	**Processing Time**
Machine A	20
Machine B	10
Machine C	6

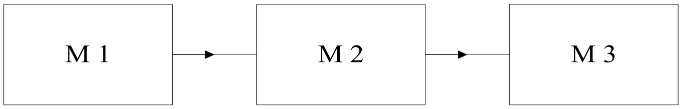


Figure 3.2. Simple flow shop line model

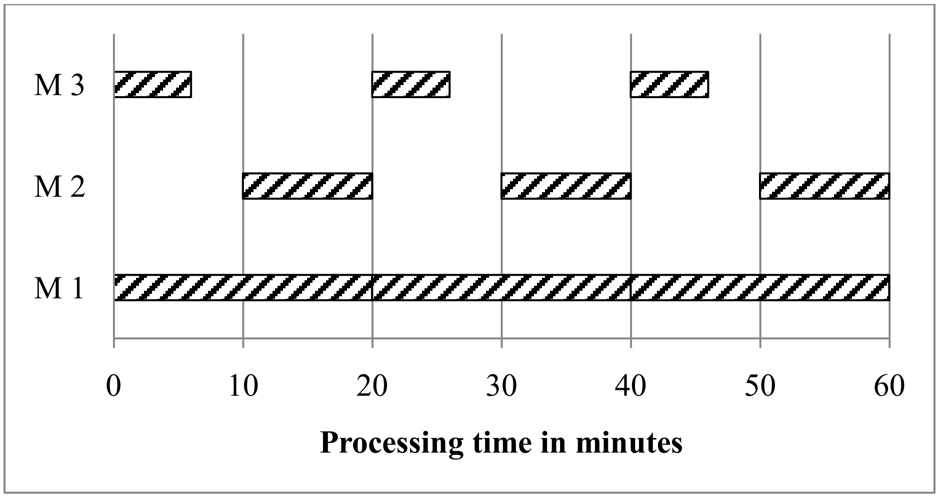


Figure 3.3. Processing-time chart with active and inactive states

In summary, Machine A was bottleneck machine for 60 minutes and Machine C was bottleneck for 6 minutes. Machine A was sole bottleneck for 54 minutes. Machine C and Machine A were shifting bottlenecks for 6 minutes. The bottleneck time for each machine was plotted in a bottleneck chart as shown in Figure 3.4.

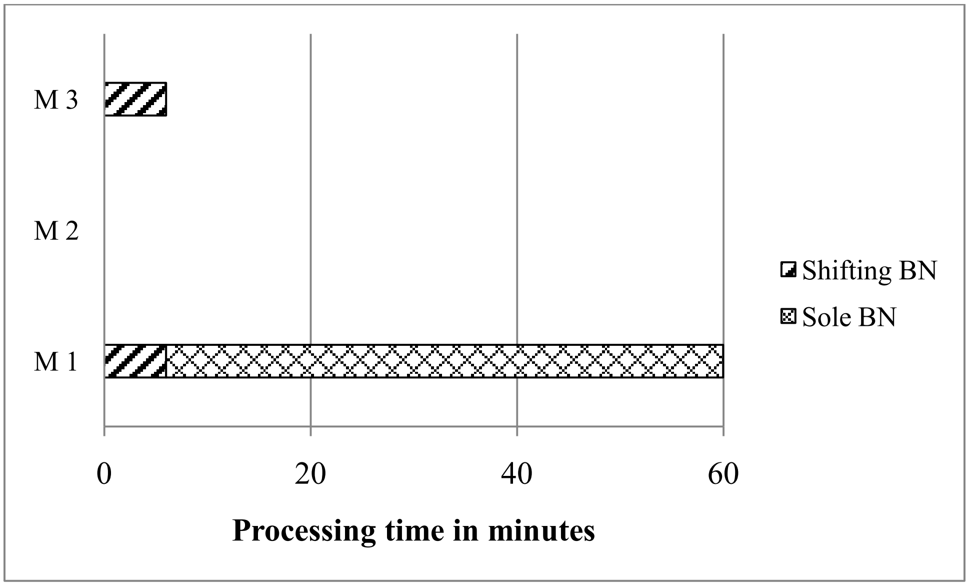


Figure 3.4. Bottleneck time chart by active duration method

3.2.2 Inactive Duration Method

In the proposed inactive duration method, bottleneck machine is defined as the machine which makes other machines inactive at any instant. Thus, a bottleneck machine must lead to blocking or starving in other machines. So, bottlenecks can be detected by tracking the inactive states of each machine. In the inactive duration method, primary step is to develop processing time chart using active and inactive times of each machine. Tracking of inactive states can be done in both directions. Machine which is upstream to the bottleneck machine will be blocked. Similarly, machine which is downstream to bottleneck machine will be starving for a new product. Therefore, the bottleneck machine can cause machines to be idle in both downstream and upstream directions. Therefore, it is important to track the inactive states in both upstream and downstream to track starving and blocking machines.

The results from simulation are used to determine the inactive in the manufacturing systems. Each machine‟s inactive states are tracked. According to nature of inactive state of each machine, bottleneck machine for each inactive state is determined. The momentary bottleneck machines are found by tracking the inactive machines at that instant. Finally, bottleneck time of all machines is determined individually and bottleneck chart is developed from calculation results. The procedure for the inactive duration method is explained in Figure 3.5.

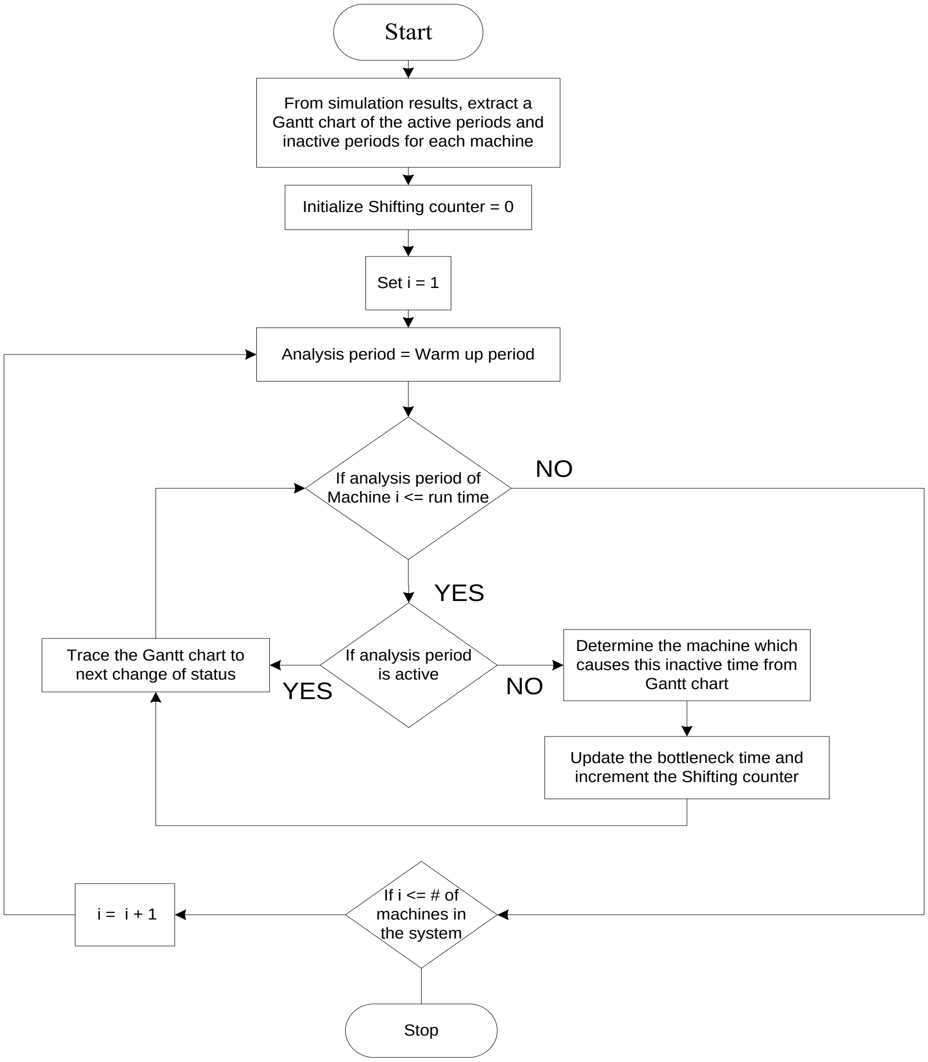


Figure 3.5. Flowchart of inactive duration method

Consider the production line shown in the Figure 3.2. From the processing time chart (Figure 3.3), bottleneck time for different machines was calculated using inactive duration method. For first ten minutes, Machine B was inactive due to Machine A. Therefore, by definition Machine A becomes bottleneck for first ten minutes. Meanwhile, Machine C was inactive from six to ten minutes. The status of its precedence machine (Machine B) was tracked and Machine B was found to be inactive due to Machine A. Therefore, Machine A is the bottleneck for this inactive state. Then, Machine A is considered to be bottleneck machine for six to ten minutes. In summary, for the first ten minutes Machine A was bottleneck machine making both Machine B and Machine C inactive. From ten to twenty minutes, Machine C was inactive due to Machine B. Therefore, Machine B becomes the bottleneck machine for the next ten minutes. This procedure was followed for the next 50 minutes and the results were plotted in the bottleneck time chart (Figure 3.6).

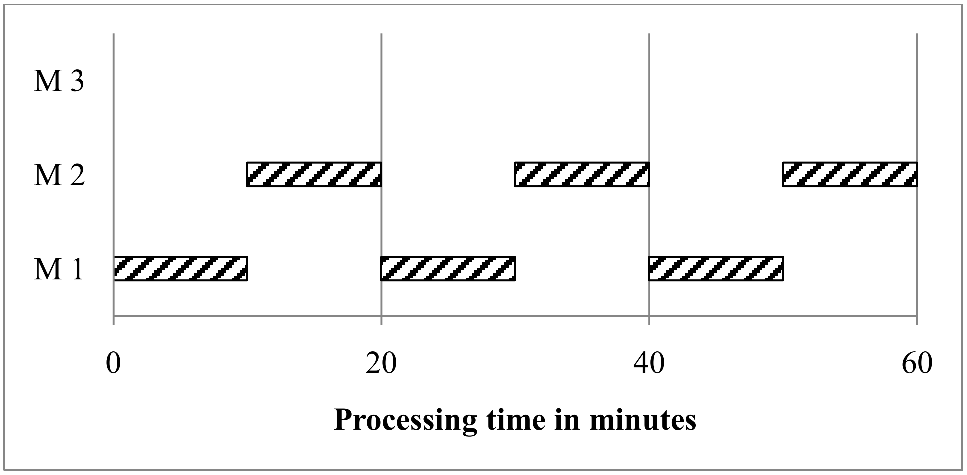


Figure 3.6. Bottleneck time chart by inactive duration method

Bottleneck time

Machine A = 10 + 10+ 10 = 30 minutes

Machine B = 10 + 10+ 10 = 30 minutes

Active duration method does not consider the bottlenecking effect of Machine B on Machine C. Active duration of Machine B is broken at many areas, since Machine A is not feeding products to Machine B. Therefore, longest active duration of Machine B was interrupted at many instants. According to active duration method, Machine B cannot become a bottleneck at any point of time and Machine C is bottleneck machine for six minutes. Machine A and Machine C start at same time and have same longest active duration for the first six minutes. Therefore, in active duration method both Machine A and Machine C become shifting bottlenecks for the first six minutes. Since Machine C is the last machine in the sequence, it can become a bottleneck only if it is blocking Machine B from moving a part to Machine C.

In the inactive duration method, the bottlenecking effect of Machine B on Machine C was clearly indicated. Since Machine C was inactive due to Machine B, Machine B becomes bottleneck machine. Thus, it is felt that the inactive duration method provides a better tracking of momenatry bottlenecks in the system.

3.3 Bottleneck Characteristics

This section details the need for additional measures for identifying the impact of bottleneck shifting and proposes new bottleneck characteristics for capturing the impact of bottleneck shifting. Analysis on bottleneck shiftiness proposed by Lawrence, and Buss (1995) has been carried out with different scenarios, to show shiftiness is not sufficient to capture the characteristics of the manufacturing system and additional measures are needed to provide key insights.

3.3.1 Need for New Measures

Lawrence, and Buss (1995) proposed a bottleneck shiftiness measure (Equation 3.1). In Equation 3.1, β is the bottleneck shiftiness measure, C_v is the coefficient of variation of bottleneck probability for different machines, and *n* is the number of machines in the system. The value of β ranges from zero to one. It is zero for a system with a single bottleneck machine and one for a system where all machines are equally likely to be bottleneck (Lawrence, and buss, 1995).

$$\beta = 1 - \frac{C_v}{\sqrt{n}} \tag{3.1}$$

Consider the different manufacturing scenarios shown in Table 3.2, 3.3, 3.4 and 3.5. In all four cases, there are six machines in the manufacturing system. The time that each machine spends as a bottleneck is given in the tables. In the first case (Table 3.2), machine 1 is a bottleneck for 100 minutes out of a total run time of 200 minutes. Probability of Machine 1 being a bottleneck is 1, because Machine 1 is the dominant bottleneck in the system. Coefficient of variation is defined as the ratio of standard deviation to its mean (Equation 3.2).

$$C_v = \frac{\sigma}{\mu} \tag{3.2}$$

Coefficient of variation for bottleneck probabilities was found to be 2.449. For this case, shiftiness is calculated as 0 using Equation 3.1 (Table 3.2).

Table 3.2. Shiftiness calculation for case 1

Machine	**BN Time**	**BN Probability**
Machine 1	100	1
Machine 2	0	0
Machine 3	0	0
Machine 4	0	0
Machine 5	0	0
Machine 6	0	0
Shiftiness		0
Total BN Time		100
Total Run Time		100

In the second case (Table 3.3), all six machines became a bottleneck machine at some instant of time during the run time of 200 minutes. The total bottleneck time for all machines is 60 minutes. The probability of being a bottleneck machine is determined for each machine. Then the coefficient of variation for bottleneck probabilities is 0.4898 and the shiftiness value is 0.8.

Table 3.3. Shiftiness calculation for case 2

Machine	**BN Time**	**BN Probability**
Machine 1	12	0.2
Machine 2	6	0.1
Machine 3	6	0.1
Machine 4	18	0.3
Machine 5	12	0.2
Machine 6	6	0.1
Shiftiness		0.8
Total BN Time		60
Total Run Time		100

In the third case (Table 3.4), all six machines are bottleneck machines for one minute each during the run time of 200 minutes. The total bottleneck time for the machines is 6 minutes. The probability of being a bottleneck machine is determined for each machine. The coefficient of variation value for bottleneck probabilities is found to be 0 and shiftiness is calculated to be 1.0.

Table 3.4 Shiftiness calculation for case 3

Machine	**BN Time**	**BN Probability**
Machine 1	1	0.1666
Machine 2	1	0.1666
Machine 3	1	0.1666
Machine 4	1	0.1666
Machine 5	1	0.1666
Machine 6	1	0.1666
Shiftiness		1
Total BN Time		6
Total Run Time		100

In the fourth case (Table 3.5), there is no bottleneck in the system during the run time of 200 minutes. The probability of being a bottleneck machine is determined for each machine as zero. Therefore, coefficient of variation for bottleneck probabilities was found to be 0 and shiftiness was calculated to be 1.0.

Table 3.5. Shiftiness calculation for case 4

Machine	**BN Time**	**BN Probability**
Machine 1	0	0
Machine 2	0	0
Machine 3	0	0
Machine 4	0	0
Machine 5	0	0
Machine 6	0	0
Shiftiness		1
Total BN Time		0
Total Run Time		100

In the first case, although there is a bottleneck for more than half the run time, bottleneck shiftiness ratio is zero. In the second case, the bottleneck time was 60 minutes and the shiftiness was 0.8. In the third case, the total bottleneck time is only 6 minutes out of a run time of 200 minutes, the bottleneck shiftiness was 1. In addition, in the fourth case there is no bottleneck in the system throughout the entire run, but shiftiness measure is found to be 1. Although, bottleneck shiftiness measure provided an understanding into the role of each machine in the system, it failed to provide some key insights. For instance, bottleneck shiftiness does not identify the number of times bottleneck shifting happens. The measure also fails to identify the severity of bottleneck problems with respect to the percentage of total bottleneck time. Hence, four new measures are developed to be used along with the shiftiness measure to identify the type of bottleneck problem and the controls that are needed to address the problem.

3.3.2 Proposed Bottleneck Characteristics

The four new measures proposed are: a) Bottleneck time ratio (α), b) Bottleneck ratio (γ), c) Bottleneck shifting frequency (φ) and d) Bottleneck Severity ratio (χ) are detailed below.

3.3.2.1 Bottleneck Time Ratio

The bottleneck time ratio (α) is the ratio of bottleneck time to total time of analysis and is defined in Equation 3.3.

$$\alpha = \frac{\text{Bottleneck Time}}{\text{Total Run Time}} \tag{3.3}$$

3.3.2.2 Bottleneck Ratio

Bottleneck ratio (τ) is defined as the ratio of number of bottleneck machines to total number of machines during the analysis period and is given by Equation 3.4.

$$\tau = \frac{\text{\# of Bottleneck Machines}}{\text{Total \# of Machines}} \tag{3.4}$$

3.3.2.3 Bottleneck Shifting Frequency

Due to random variations in the processing times of machines, there may be shifting in the bottlenecks between machines in the system. The frequency of bottleneck shifts between the machines is captured using Bottleneck Shifting Frequency (φ). Therefore, to study the impact of variability on shifting of bottlenecks, it is necessary to analyze the total number of times bottleneck shifts from one machine to another. The bottleneck shifting frequency is defined as the ratio of number of machines that have been identified as bottleneck to the number of times that a bottleneck shift happens (Equation 3.5).

$$\upsilon = 1 - \frac{\text{Total \# of Bottleneck Machines}}{\text{Total \# of Bottleneck Shifts}} \tag{3.5}$$

3.3.2.4 Bottleneck Severity Ratio

Bottleneck Severity Ratio (χ) is the ratio between the numbers of times that bottleneck occurs in the system to the total number of inactive states. This measure is useful in determining the possibility of bottleneck occurring every time an inactive state occurs. This will help in determining the importance of bottleneck. For example, if the ratio is low, it implies that there are not enough products in the system and the system has excess capacity. If the ratio is high and the shiftiness is 0, it implies that for every occurrence of inactive state, the same machine is acting as the bottleneck.

$$\chi = \frac{\text{\# of Inactive States with Bottleneck}}{\text{Total \# of Inactive States}} \qquad (3.6)$$

3.4 Variability in Bottleneck Shifting

There are several reasons for bottleneck shifting. Shifting may be the result of schedules, failure of machines, delays in material handling etc. One of the objectives of this research is to identify the impact of variability in the processing times on the bottleneck shifting measures. Variability of the system can be classified into three types such as low, medium and high variability. Hopp, & Spearman, (1996) defined levels of variability using the coefficient of variation (C_v) of the system (Table 3.6). There are many reasons that affect variability (Hopp et al., 1996), as follows: (a) random outages, (b) difference in operator, machine, material, (c) setup times, (d) operator unavailability, and (e) rework.

Table 3.6. Types of variability and its C_V value

Variability	**C_v Value**
Low	$C_v < 0.75$
Medium	$0.75 \le C_v < 1.33$
High	$C_v \ge 1.33$

Goldratt (1984) explained that production disturbances may lead to one or more production bottlenecks in a system. Thus, it is critical to identify and analyze the impact of variability on bottleneck shifting.

3.5 Case Study 1 for Impact of Variability on Bottlenecks

Consider a flow shop line with three machines in series as shown in Figure 3.7. This case study consists of three sections (a) processing times with low variability, (b) processing times with medium variability and (c) processing times with high variability. The experimental setup with warm up period, number of calculations and run length were calculated. The processing times for each machine with no variability are tabulated in Table 3.7.

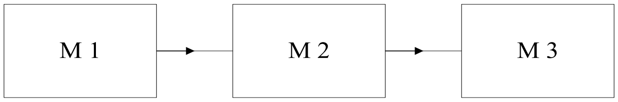


Figure 3.7. Case study 1 - flow shop line model

Table 3.7. Processing times for no variability case

Machine	Processing Time (minutes)
Machine 1	30
Machine 2	30
Machine 3	30

3.5.1 Warm-up Time

Steady state discrete event simulation has two curses, such as initial bias and auto correlations (Whitt, 1991). In this case study, initial bias is addressed by deleting warm up period data and auto correlations by simulating a model with long run. In a steady state simulation, elimination of initial bias is vital (Yucesan et al., 2002). To avoid this initial transient, model was run for warm up period and data of warm up period was deleted. A warm up period for steady state simulation is determined by simulating the model with long run length. Warm up period was calculated using Throughput–Time chart (Figure 3.8). Warm up period starts from the start of simulation run and ends at the point in which throughput becomes stable with less fluctuation (Yucesan et al. 2002). For this case study, the warm up period was determined to be 500 minutes.

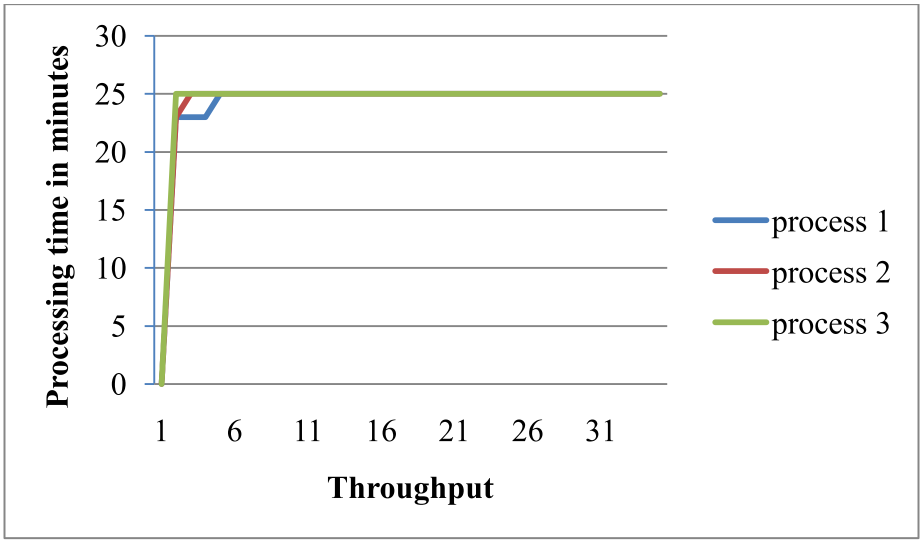


Figure 3.8. Case study 1 - throughput and time chart

3.5.2 Replication and Run Length

Auto correlations between successive processes can be avoided using number of independent replications. Whitt (1991) proposed that one run will be more efficient than number of replications in a steady state simulation. For accuracy purpose, run length is assumed twice the warm up period in this case study. The model has been simulated for a single run for 1000 minutes (twice the warm up period).

3.5.3 High Variability

For the high variability case, the processing time variations follow a triangular distribution. Processing times of each station with mean, mode, maximum and minimum value is mentioned in Table 3.8.There is no buffer space before any of the machines in the system. The processing time chart was developed using the active and inactive states of all machines (Figure 3.9). The bottleneck time of each machine was found by analyzing processing time chart as in Figure 3.9.

Table 3.8. Processing times for high variability case

Machine	Mean	Minimum	Mode	Maximum
Machine 1	30	1.5	36	52.5
Machine 2	30	1.5	36	52.5
Machine 3	30	1.5	36	52.5

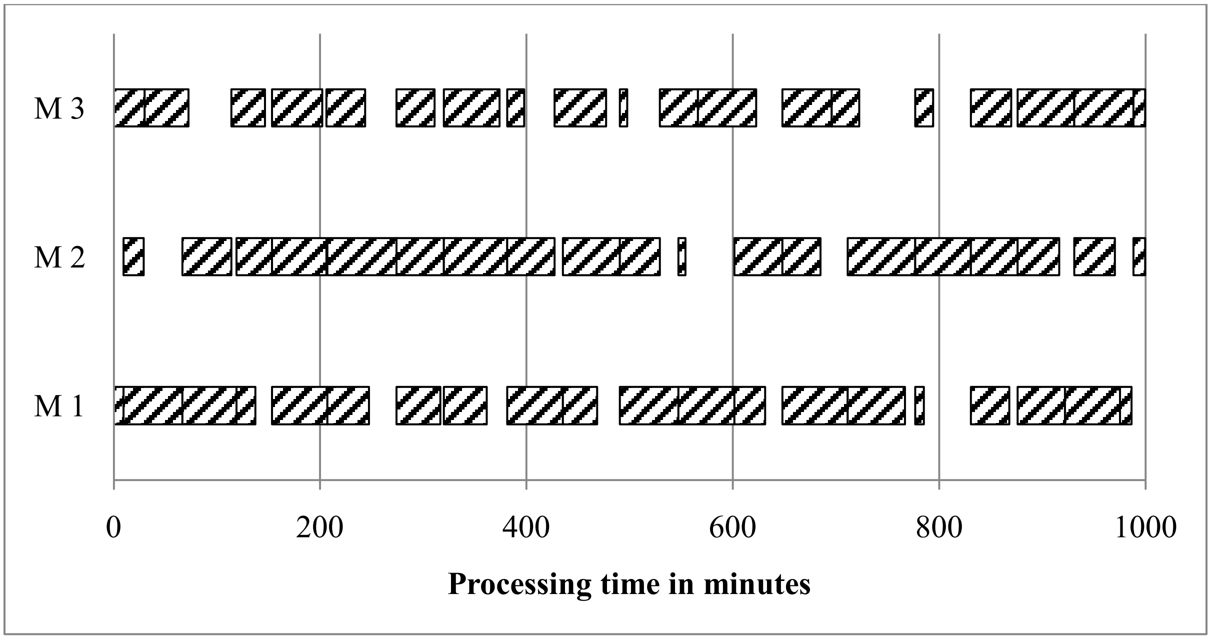


Figure 3.9. Processing time chart for high variability

Based on inactive duration analysis, bottleneck machine and bottleneck time were determined. The number of bottleneck shifts were also found using processing time chart.

Bottleneck Characteristics

The BN characteristics such as shiftiness, BN ratio, BN time ration, BN shifting frequency and BN severity ratio for high variability case were calculated using inactive duration method and described as follows.

Shiftiness Measure

The shiftiness measure for high variability with no buffer case was calculated as 0.944. Bottleneck shifts between two machines in the system throughout the entire run time. C_v was found to be 0.0965 (Table 3.9).

Table 3.9. Shiftiness calculation for high variability

Machine	**Bottleneck Time**	**Bottleneck Probability**
Machine 1	168.4	0.355
Machine 2	140.44	0.296
Machine 3	164.87	0.348
Mean		157.903
SD		15.226
C_v		0.0964
$\sqrt{n}$		1.732
$C_v / \sqrt{n}$		0.056
Shiftiness		0.944

Bottleneck Time Ratio

The bottleneck time was 473.71 minutes and the total run time was 1000 minutes. Therefore, the bottleneck ratio was found to be 47.37%.

$$\alpha = \frac{473.71}{1000}$$

$$\alpha = 0.4737$$

Bottleneck Ratio

Machine 1, machine 2 and machine 3 were bottlenecks in the run time. Therefore, number of bottlenecks in the total run was three.

$$\tau = \frac{3}{3}$$

$$\tau = 1$$

Bottleneck Shifting Frequency

Number of times bottleneck shifted in the total run time was calculated. In this case study, the bottleneck was shifted in between two machines such as Machine 1 and Machine 2. The number of bottleneck shifts was found to be 25 times out of 38 inactive states in the total run time.

$$\upsilon = 1 - \frac{3}{25}$$

$$\upsilon = 0.88$$

Bottleneck Severity Ratio

In this case, total number of inactive states in the total run was about 38. Each inactive state lead to a bottleneck machine and therefore χ value was found to be 1. This proves that market is not a constraint for any of the inactive state.

$\chi = 1$

Bottleneck characteristics for high variability case with no buffer were calculated and listed in Table 3.10.

Table 3.10. Bottleneck characteristics for high variability

RESULTS					
# of Machines	**# of BN Machines**	**Run Time (minutes)**	**BN Time (minutes)**	**# of Inactive Durations**	**# of BN Shifts**
3	3	1000	473.71	38	25

Bottleneck Characteristics				
β **Shiftiness**	**α** **BN time ratio**	**τ** **BN ratio**	**φ** **BN Shifting frequency**	**χ** **BN severity ratio**
0.944	0.474	1	0.88	1

3.5.4 Medium Variability

For the medium variability case, the processing times of each station with mean, mode, maximum and minimum value is provided in Table 3.11.

Table 3.11. Processing times of each machine in medium variability

Machine	Mean	Minimum	Mode	Maximum
Machine 1	30	12	32.4	45.6
Machine 2	30	12	32.4	45.6
Machine 3	30	12	32.4	45.6

The processing time chart was developed using the active and inactive states of all machines (Figure 3.10).

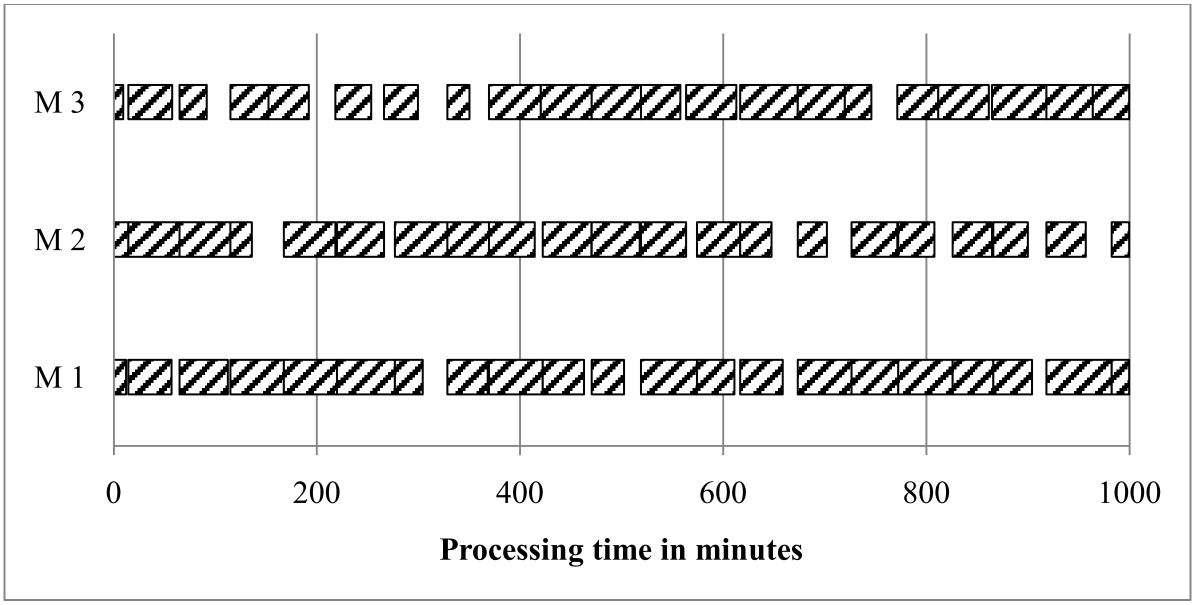


Figure 3.10. Processing time chart for medium variability

The bottleneck time of each machine was found by analyzing processing time chart. Based on inactive duration analysis, bottleneck machine and bottleneck time were determined. The number of bottleneck shifts was also found using processing time chart.

Bottleneck characteristics were determined and listed in Table 3.12.

Table 3.12. Bottleneck characteristics for medium variability

RESULTS					
# of Machines	**# of BN Machines**	**Run Time (minutes)**	**BN Time (minutes)**	**# of Inactive Durations**	**# of BN Shifts**
3	3	1000	404.98	34	19

Bottleneck Characteristics				
β Shiftiness	**α BN time ratio**	**τ BN ratio**	**φ BN Shifting frequency**	**X BN severity ratio**
0.864	0.404	1	0.842	1

3.5.5 Low Variability

For low variability case, processing times of each station with mean, mode, maximum and minimum value is mentioned in Table 3.13. The processing time chart is shown in Figure 3.11. The bottleneck time of each machine was found by analysing processing time chart. Based on inactive duration analysis, bottleneck machine and bottleneck time were determined. The number of bottleneck shifts were also found using processing time chart. Bottleneck characteristics were determined and listed in Table 3.14.

Table 3.13. Processing times of low variability case

Machine	Mean	Minimum	Mode	Maximum
Machine 1	30	27	28.2	34.8
Machine 2	30	27	28.2	34.8
Machine 3	30	27	28.2	34.8

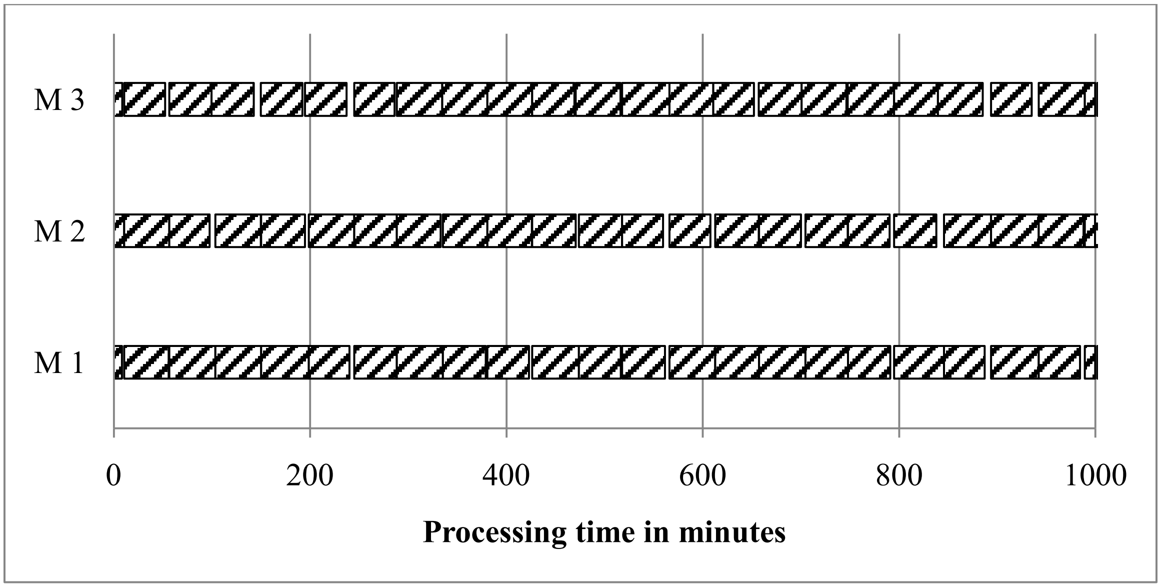


Figure 3.11. Processing time chart for low variability

Table 3.14. Bottleneck characteristics for low variability

RESULTS					
# of Machines	# of BN Machines	Run Time (minutes)	BN Time (minutes)	# of Inactive Durations	# of BN Shifts
3	3	1000	111.78	33	14

Bottleneck Characteristics				
β Shiftiness	α BN time ratio	τ BN ratio	φ BN Shifting frequency	X BN severity ratio
0.696	0.112	1	0.786	1

3.5.6 Results of Case Study 1

From the case studies conducted, impact of variability on bottleneck shifting is indicated through the bottleneck characteristics and is shown in Table 3.15 and Figure 3.12. Increase in variability increases BN time, shiftiness ratio and BN shifting frequency.

Table 3.15. Bottleneck characteristic results for case study 1

Results	Low variability	Medium variability	High variability
# of Machines	3	3	3
# of BN Machines	3	3	3
Run Time	1000	1000	1000
BN Time	111.78	404.98	473.71
# of Inactive Durations	33	34	38
# of BN Shifts	14	19	25
Shiftiness, β	0.696	0.864	0.944
BN time ratio, α	0.112	0.404	0.474
BN ratio, τ	1	1	1
BN shifting frequency, φ	0.786	0.842	0.88
BN severity ratio, χ	1	1	1

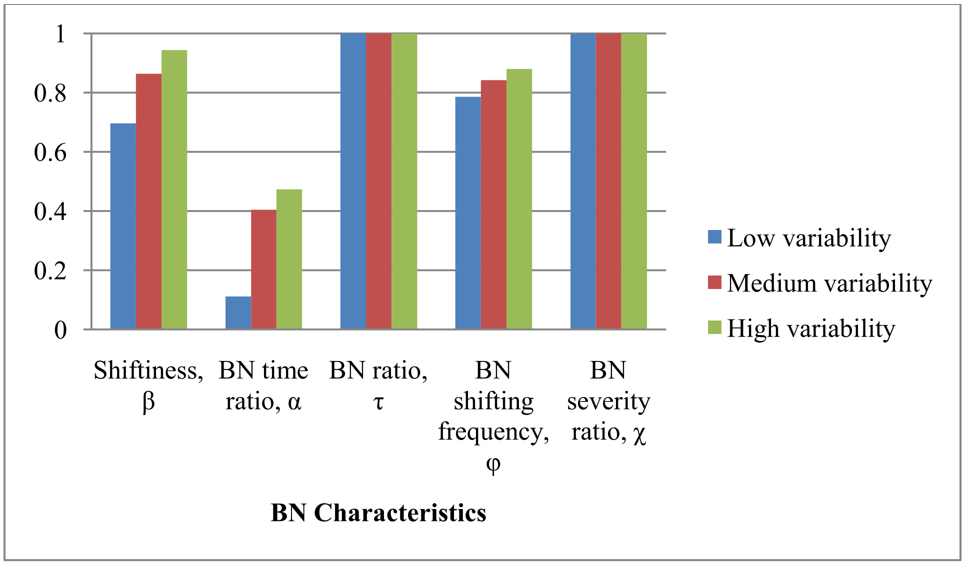


Figure 3.12. Bottleneck characteristics comparison chart for case study 1

BN characteristics increase with increase in levels of variability. Increase in BN characteristics clearly indicate the increase in BN time and BN shifting between different machines.

3.6 Additional Case Studies

The developed BN identification methodology is analyzed using 7 additional case studies. Each case study is tested with three levels of variability. BN characteristics are calculated for all the above mentioned models. All these case studies assume no buffer before each machine.

3.6.1 Case Study 2

Consider a production line as shown in Figure 3.13. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 3.16. BN characteristics of three levels of variability are compared and plotted in Figure 3.14. Model with high level of variability fall under scenario 3 (most critical scenario) and models with other two levels of variability scenarios are in non critical region. Other than shiftiness, all other bottleneck characteristics found to be increasing with increase in level of variability (Figure 3.14).

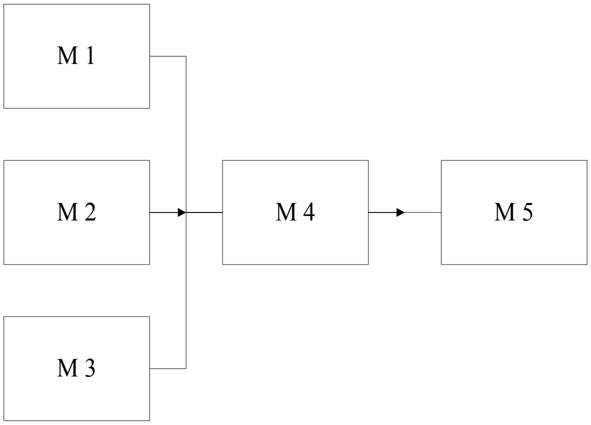


Figure 3.13. Model for case study 2 with no buffer

Table 3.16. Bottleneck characteristic results for case study 2

RESULTS	Low Variability	Medium Variability	High Variability
# of Machines	5	5	5
# of BN Machines	5	5	5
Run Time	1000	1000	1000
BN Time	121.64	298.64	505.64
# of Inactive Durations	10	15	25
# of BN Shifts	11	12	15
Shiftiness, β	0.85773	0.8907	0.8764
BN time ratio, α	0.12164	0.29864	0.50564
BN ratio, τ	1	1	1
BN shifting frequency, φ	0.54545	0.54545	0.66667
BN severity ratio, χ	1	1	1

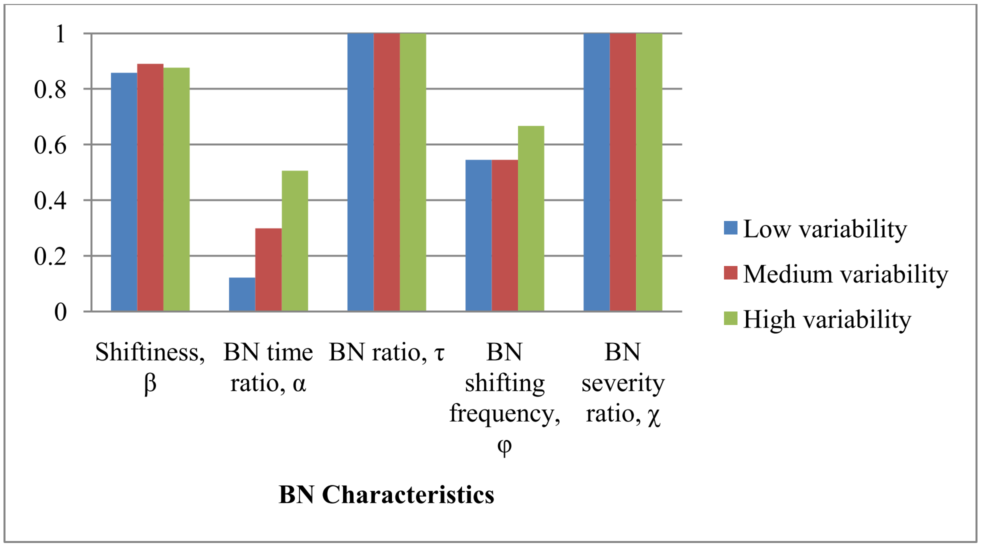


Figure 3.14. Bottleneck characteristics comparison chart for case study 2

3.6.2 Case Study 3

Consider a production line as shown in Figure 3.15. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 3.17. BN characteristics of three levels of variability are compared and plotted in Figure 3.16.

All three levels of variability scenarios are in non critical region. Other than shiftiness, all other bottleneck characteristics found to be increasing with increase in level of variability (Figure 3.16).

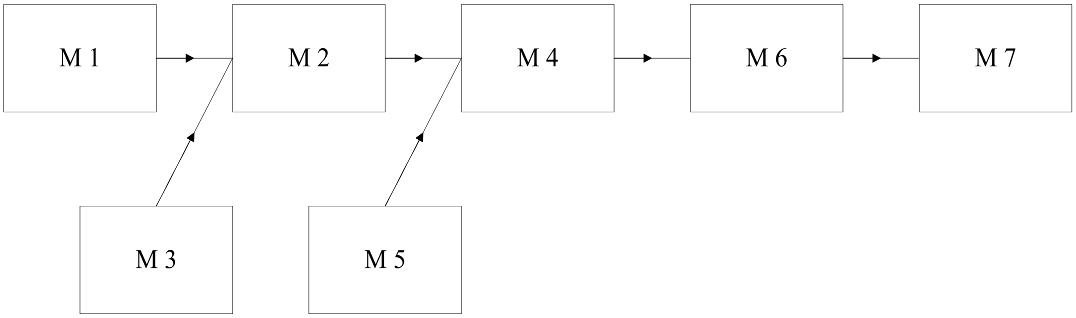


Figure 3.15. Model for case study 3 without buffer

Table 3.17. Bottleneck characteristic results for case study 3

RESULTS	**Low Variability**	**Medium Variability**	**High Variability**
# of Machines	7	7	7
# of BN Machines	7	7	7
Run Time	1000	1000	1000
BN Time	226.58	781.948	889.86
# of Inactive Durations	101	118	120
# of BN Shifts	28	30	31
Shiftiness, β	0.80995	0.86137	0.74885
BN time ratio, α	0.22658	0.78195	0.88986
BN ratio, τ	1	1	1
BN shifting frequency, φ	0.75	0.76667	0.77419
BN severity ratio, χ	1	1	1

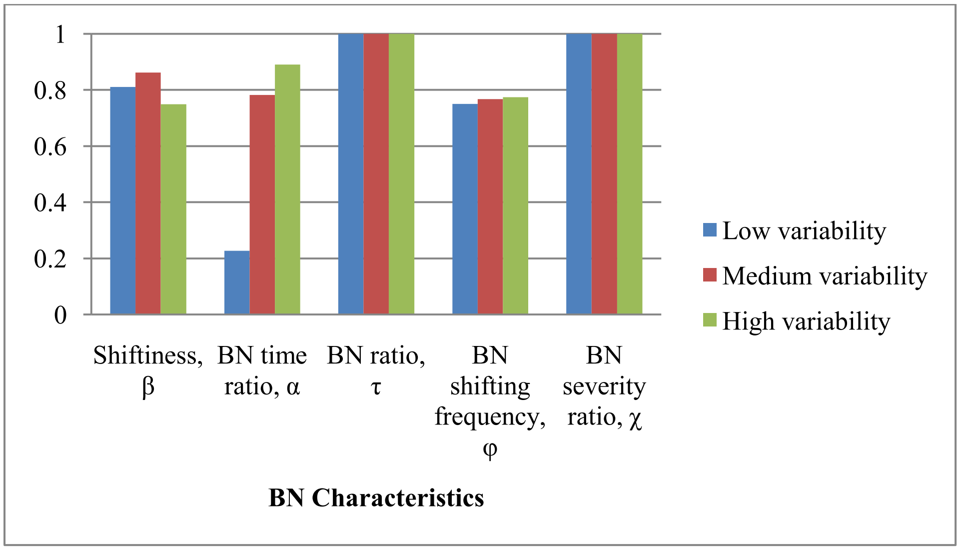


Figure 3.16. Bottleneck characteristics comparison chart for case study 3

3.6.3 Case Study 4

Consider a production line as shown in Figure 3.17. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 3.18. BN characteristics of three levels of variability are compared and plotted in Figure 3.18.

Model with high and medium level of variability fall under scenario 3 (most critical scenario) and model with low level of variability scenario is in non critical region. All BN characteristics found to be increasing with increase in level of variability (Figure 3.18).

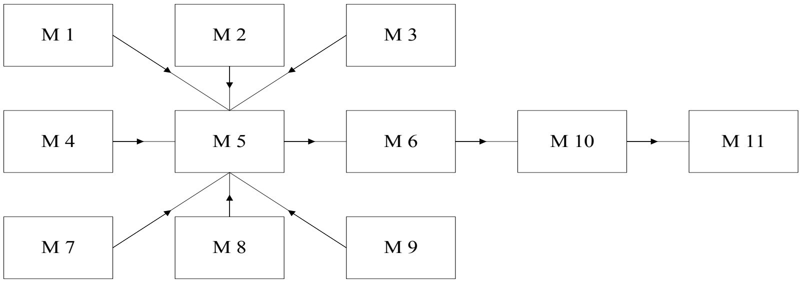


Figure 3.17. Model for case study 4 without buffer

Table 3.18. Bottleneck characteristic results for case study 4

RESULTS	Low Variability	Medium Variability	High Variability
# of Machines	11	11	11
# of BN Machines	5	6	7
Run Time	1000	1000	1000
BN Time	247.60	508.89	966.25
# of Inactive Durations	63	125	125
# of BN Shifts	15	25	40
Shiftiness, β	0.56	0.61467	0.6477
BN time ratio, α	0.2476	0.50889	0.96626
BN ratio, τ	0.45455	0.54545	0.63636
BN shifting frequency, φ	0.66667	0.76	0.825
BN severity ratio, χ	1	1	1

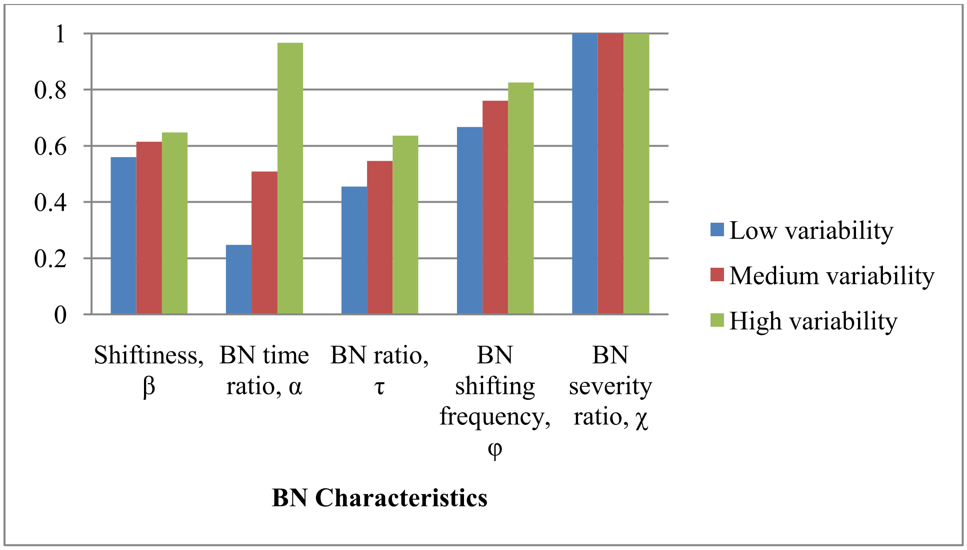


Figure 3.18. Bottleneck characteristics comparison chart for case study 4

3.6.4 Case Study 5

Consider a production line as shown in Figure 3.19. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 3.19. BN characteristics of three levels of variability are compared and plotted in Figure 3.20.

Model with high and medium level of variability fall under scenario 3 (most critical scenario) and model with low level of variability scenario is in non critical region. Other than shiftiness, all other bottleneck characteristics found to be increasing with increase in level of variability (Figure 3.20).

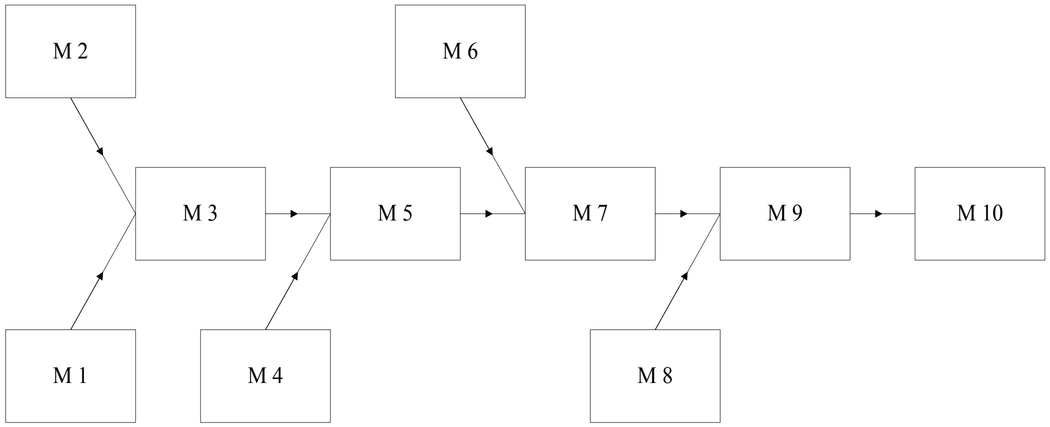


Figure 3.19. Model for case study 5 without buffer

Table 3.19. Bottleneck characteristic results for case study 5

RESULTS	**Low Variability**	**Medium Variability**	**High Variability**
# of Machines	10	10	10
# of BN Machines	9	10	10
Run Time	1000	1000	1000
BN Time	275.793	960.528	1000
# of Inactive Durations	143	170	321
# of BN Shifts	36	45	65
Shiftiness, β	0.66552	0.72314	0.53887
BN time ratio, α	0.27579	0.96053	1
BN ratio, τ	0.9	1	1
BN shifting frequency, φ	0.75	0.77778	0.86154
BN severity ratio, χ	1	1	1

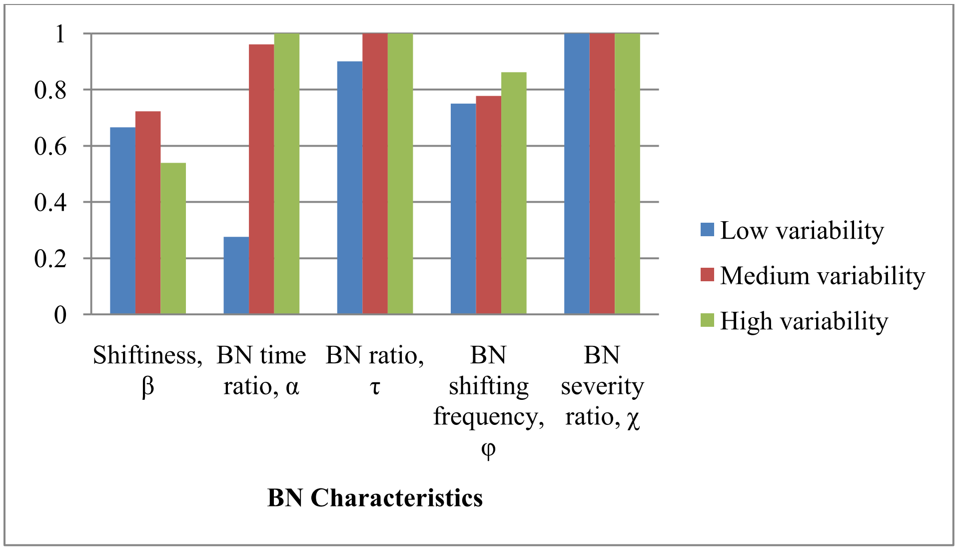


Figure 3.20. Bottleneck characteristics comparison chart for case study 5

3.6.5 Case Study 6

Consider a production line as shown in Figure 3.21. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 3.20. BN characteristics of three levels of variability are compared and plotted in Figure 3.22.

Model with high and medium level of variability fall under scenario 3 (most critical scenario) and model with low level of variability scenarios is in non critical region. Other than shiftiness and BN shifting frequency, all other bottleneck characteristics found to be increasing with increase in level of variability (Figure 3.22).

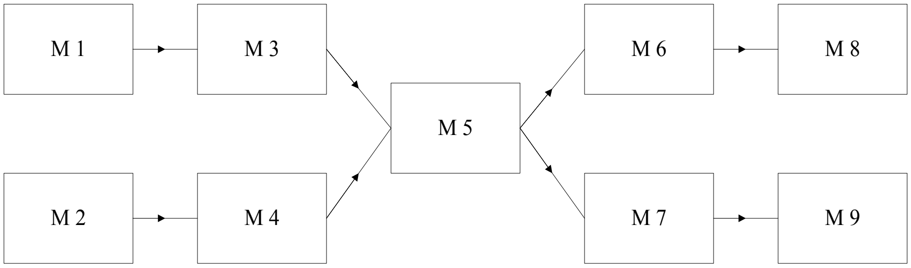


Figure 3.21. Model for case study 6 without buffer

Table 3.20. Bottleneck characteristic results for case study 6

RESULTS	**Low Variability**	**Medium Variability**	**High Variability**
# of Machines	9	9	9
# of BN Machines	9	9	9
Run Time	1000	1000	1000
BN Time	477.086	1000	1000
# of Inactive Durations	143	154	253
# of BN Shifts	55	64	123
Shiftiness, β	0.71273	0.67243	0.72234
BN time ratio, α	0.47709	1	1
BN ratio, τ	1	1	1
BN shifting frequency, φ	0.8363	0.8593	0.9918
BN severity ratio, χ	1	1	1

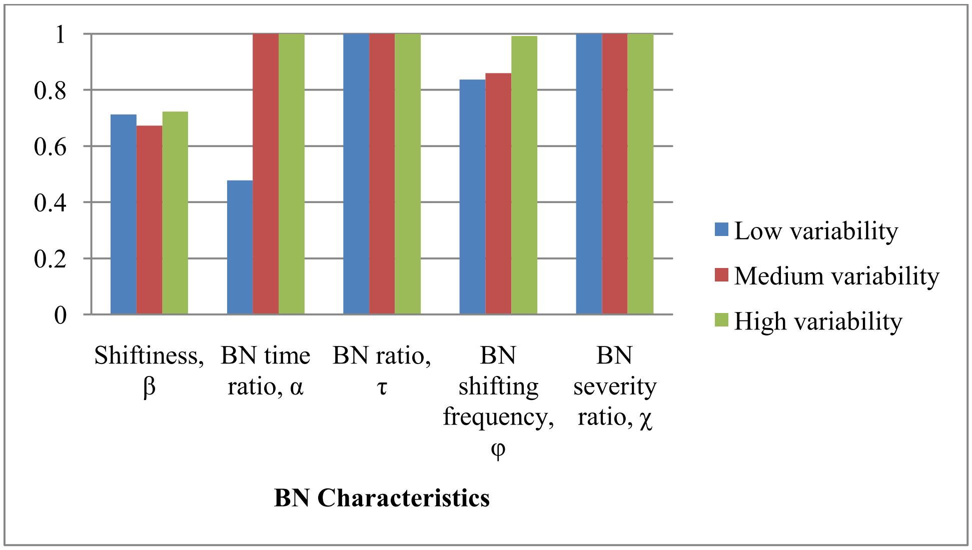


Figure 3.22. Bottleneck characteristics comparison chart for case study 6

3.6.6 Case Study 7

Consider a production line as shown in Figure 3.23. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 3.21. BN characteristics of three levels of variability are compared and plotted in Figure 3.24.

Models with all three levels of variability scenarios are in most critical region (Scenario 3). Other than shiftiness and BN shifting frequency, all other bottleneck characteristics found to be increasing with increase in level of variability (Figure 3.24).

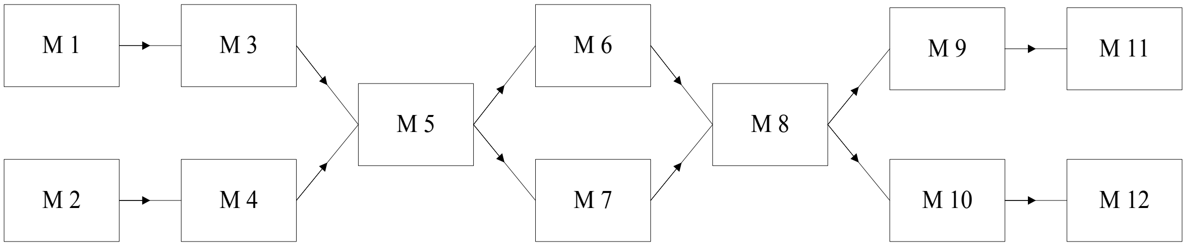


Figure 3.23. Model for case study 7 without buffer

Table 3.21. Bottleneck characteristic results for case study 7

RESULTS	Low Variability	Medium Variability	High Variability
# of Machines	12	12	12
# of BN Machines	12	12	12
Run Time	1000	1000	1000
BN Time	538.449	1000	1000
# of Inactive Durations	207	212	210
# of BN Shifts	40	42	67
Shiftiness, β	0.7407	0.79011	0.71848
BN time ratio, α	0.53845	1	1
BN ratio, τ	1	1	1
BN shifting frequency, φ	0.7	0.7143	0.8209
BN severity ratio, χ	1	1	1

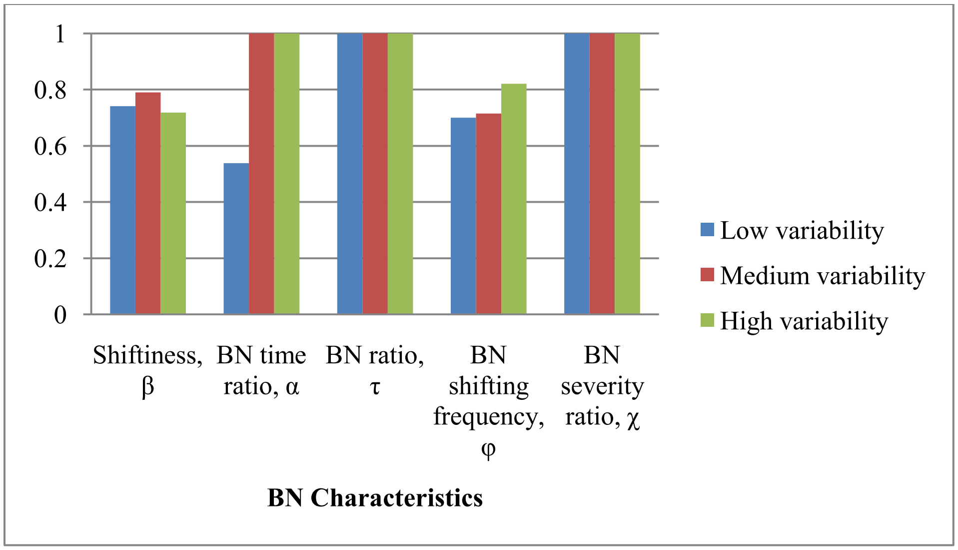


Figure 3.24. Bottleneck characteristics comparison chart for case study 7

3.6.7 Case Study 8

Consider a production line as shown in Figure 3.25. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 3.22. BN characteristics of three levels of variability are compared and plotted in Figure 3.26.

Model with high and medium level of variability fall under scenario 3 (most critical scenario) and model with other low level of variability scenario is in non critical region. All BN characteristics found to be increasing with increase in level of variability (Figure 3.26).

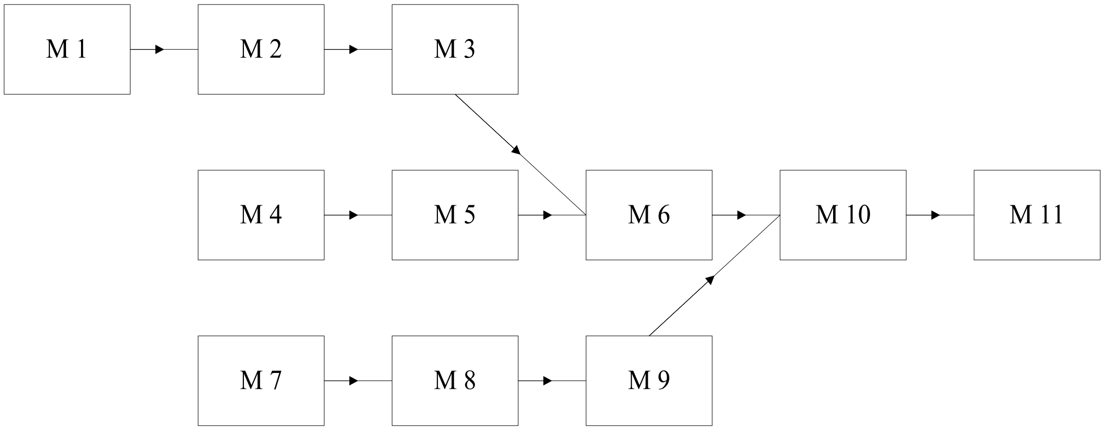


Figure 3.25. Model for case study 2 without buffer

Table 3.22. Bottleneck characteristic results for case study 8

RESULTS	**Low Variability**	**Medium Variability**	**High Variability**
# of Machines	11	11	11
# of BN Machines	11	11	11
Run Time	1000	1000	1000
BN Time	346.532	1000	1000
# of Inactive Durations	118	123	123
# of BN Shifts	41	42	51
Shiftiness, β	0.76675	0.76936	0.82788
BN time ratio, α	0.34653	1	1
BN ratio, τ	1	1	1
BN shifting frequency, φ	0.73171	0.7381	0.78431
BN severity ratio, χ	1	1	1

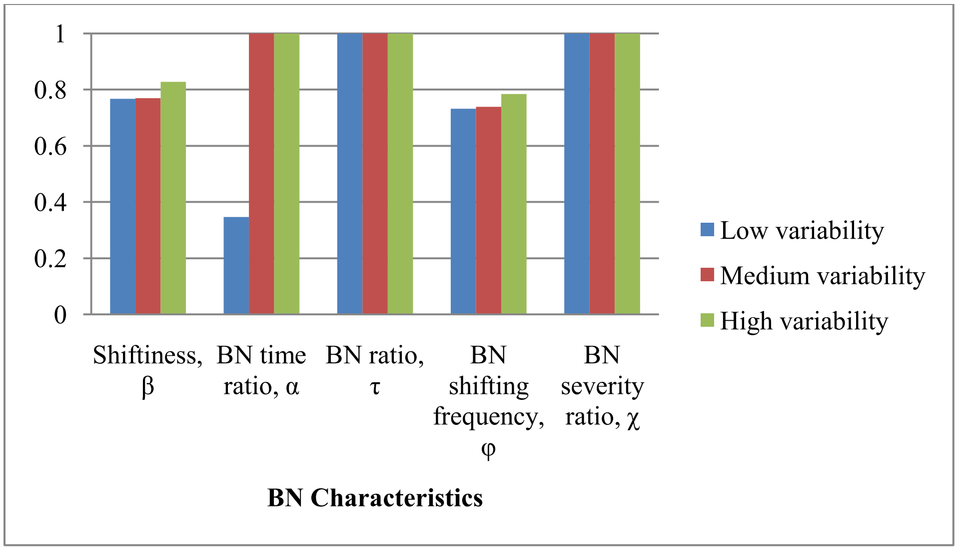


Figure 3.26. Bottleneck characteristics comparison chart for case study 8

3.7 Case Study Results and Analysis

When analyzing production system in the perspective of bottlenecks, BN time, total number of BN machines, total number of inactive durations and number of BN shifts are the key factors that need to be addressed. Case study results for different levels of variability on these factors are analyzed and discussed below.

3.7.1 Bottleneck Time

BN time depends on various factors such as arrival time of the part, machine status and processing time of each machine in the system. In all the case studies, constant arrival time, reliable line and variable processing time are assumed. Therefore, the impact of processing time variability on BN time is analyzed. Eight case studies are conducted with three levels of variability (low, medium and high). From the case study results, it can be inferred that increase in variability increases the total BN time of the system. It clearly indicates that there is an increasing trend of BN time with increase in variability from low to high.

3.7.2 Total Number of Bottleneck Machines and Bottleneck Shifting

BN shifting depends on different factors such as number of BN machines in the system, arrival time of the part, machine status and processing time of each machine in the system. Case study results show that the number of BN machines in the system increases with increase in variability. It also proves that increase in variability increases the number of BN shifts from one machine to another. Therefore, it shows an increasing trend in the number of times the BN shifts and total number of BN machines in the system with increase in variability from low to high.

3.7.3 Total Number of Inactive Durations

In most of the case studies, it was inferred that total number of inactive durations in the system increases with increase in variability. Therefore, the results show that there is an increasing trend in the number of inactive durations in the total run time with increase in variability from low to high.

Based on the results from case studies, it can be concluded that increase in variability

1. Increases the total BN time of the system
2. Increases the number of BN machines and number of times BN shifts from one machine to another
3. Increases the total number of inactive durations in the total run time

Whenever the variability increases from low variability to medium variability and medium variability to high variability, there is an increase in BN time, number of BN machines, number of BN shifts and number of inactive durations. It denotes the degradation of the system. Continuous increase of all these factors indicates that the system is degrading continuously. If this is uncontrolled, then it will lead to serious consequences (difficult to detect BN machines) and production losses. Thus, it makes the system more complicated and hard to solve the problem. Therefore, whenever there is increase in BN time, it is better to detect the BN machines and implement control strategies.

3.8 Conclusion

In this chapter, new BN detection method (inactive duration method) is proposed to overcome the defects of the existing BN detection method (active duration method). Existing BN shiftiness measure fails to capture the criticality of BN and BN shifting. Therefore, four new measures such as bottleneck shifting frequency, bottleneck time ratio, bottleneck ratio and bottleneck severity ratio are developed. The impact of variability on BNs and shifting of bottlenecks in production lines without buffer are analyzed using eight case studies. BN time, number of BN machines, number of inactive durations, and number of BN shifts between different machines increases with increase in variability.

CHAPTER 4

OPTIMAL BUFFER SIZE DETERMINATION AND BOTTLENECK METHODOLOGY - BUFFER CASES

4.1 Introduction

Case studies tested in chapter 3 showed that increase in variability may increase the probability of machines being bottleneck and shifting of bottlenecks between different machines in the system. In the case studies discussed in the previous chapter, the system was assumed to have no buffers before each machine. In this chapter, the performance of production lines with buffer is examined. A heuristic procedure for determining optimal buffer size based on bottleneck time is also developed. Case studies with buffer scenarios for different levels of variability are detailed first. Section 4.2 describes production lines with buffer and explains the need for determining optimal buffer size. Section 4.3 lists the set of notations used in optimal buffer determination heuristic. Section 4.4 details the various steps involved in the determination of optimal buffer sizes for all machines in the system. Section 4.5 explains the heuristic with the use of a case study. Section 4.6 discusses results of additional case studies for production lines with buffer scenarios. Section 4.7 summarizes the results and interpretations for production line with buffers.

4.2 Production Lines with Buffer

Bottleneck machine is a machine which makes other machines to be inactive. For production lines with buffer, bottlenecks can be classified into machine bottlenecks and buffer bottlenecks. Machine bottlenecks are machines which make other machines to be inactive, whereas buffer bottlenecks are buffers which make machines to be inactive. Performance analysis of each machine is evaluated by determining machine bottlenecks. This can be done by eliminating buffer bottlenecks in the system, through providing excess buffer spaces before each machine. Excess buffers may increase the total WIP in the system. Therefore, there should be a tradeoff between the WIP and buffer spaces in the system. The determination of optimal buffer size is vital to eliminate buffer bottlenecks in the system.

4.3 Notations

m	Total number of machines in the system
X,Y	Float values
s	Total number of starved machines in the system
t	Total number of bottleneck machines in the system
M_c	Set of machines, where $1 \le c \le m$
S_c	Set of starved machines, where $1 \le c \le m$
B_c	Set of buffer assigned to each machine, $1 \le c \le m$
A_c	Set of actual buffer size used in uniform buffer case, $1 \le c \le m$
T	Total bottleneck time, $T = \sum_{i=1}^{t} T_i$
n	Initial buffer size
U	Uniform buffer size
Q_c	Set of optimal buffer sizes of all machines, where $1 \le c \le m$

4.4 Optimal Buffer Size Determination

The essential qualitative properties of production system are monotonicity and concavity. When all other buffers are held constant or increased, “increase in buffer size increases the production rate” (Gershwin, & Schor, 2000). This phenomenon is called monotonicity. Concavity is the phenomenon in which increase in production rate decreases when there is a unit buffer increase (Gershwin, & Schor, 2000). As the number of units in buffer is increased, concavity leads to a situation in which any further increase in buffer does not contribute to increase in production rate (loss of continuity). Based on these phenomena, a two step heuristic for the determination of optimal buffer size has been developed. In the first step, uniform buffer before each machine is determined. The result of the first step may be suboptimal. In the second step, a reduction of the buffer before each machine is performed to result in a near optimal solution.

4.4.1 Uniform Buffer Size Heuristic

In the first step, an iterative procedure for identifying a uniform buffer for all machines is developed. The main objective of this step is to eliminate buffer bottlenecks in the system.

Initially, buffer sizes of all machines are equal and assumed to be in concavity region. In the concavity region for every unit increase in buffer size before all machines, the rate of increase in throughput decreases. In this method, BN time has been used instead of throughput. Throughput is inversely proportional to BN time. Therefore, concavity can also be defined as decrease in BN time reduces as the buffer size increases and vice versa.

The throughput increases with increase in buffer size in monotonicity region. In concavity region (Figure 1), increase in throughput gradually decreases with increase in unit buffer size. Beyond concavity region, continuity of throughput increase does not hold good. This region is called as discontinuous region. In this region, throughput remains same for the further increase in buffer size. In other words, BN time will not reduce further with increase in buffer size in discontinuous region.

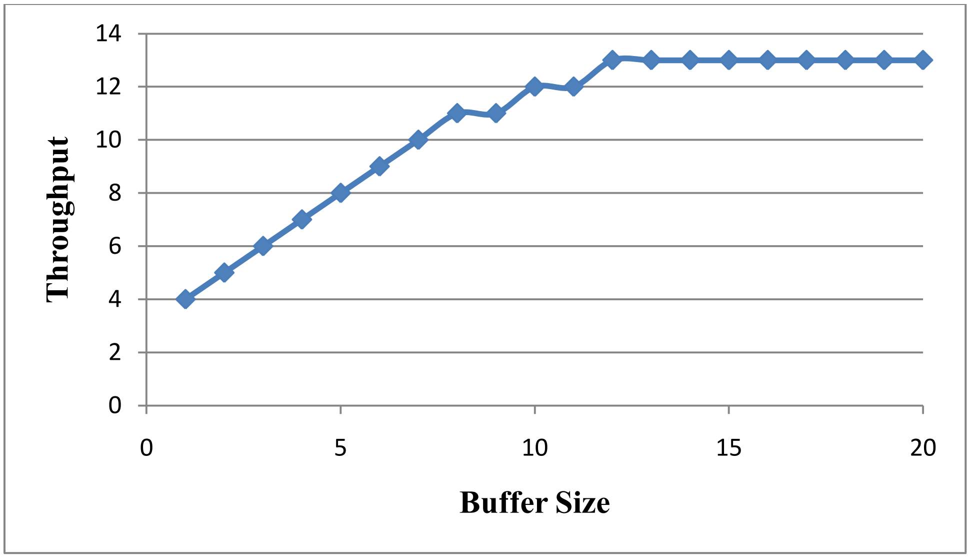


Figure 4.1. Buffer characteristic Chart

Gradual unit decrease in buffer size of all machines simultaneously reaches the concavity region of production line at some point. The buffer size corresponding to the intersection point of concavity region and discontinuity region is the uniform buffer size for all machines in the system. The result of this step is suboptimal. The heuristic procedure is shown in Figure 4.2 determines the uniform buffer size for all machines.

For a „m‟machine problem,

$$M_c = \{M_1, M_2, M_3, \ldots\ldots\ldots M_m\} \tag{4.1}$$

$$S_c = \begin{Bmatrix} 1, \text{ Starved machine} \\ 0, \text{ Otherwise} \end{Bmatrix} \tag{4.2}$$

$$S_c = \{S_1, S_2, S_3, \ldots\ldots\ldots S_m\} \tag{4.3}$$

$$B_c = \{B_1, B_2, B_3, \ldots\ldots\ldots B_m\} \tag{4.4}$$

$$Q_c = \{Q_1, Q_2, Q_3, \ldots\ldots\ldots Q_m\} \tag{4.5}$$

$$T_c = \{T_1, T_2, T_3, \ldots\ldots\ldots T_m\} \tag{4.6}$$

$$A_c = \{A_1, A_2, A_3, \ldots\ldots\ldots A_m\} \tag{4.7}$$

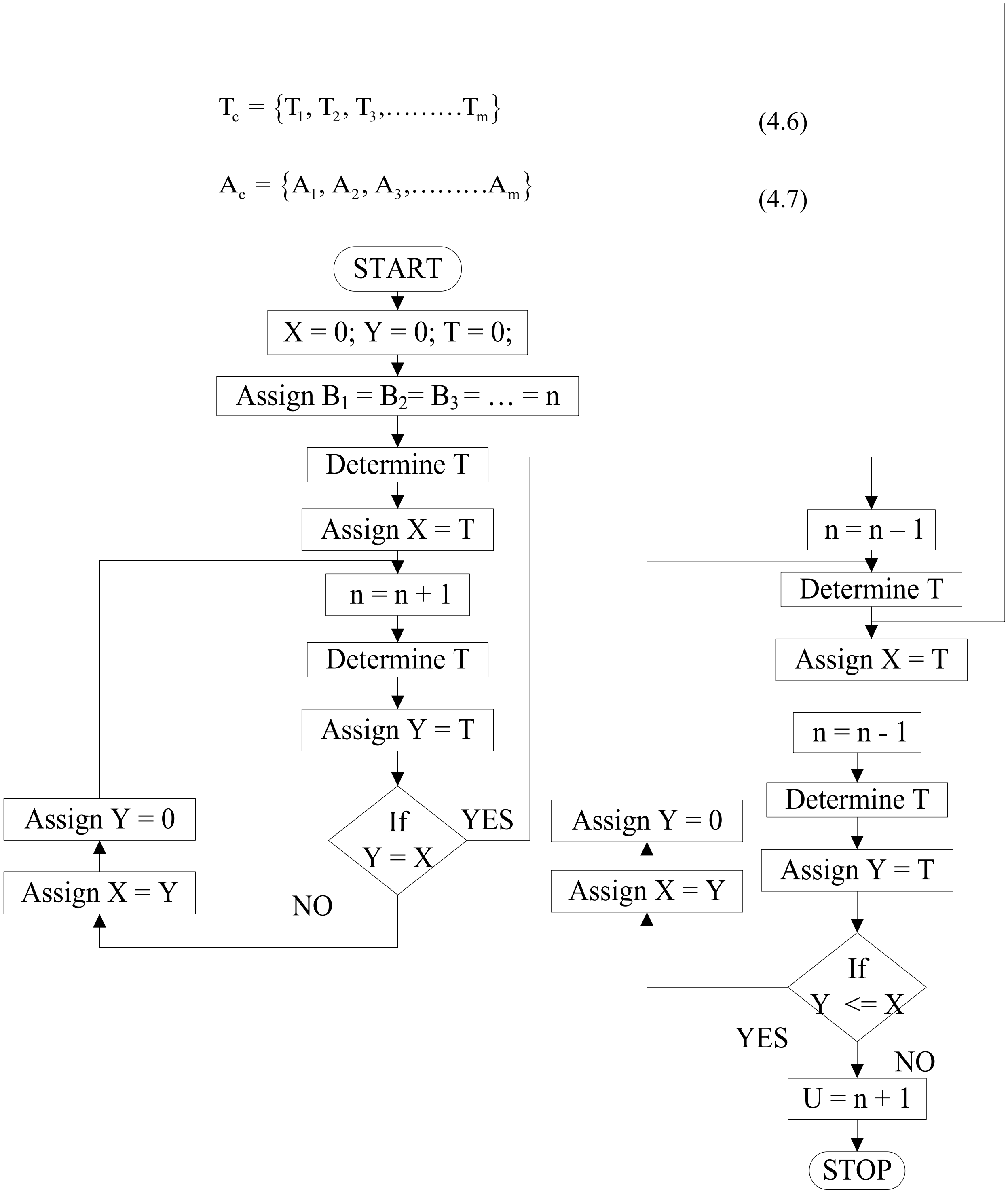


Figure 4.2. Flowchart for uniform buffer determination heuristic.

The buffer size determined in this step is the same for all machines in the system. The uniform buffer size that is calculated is used as an input to the optimal buffer size determination.

4.4.2 Optimal Buffer Size Determination

The second step is to determine optimal buffer size before each machine in the production line. In the first step, all buffers are reduced simultaneously while in this step the same procedures are used but each buffer is analyzed separately and each buffer‟s monotonicity region is achieved through optimal buffer size. The heuristic procedure shown in Figure 4.3 determines the optimal buffer size for all machines.

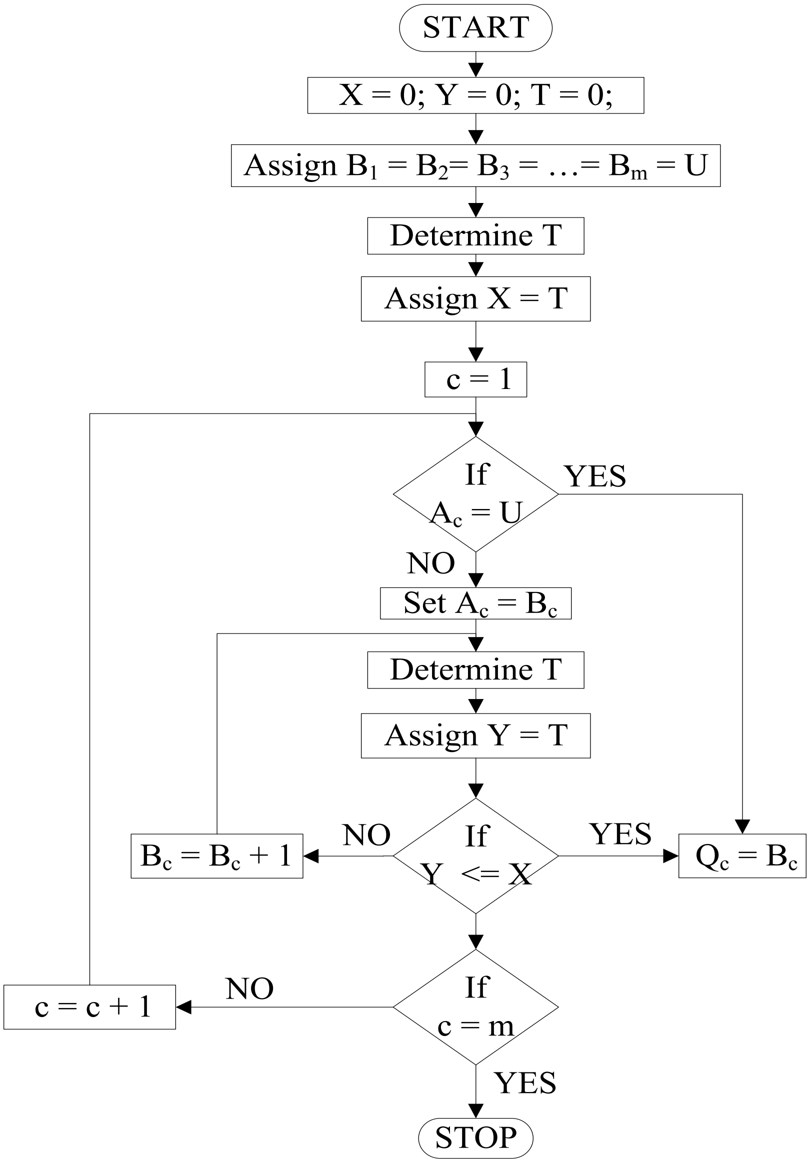


Figure 4.3. Flowchart for optimal buffer determination heuristic.

The above two step heuristic method is applied to production lines with buffer and optimal buffer size is determined to avoid buffer bottlenecks in the system.

4.5 Case Study 1

The same case study discussed in Chapter 3 is used for detailing the heuristic procedure for this chapter. The production line in the case study consists of three machines as shown in Figure 3.7. Buffers have been added before each machine. Case study consists of three sections (a) processing times with high variability, (b) processing times with medium variability and (c) processing times with low variability. Each case was analyzed with optimal buffer size. Performance measures such as shiftiness, bottleneck ratio, bottleneck time ratio, bottleneck shifting frequency, and bottleneck severity ratio were calculated for each case.

4.5.1 High Variability

Processing time variations follow triangular distribution. Processing times of each station with mean, mode, maximum and minimum value is given below in Table 4.1.

Table 4.1. Processing times (minutes) of each machine with high variability

Machine	Mean	Minimum	Mode	Maximum
Machine 1	30	1.5	36	52.5
Machine 2	30	1.5	36	52.5
Machine 3	30	1.5	36	52.5

Optimal buffer size for each machine was determined based on two-step heuristic procedure. The first step is to determine uniform buffer size. Table 4.2 shows the bottleneck time of the production system at various buffer sizes. From the table, uniform buffer size is 3, as it can be seen that further reduction in buffer size increases the bottleneck time.

Table 4.2. Uniform buffer size determination

Buffer Capacity	**BN Time**
11	120.36
10	120.36
…	120.36
4	120.36
3	**120.36**
2	234.56
1	354.23

The second step is to determine the optimal buffer size for each machine. Table 4.3 shows the optimal buffer size for three machines along with bottleneck time.

Table 4.3. Optimal buffer size determination

Buffer Capacity	**Machine 1**	**Machine 2**	**Machine 3**
	BN Time	**BN Time**	**BN Time**
3	120.36	**120.36**	120.36
2	120.36	457.82	**120.36**
1	**120.36**	-	221.67

After estimating the optimal buffer size, the model is run for 1000 minutes. The output file generated is used to develop processing time chart (Figure 4.4). Bottleneck time of each machine is determined by analysing the processing time chart.

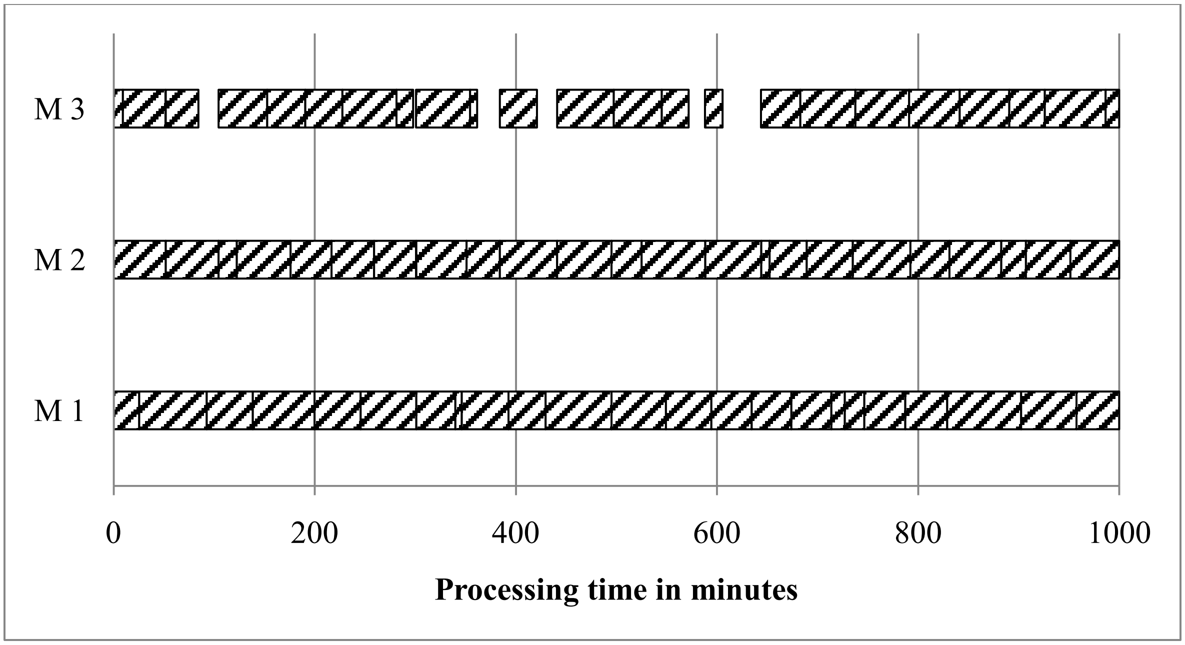


Figure 4.4. Processing time chart for high variability

Bottleneck machine, bottleneck shifts, and bottleneck time were determined from the chart based on inactive duration method. The next step is to calculate the bottleneck characteristics which includes, bottleneck shiftiness measure, bottleneck time ratio, bottleneck ratio, bottleneck shifting frequency, and bottleneck severity ratio.

4.5.1.1 Bottleneck Characteristics

Bottleneck Shiftiness Measure

As discussed earlier, bottleneck shiftiness measure is given by (Lawrence, & Buss, 1994),

$$\beta = 1 - \frac{C_v}{\sqrt{n}}$$

Table 4.4 shows the calculation of bottleneck shiftiness measure. The shiftiness measure was calculated as 0.0054. Bottleneck shifts between machines 1 & 2 in the system throughout the entire run time.

Table 4.4. Bottleneck shiftiness measure calculation

Machine	Bottleneck Time	Bottleneck Probability
Machine 1	0.44	0.003659
Machine 2	119.82	0.996341
Machine 3	0	0
Mean		40.08667
SD		69.05144
C_v		1.722554
$\sqrt{n}$		1.732
$C_v / \sqrt{n}$		0.994517
Shiftiness		0.005483

Bottleneck Time Ratio

Bottleneck time = 120.36 minutes

Total run time = 1000 minutes

$$\alpha = \frac{\text{Bottleneck Time}}{\text{Total Run Time}}$$

$$\alpha = \frac{120.36}{1000}$$

$$\alpha = 0.1203$$

Bottleneck Ratio

Machine 1 and machine 2 are the bottlenecks in the run time. Therefore, number of bottlenecks in the total run was two.

$$\tau = \frac{\text{\# of Bottleneck Machines}}{\text{Total \# of Machines}}$$

$$\tau = \frac{2}{3}$$

$$\tau = 0.667$$

Bottleneck Shifting Frequency

The number of bottleneck shifts was found to be 3 times out of 7 inactive states in the total run time.

$$\upsilon = 1 - \frac{\text{Total \# of Bottleneck Machines}}{\text{Total \# of Bottleneck Shifts}}$$

$$\upsilon = 1 - \frac{2}{3}$$

$$\upsilon = 0.333$$

Bottleneck Severity Ratio

Total number of inactive states in the total run was 8. Each inactive state lead to a bottleneck machine and therefore χ value found to be 1. This proves that market is not a constraint for any of the inactive state.

$$\chi = \frac{\text{\# of Inactive States with Bottleneck}}{\text{Total \# of Inactive States}}$$

$$\chi = \frac{8}{8}$$

$$\chi = 1$$

Bottleneck characteristics for high variability case were calculated and listed in Table 4.5.

Table 4.5. Bottleneck characteristics for high variability – buffer case

RESULTS					
# of Machines	**# of BN Machines**	**Run Time (minutes)**	**BN Time (minutes)**	**# of Inactive Durations**	**# of BN Shifts**
3	2	1000	120.36	8	3

BOTTLENECK CHARACTERISTICS				
β	α	$\boldsymbol{\tau}$	φ	χ
0.0055	0.1203	0.6667	0.3333	1

4.5.2 Medium Variability

Processing time variations follow triangular distribution. Processing times of each station with mean, mode, maximum and minimum value is given in Table 4.6.

Table 4.6. Processing times of each machine with medium variability

Machine	Mean	Minimum	Mode	Maximum
Machine 1	30	12	32.4	45.6
Machine 2	30	12	32.4	45.6
Machine 3	30	12	32.4	45.6

The first step is to determine uniform buffer size. For medium variability, uniform buffer size is found to be 2. The second step is to determine the optimal buffer size for each machine. Table 4.7 shows the optimal buffer size for three machines.

Table 4.7. Optimal buffer sizes for all machines

Machines	Optimal Buffer Size
1	1
2	2
3	2

The processing time chart for medium variability is shown in Figure 4.5. Bottleneck time of each machine was found by analysing processing time chart. Bottleneck characteristics were calculated and listed in Table 4.8.

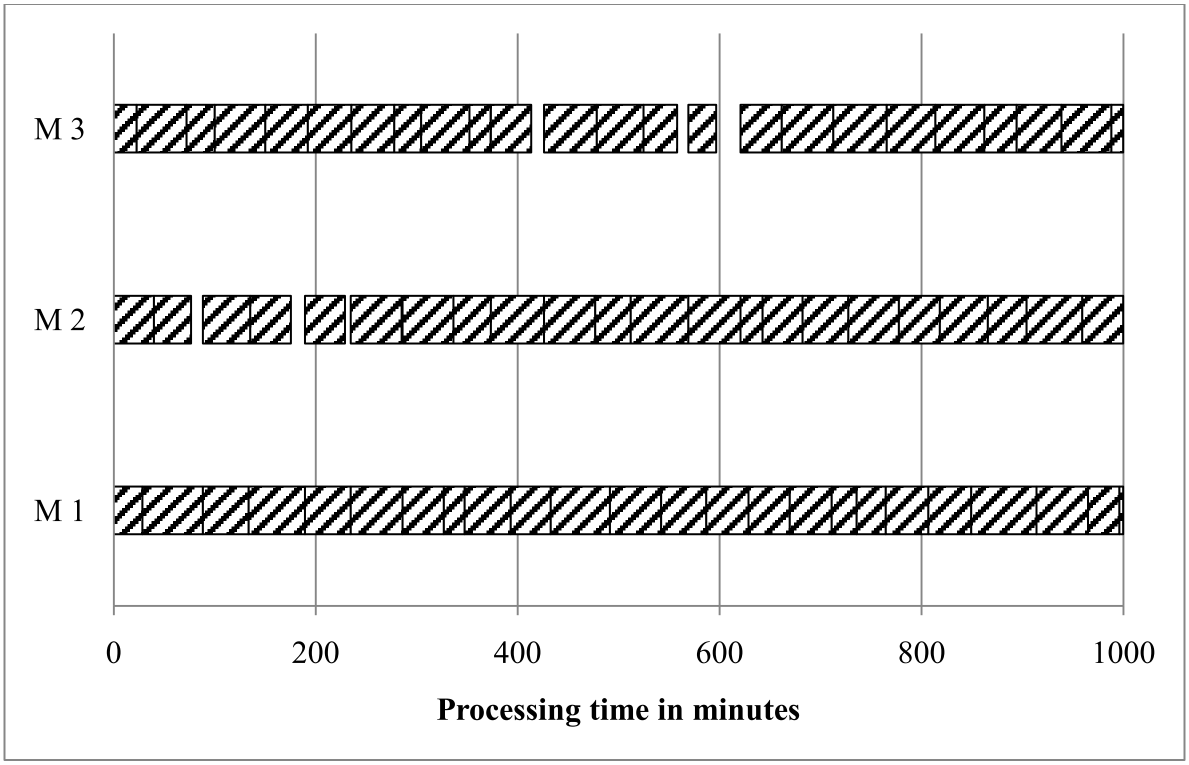


Figure 4.5. Processing time chart for medium variability

Table 4.8. Bottleneck characteristics for medium variability – buffer case

RESULTS					
# of Machines	**# of BN Machines**	**Run Time (minutes)**	**BN Time (minutes)**	**# of Inactive Durations**	**# of BN Shifts**
3	2	1000	80.95	8	2
BOTTLENECK CHARACTERISTICS					
β	α	τ	φ	χ	
0.471	0.8095	0.6667	0	1	

4.5.3 Low Variability

Processing time variations follow triangular distribution. Processing times of each station with mean, mode, maximum and minimum value is given in Table 4.9.

Table 4.9. Processing times of each machine in low variability – buffer case

Machine	Mean	Minimum	Mode	Maximum
Machine 1	30	27	28.2	34.8
Machine 2	30	27	28.2	34.8
Machine 3	30	27	28.2	34.8

The first step is to determine uniform buffer size. For low variability, uniform buffer size is found to be 1.The second step is to determine the optimal buffer size for each machine. Table 4.10 shows the optimal buffer size for three machines.

Table 4.10. Optimal buffer sizes for all machines

Machines	Optimal Buffer Size
1	1
2	1
3	1

The processing time chart for low variability is shown in Figure 4.5. Bottleneck time of each machine was found by analysing processing time chart. Bottleneck characteristics were calculated and is listed in Table 4.11.

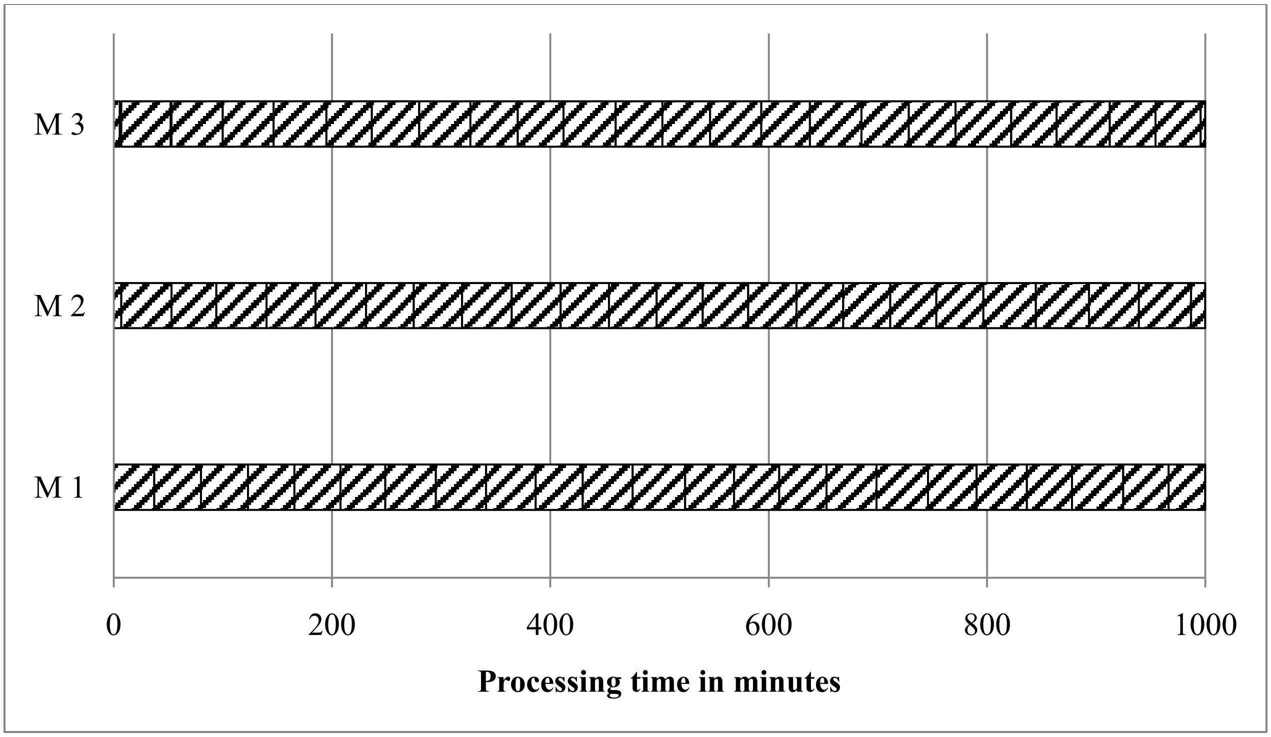


Figure 4.6. Processing time chart for low variability

Table 4.11. Bottleneck characteristics for low variability

RESULTS					
# of Machines	**# of BN Machines**	**Run Time (minutes)**	**BN Time (minutes)**	**# of Inactive Durations**	**# of BN Shifts**
3	1	1000	2.52	2	1

BOTTLENECK CHARACTERISTICS				
β	α	**τ**	φ	χ
0	0.025	0.333	0	1

4.5.4 Results of Case Study 1

Table 4.12 is the summary of the BN characteristics of all levels of variability for case study 1. Here, all three levels of variability scenarios are in non-critical region. Other than shiftiness, all other bottleneck characteristics is found to be increasing with increase in level of variability (Figure 4.7).

Table 4.12. Bottleneck characteristic results for case study 1

Results	**Low Variability**	**Medium variability**	**High variability**
# of Machines	3	3	3
# of BN Machines	2	2	2
Run Time	1000	1000	1000
BN Time	2.52	80.95	120.26
# of Inactive Durations	2	8	8
# of BN Shifts	2	2	3
Shiftiness, β	0	0.471	0.006
BN time ratio, α	0.025	0.081	0.120
BN ratio, τ	0.333	0.667	0.667
BN shifting frequency, φ	0	0	0.333
BN severity ratio, χ	1	1	1

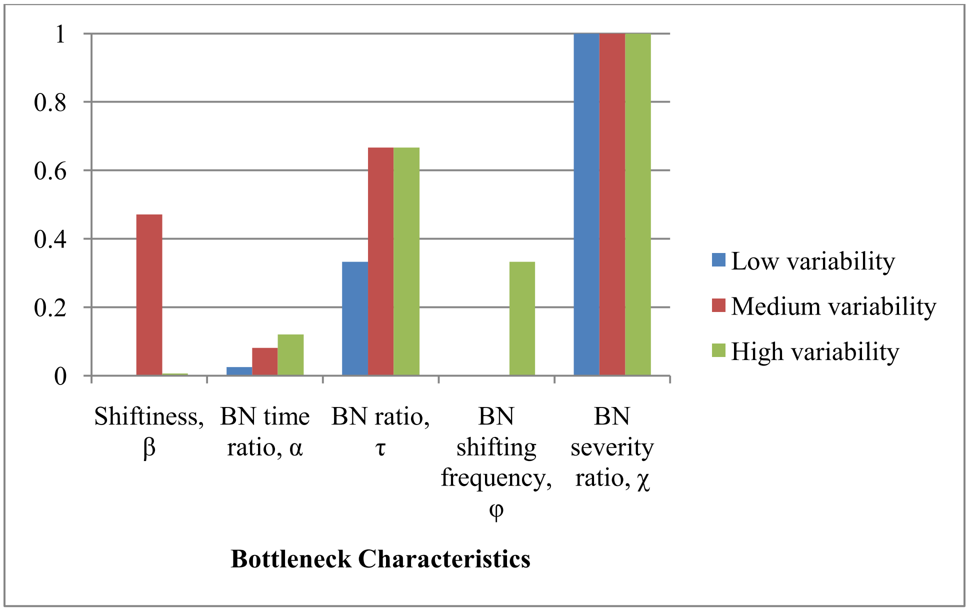


Figure 4.7. Bottleneck characteristics comparison chart for case study 1

4.6 Additional Case Studies

BN identification methodology and buffer size determination used in case study 1 is extended to 7 more case studies. Each case study is tested with three levels of variability. BN characteristics are calculated for all the above mentioned models. All these case studies have optimal buffer before each machine.

4.6.1 Case Study 2

Consider a production line as shown in Figure 3.13. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 4.13. BN characteristics of three levels of variability are compared and plotted in Figure 4.8.

Table 4.13. Bottleneck characteristic results for case study 2

RESULTS	Low Variability	Medium Variability	High Variability
# of machines	5	5	5
# of BN machines	4	4	4
Run time	1000	1000	1000
BN time	13.22	20.48	63.914
# of Inactive durations	7	14	15
# of BN shifts	6	8	11
Shiftiness, β	0.6514	0.6408	0.5387
BN time ratio, α	0.0132	0.0205	0.0639
BN ratio, τ	0.8	0.8	0.8
BN shifting frequency, φ	0.1667	0.375	0.5454
BN severity ratio, χ	1	1	1

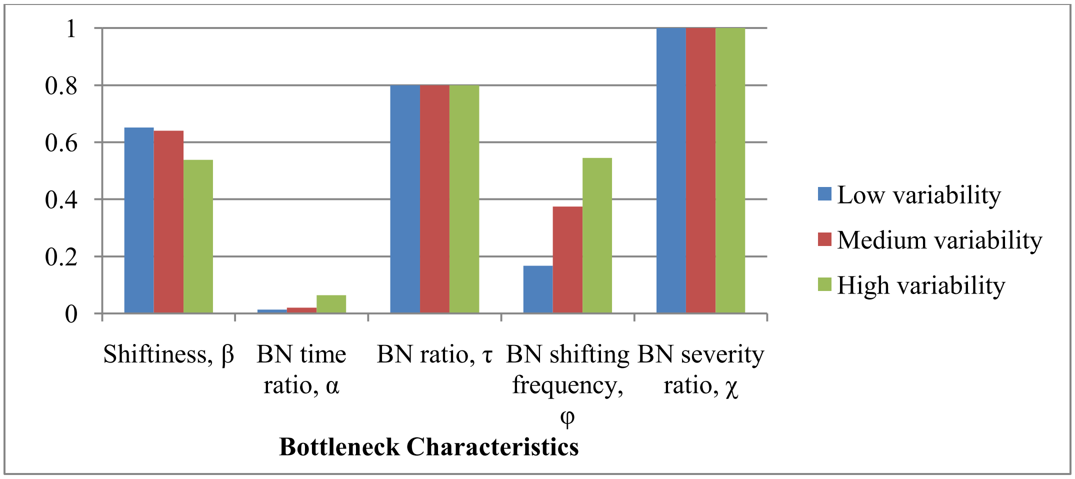


Figure 4.8. Bottleneck characteristics comparison chart for case study 2

All three levels of variability scenarios are in non-critical region. Other than shiftiness, all other bottleneck characteristics found to be decreasing with decrease in level of variability.

4.6.2 Case Study 3

Consider a production line as shown in Figure 3.15. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 4.14. BN characteristics of three levels of variability are compared and plotted in Figure 4.9.

Table 4.14. Bottleneck characteristic results for case study 3

RESULTS	Low Variability	Medium Variability	High Variability
# of machines	7	7	7
# of BN machines	3	3	5
Run time	1000	1000	1000
BN time	56.771	203.08	371.663
# of Inactive durations	16	26	21
# of BN shifts	7	10	17
Shiftiness, β	0.57177	0.58185	0.68558
BN time ratio, α	0.05677	0.20308	0.37166
BN ratio, τ	0.42857	0.42857	0.71429
BN shifting frequency, φ	0.57143	0.7	0.70588
BN severity ratio, χ	1	1	1

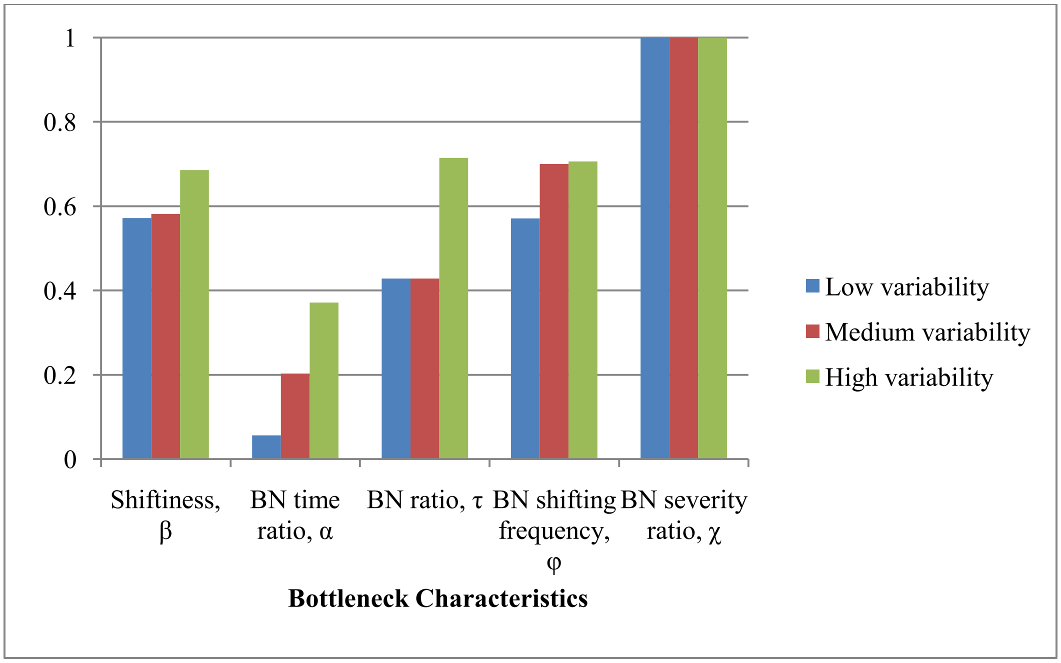


Figure 4.9. Bottleneck characteristics comparison chart for case study 3

Models with all levels of variability are in non critical region. All bottleneck characteristics like found to be increasing with increase in level of variability.

4.6.3 Case Study 4

Consider a production line as shown in Figure 3.17. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 4.15. BN characteristics of three levels of variability are compared and plotted in Figure 4.10.

Table 4.15. Bottleneck characteristic results for case study 4

RESULTS	**Low Variability**	**Medium Variability**	**High Variability**
# of machines	11	11	11
# of BN machines	1	2	2
Run time	1000	1000	1000
BN time	22.6811	43.931	240.042
# of Inactive durations	11	17	22
# of BN shifts	1	3	7
Shiftiness, β	0	0.08266	0.31378
BN time ratio, α	0.02268	0.04393	0.24004
BN ratio, τ	0.09091	0.18182	0.18182
BN shifting frequency, φ	0	0.33333	0.71429
BN severity ratio, χ	1	1	1

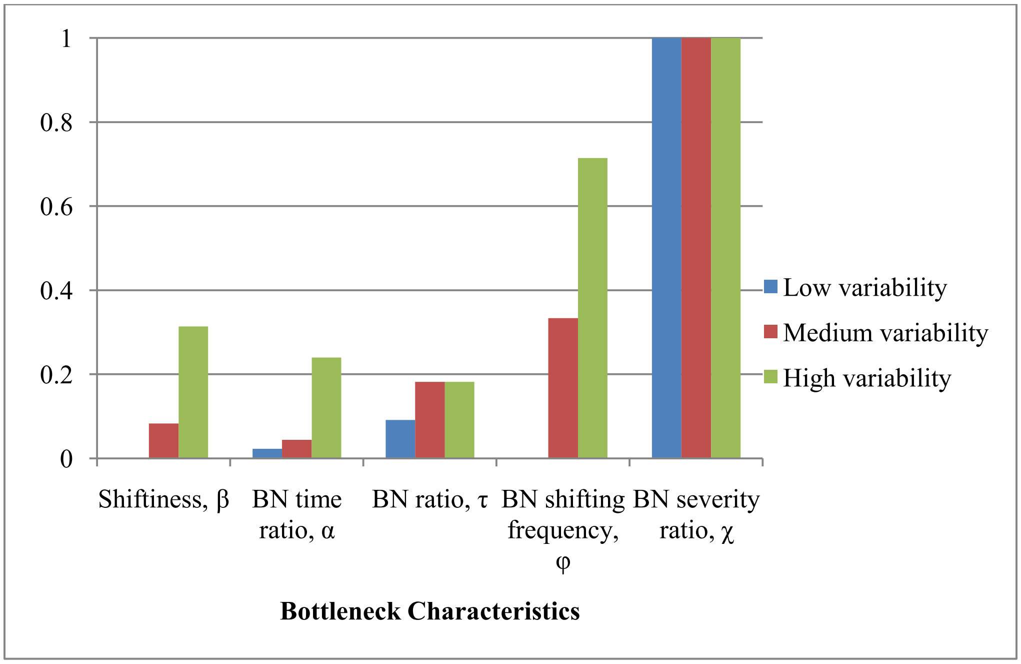


Figure 4.10. Bottleneck characteristics comparison chart for case study 4

Models with all levels of variability are in non critical region. All BN characteristics found to be increasing with increase in level of variability.

4.6.4 Case Study 5

Consider a production line as shown in Figure 3.19. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 4.16. BN characteristics of three levels of variability are compared and plotted in Figure 4.11.

Table 4.16. Bottleneck characteristic results for case study 5

RESULTS	Low Variability	Medium Variability	High Variability
# of machines	10	10	10
# of BN machines	4	4	4
Run time	1000	1000	1000
BN time	92.1617	186.924	327.395
# of Inactive durations	15	20	25
# of BN shifts	6	8	13
Shiftiness, β	0.29266	0.46274	0.43817
BN time ratio, α	0.09216	0.18692	0.3274
BN ratio, τ	0.4	0.4	0.4
BN shifting frequency, φ	0.3333	0.5	0.69231
BN severity ratio, χ	1	1	1

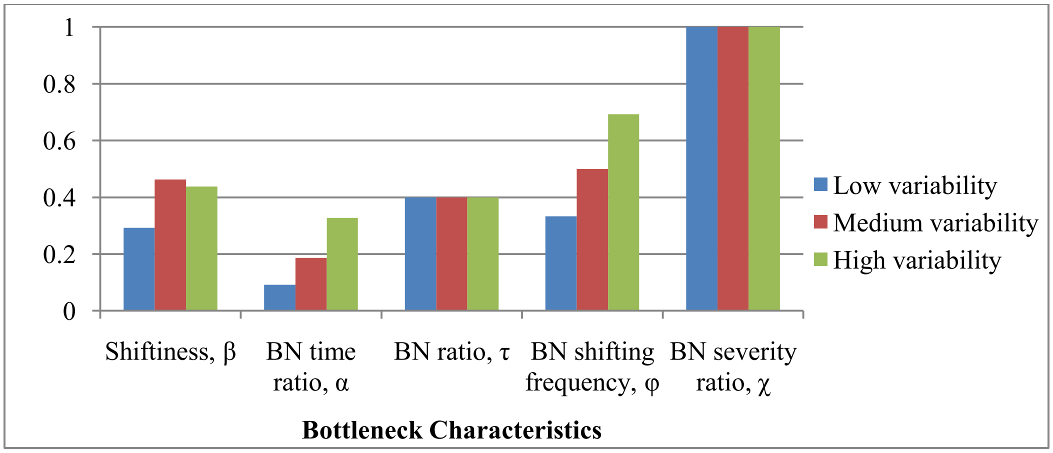


Figure 4.11. Bottleneck characteristics comparison chart for case study 5

Models with all levels of variability are in non critical region. Other than shiftiness and BN shifting frequency, all other bottleneck characteristics found to be increasing with increase in level of variability (Figure 4.11).

4.6.5 Case Study 6

Consider a production line as shown in Figure 3.21. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 4.17. BN characteristics of three levels of variability are compared and plotted in Figure 4.12.

Table 4.17. Bottleneck characteristic results for case study 6

RESULTS	**Low Variability**	**Medium Variability**	**High Variability**
# of machines	9	9	9
# of BN machines	6	7	8
Run time	1000	1000	1000
BN time	146.005	327.37	468.162
# of Inactive durations	26	28	30
# of BN shifts	10	13	25
Shiftiness, β	0.42915	0.66334	0.75503
BN time ratio, α	0.14601	0.32737	0.46816
BN ratio, τ	0.66667	0.77778	0.88889
BN shifting frequency, φ	0.4	0.46154	0.68
BN severity ratio, χ	1	1	1

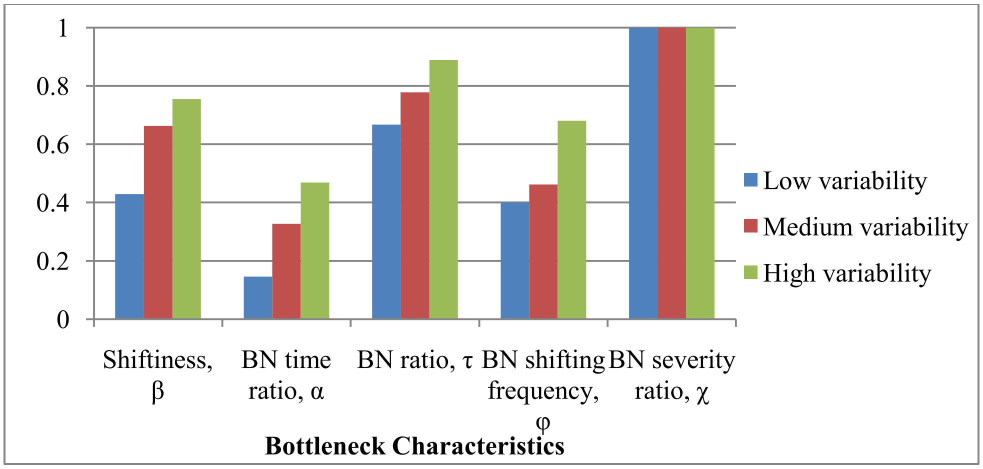


Figure 4.12. Bottleneck characteristics comparison chart for case study 6

Models with all levels of variability are in non critical region. All BN characteristics found to be increasing with increase in level of variability.

4.6.6 Case Study 7

Consider a production line as shown in Figure 3.23. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 4.18. BN characteristics of three levels of variability are compared and plotted in Figure 4.13.

Table 4.18. Bottleneck characteristic results for case study 7

RESULTS	Low Variability	Medium Variability	High Variability
# of machines	12	12	12
# of BN machines	6	9	10
Run time	1000	1000	1000
BN time	79.4662	627.095	1000
# of Inactive durations	32	56	145
# of BN shifts	12	23	36
Shiftiness, β	0.46169	0.59726	0.65996
BN time ratio, α	0.07947	0.6271	1
BN ratio, τ	0.5	0.75	0.83333
BN shifting frequency, φ	0.5	0.6087	0.72222
BN severity ratio, χ	1	1	1

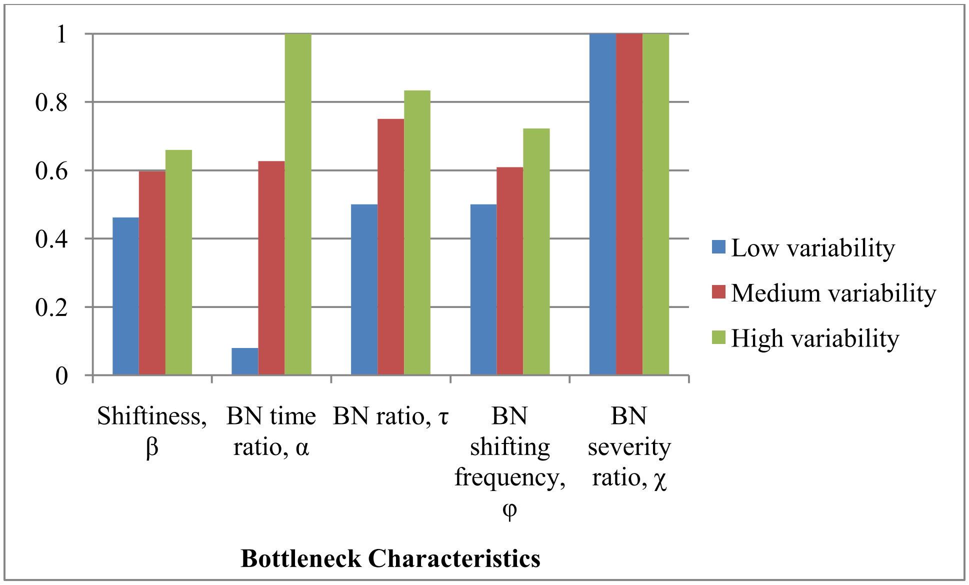


Figure 4.13. Bottleneck characteristics comparison chart for case study 7

Models with high and medium level of variability fall under scenario 3 (most critical scenario) and model with low level of variability scenario is in non critical region. All BN characteristics found to be increasing with increase in level of variability.

4.6.7 Case Study 8

Consider a production line as shown in Figure 3.25. BN identification is carried out by inactive duration method for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 4.19. BN characteristics of three levels of variability are compared and plotted in Figure 4.14.

Table 4.19. Bottleneck characteristic results for case study 8

RESULTS	**Low Variability**	**Medium Variability**	**High Variability**
# of machines	11	11	11
# of BN machines	7	7	7
Run time	1000	1000	1000
BN time	161.077	515.342	957.173
# of Inactive durations	45	45	57
# of BN shifts	16	17	21
Shiftiness, β	0.69477	0.68086	0.62875
BN time ratio, α	0.16108	0.51534	0.95717
BN ratio, τ	0.63636	0.63636	0.63636
BN shifting frequency, φ	0.5625	0.58824	0.66667
BN severity ratio, χ	1	1	1

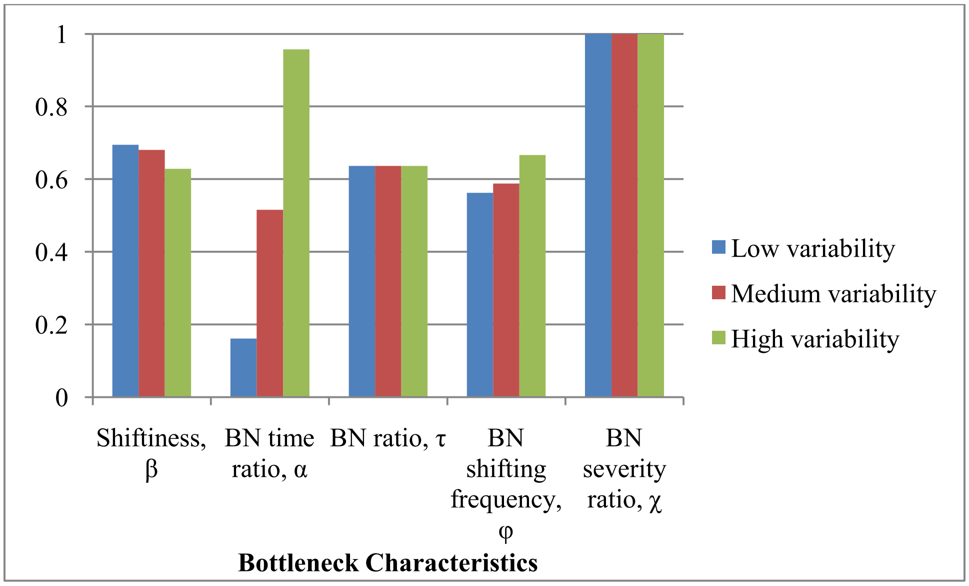


Figure 4.14. Bottleneck characteristics comparison chart for case study 8

Models with high and medium level of variability fall under most critical region and model with low level of variability is in non critical region. Other than shiftiness, all other bottleneck characteristics found to be increasing with increase in level of variability.

4.7 Case Study Results and Analysis

When analyzing production system with buffers in the perspective of bottlenecks, BN time, total number of BN machines, total number of inactive durations, number of BN shifts and optimal buffer size are the key factors that need to be addressed. Case study results for different levels of variability on these factors are analyzed and discussed below.

4.7.1 Bottleneck Time

BN time depends on various factors such as arrival time of the part, machine status and processing time of each machine in the system. In all the case studies, constant arrival time, reliable line and variable processing time are assumed. Eight case studies are conducted with three levels of variability (low, medium and high). From the case study results, it can be inferred that increase in variability increases the total BN time of the system. It clearly indicates that there is an increasing trend of BN time with increase in variability from low to high.

4.7.2 Total Number of Bottleneck Machines and Bottleneck Shifting

BN shifting depends on different factors such as number of BN machines in the system, arrival time of the part, machine status and processing time of each machine in the system. Case study results show that the number of BN machines in the system increases with increase in variability. It also proves that increase in variability increases the number of BN shifts from one machine to another. Therefore, it shows an increasing trend in the number of times the BN shifts and total number of BN machines in the system with increase in variability from low to high.

4.7.3 Total Number of Inactive Durations

In most of the case studies, it was inferred that total number of inactive durations in the system increases with increase in variability. Therefore, the results show that there is an increasing trend in the number of inactive durations in the total run time with increase in variability from low to high.

4.7.4 Optimal Buffer Size for Each Machine

Case study results show that the number of optimal buffer size for each machine in the system increases with increase in variability. Therefore, it shows an increasing trend in the optimal buffer size for each machine with increase in variability from low to high.

Based on the results from case studies, it can be concluded that increase in variability

1. Increases the total BN time of the system
2. Increases the number of BN machines and number of times BN shifts from one machine to another
3. Increases the total number of inactive durations in the total run time
4. Increases the optimal buffer sizes for each machine

Whenever the variability increases from low variability to medium variability and medium variability to high variability, there is an increase in BN time, number of BN machines, number of BN shifts, number of inactive durations and optimal buffer size of each machine. It denotes the degradation of the system. Continuous increase of all these factors indicates that the system is degrading continuously. If this is uncontrolled, then it will lead to serious consequences (difficult to detect BN machines) and production losses. Thus, it makes the system more complicated and hard to solve the problem. Therefore, whenever there is increase in BN time, it is better to detect the BN machines and implement control strategies.

4.8 Conclusion

From the case studies conducted, impact of variability on bottleneck shifting is clearly indicated through BN characteristics. The results clearly show that inclusion of optimal buffers reduces BN time and BN shifting. Case studies were conducted for production lines with optimal buffer. It also proved that increase in variability increases the BN time and shifting of BN between different machines. In the next chapter, BN characteristics are analyzed with different possible scenarios in the manufacturing setting and different control strategies are demonstrated with case studies.

CHAPTER 5

ANALYSIS OF BOTTLENECK CHARACTERISTICS

5. 1 Introduction

Chapter 3 and Chapter 4 explained proposed methodology for identification of BN and BN shifting in production lines with and without buffer. In this chapter, BN characteristics are analyzed with different scenarios and different control strategies for each scenario are suggested. Section 5.2 discusses the introduction of BN characteristics. Section 5.3 discusses the different combination of BN characteristics and possible scenarios in a manufacturing setting. Section 5.4 discusses the different scenarios with possible methods of improvement and user selection option based on cost and performance. Section 5.5 discusses the conclusion drawn from these scenarios.

5.2 Bottleneck Characteristics

Shiftiness measure (Lawrence & Buss, 1995) is not sufficient to analyze BN and shifting BN in a production system. Therefore, four new BN characteristics have been proposed to analyze different facets of BNs. The measures include, BN ratio captures total number of BN machines in the system, BN time ratio computes total BN time of the system, BN shifting ratio determines the frequency of BN shifts between different machines in the system, and BN severity ratio identifies the influence of market constraint during run time. These five factors give an indication of the manufacturing system condition and BN behaviors.

5.3 Analysis of Bottleneck Characteristics

This section details the analysis of BN characteristics at two levels (low and high). As there are five bottleneck characteristics for bottleneck shifting, the permutation of analysis may lead to 120 scenarios. However, several of these situations are not important and may not occur. The following constraints are used to eliminate unimportant and unrealistic scenarios. There are two strategies that can be used to mitigate the impact of a BN: a) increase buffer size or b) increase machine capacity.

a) If α is low, then it indicates that BN time is low and this may not have severe impact in the system. Therefore, these situations are not critical to be analyzed.

b) If β is high, τ should be definitely high. Shiftiness ratio will be high, only when all machines act as bottleneck machines and each machine have equal bottleneck time. Obviously, if all machines become BN machine then BN ratio will be high.

c) If β is low, τ can be high or low. Shiftiness ratio will be low, only when there are few dominant BN machines in the system. Therefore, this may happen with both high and low BN ratio scenarios. Let us consider a production line with five machines in the system.

    1) Scenario 1: In the first scenario, total BN time was found to be 114 minutes and all machines in the system act as BN machine. Machine 3 have high BN time about 100 minutes and all other machines have BN time of 1 minute each. Since BN time is not equally distributed between all machines in the system, shiftiness ratio is found to be 0.078.

    2) Scenario 2: In the second scenario, total BN time was found to be 114 minutes and Machine 3 was the single dominant BN machine in the system with BN time about 114 minutes. Since there is single dominant BN machine in the system, shiftiness ratio is found to be 0.

These two scenarios clearly show that τ can be high or low when β is low. By analyzing all these situations, twelve scenarios (Table 5.1) have been identified for further analysis.

Table 5.1. Possible scenarios to compare bottleneck characteristics

Bottleneck Characteristics	**Shiftiness β**	**Bottleneck Time Ratio α**	**Bottleneck Ratio τ**	**Bottleneck Shifting Frequency φ**	**Bottleneck Severity Ratio χ**
Scenario 1	Low	High	Low	High	High
Scenario 2	Low	High	Low	Low	High
Scenario 3	High	High	High	High	High
Scenario 4	Low	High	High	High	High
Scenario 5	High	High	High	Low	High
Scenario 6	Low	High	High	Low	High
Scenario 7	Low	High	Low	High	Low
Scenario 8	Low	High	Low	Low	Low
Scenario 9	High	High	High	High	Low
Scenario 10	Low	High	High	High	Low
Scenario 11	High	High	High	Low	Low
Scenario 12	Low	High	High	Low	Low

5.3.1 β – Low, α – High, τ – Low, φ – High, χ – High

In this case, shiftiness and bottleneck ratio is low. It clearly indicates that number of bottleneck machines in the system is low and bottleneck time is not equally distributed to all machines. This shows that there are a few dominant bottleneck machines in the system. High shifting frequency clearly shows BN shifts frequently between few dominant BN machines. It shows that the dominant bottleneck machines have high bottleneck time. The dominant bottlenecks should be controlled. This type of manufacturing system can be controlled by increasing the capacity of the dominant machine.

5.3.2 β – Low, α – High, τ – Low, φ – Low, χ - High

In this case, there are a few dominant bottleneck machines in the system. Bottleneck time is high and shifting frequency between all machines is low. High severity factor shows that there is no market constraint. Low shifting frequency clearly shows BN does not shift frequently between few dominant BN machines. Hence, this system will require control of the dominant bottleneck machines and increase in capacity of BN machines

5.3.3 β – High, α – High, τ – High, φ – High, χ – High

Shiftiness and bottleneck ratio are high, number of bottleneck machines is more and bottleneck time is equally distributed to all machines. Bottleneck time is high and shifting frequency between all machines is high. It shows that all machines have high bottleneck time and equally distributed between all machines. Bottleneck also shift from one machine to another machine very often and high severity factor shows that there is no market constraint. This is the worst case that can occur in a manufacturing system and all bottleneck machines are constantly under pressure. This may require continuous monitoring of several machines. In this type of situation, both buffers and increasing machine capacity has to be analyzed for mitigation.

5.3.4 β – Low, α – High, τ – High, φ – High, χ – High

Shiftiness is low and bottleneck ratio is high; this shows that the number of bottleneck machines in the system is more but bottleneck time is not equally distributed to all machines. Bottleneck time is high and shifting frequency between all machines is high. It shows that the dominant bottleneck machines have high bottleneck time and bottleneck shifts from one machine to another machine very often in the system. High severity factor shows that there is no market constraint. Thus the control strategy in this case is to alleviate the dominant bottleneck machines.

In this type of situation, both buffers and increasing machine capacity has to be analyzed for mitigation.

5.3.5 β – High, α – High, τ – High, φ – Low, χ - High

Shiftiness and bottleneck ratio are high, number of bottleneck machines is more and bottleneck time is equally distributed to all machines. Bottleneck time is high and shifting frequency between all machines is low. It shows that all machines have high bottleneck time, but bottleneck does not shift from one machine to another machine very often. High severity factor shows that there is no market constraint. In this case, all bottleneck machines may require continuous monitoring and speeding up to eliminate the bottlenecks. In this type of situation, both buffers and increasing machine capacity has to be analyzed for mitigation.

5.3.6 β – Low, α – High, τ – High, φ – Low, χ – High

Most machines become bottlenecks. However, since shiftiness is low there are a few dominant bottlenecks, and bottleneck time is not equally distributed to all machines. Bottleneck time is high and shifting frequency between all machines is low. It shows that the dominant bottleneck machines have high bottleneck time and bottleneck does not shift from one machine to another machine very often. High severity factor shows that there is no market constraint. Hence, control of the dominant bottlenecks is the best strategy to be followed by increasing capacity of the dominant machines.

5.3.7 β – Low, α – High, τ – Low, φ – High, χ – Low

In this case, there are a few dominant bottleneck machines and these machines become bottlenecks for a large time. There is a frequent shifting between the bottleneck machines. However, the dominant bottleneck machines will have to be controlled and capacity of BN machines have to be increased to get better system performance. Low BN severity ratio shows that market is also a constraint other than BN machines. But in this scenario, irrespective of severity ratio, BN time of machines is high; therefore it is critical to be analyzed.

5.3.8 β – Low, α – High, τ – Low, φ – Low, χ - Low

In this case, there are a few dominant bottleneck machines in the system. Bottleneck time is high and shifting frequency between all machines is low. Low severity factor shows that there is market constraint, but high BN time ratio makes this scenario to be critical and to be analyzed. Hence, this system will require control of the dominant bottleneck machines. Increasing the capacity of the BN machines may mitigate this situation.

5.3.9 β – High, α – High, τ – High, φ – High, χ – Low

Shiftiness and bottleneck ratio are high, number of bottleneck machines is more and bottleneck time is equally distributed to all machines. Bottleneck time is high and shifting frequency between all machines is high. It shows that all machines have high bottleneck time and equally distributed between all machines. Bottleneck also shift from one machine to another machine very often. Low severity factor shows that there is a market constraint, but high BN time ratio makes this scenario to be critical. This is one of the worst cases that can occur in a manufacturing system and all bottleneck machines are constantly under pressure. This may require continuous monitoring of several machines.

5.3.10 β – Low, α – High, τ – High, φ – High, χ – Low

Shiftiness is low and bottleneck ratio is high; this shows that the number of bottleneck machines in the system is more but bottleneck time is not equally distributed to all machines. Bottleneck time is high and shifting frequency between all machines is high. It shows that the dominant bottleneck machines have high bottleneck time and bottleneck shifts from one machine to another machine very often in the system. Low severity factor shows that there is market constraint, but high BN time ratio makes this scenario to be critical. Thus the control strategy in this case is to alleviate the dominant bottleneck machines.

5.3.11 β – High, α – High, τ – High, φ – Low, χ - Low

Shiftiness and bottleneck ratio are high, number of bottleneck machines is more and bottleneck time is equally distributed to all machines. Bottleneck time is high and shifting frequency between all machines is low. It shows that all machines have high bottleneck time and equally distributed between all machines. But the bottleneck does not shift from one machine to another machine very often. Low severity factor shows that there is market constraint, but high BN time ratio makes this scenario to be critical. In this case, all bottleneck machines may require continuous monitoring and speeding up to eliminate the bottlenecks.

5.3.12 β – Low, α – High, τ – High, φ – Low, χ – Low

Most machines become bottlenecks. However, since shiftiness is low there are a few dominant bottlenecks, and bottleneck time is not equally distributed to all machines. Bottleneck time is high and shifting frequency between all machines is low. It shows that the dominant bottleneck machines have high bottleneck time and bottleneck does not shift from one machine to another machine very often. Low severity factor shows that there is market constraint, but high BN time ratio makes this scenario to be critical. Hence, control of the dominant bottlenecks is the best strategy to be followed.

Thus, the new proposed measures are capable of capturing various bottleneck and bottleneck shifting scenarios that may occur in the system.

5.4 Scenarios with case studies

The 12 scenarios analyzed can be divided based on BN severity ratio. In first six scenarios, high BN severity ratio shows that there is no market constraint. In last six scenarios, low BN severity ratio shows that there is a market constraint but BN time is high in all scenarios. Other than BN severity ratio, the last six scenarios are similar to first six scenarios respectively. Therefore, both situations may have same control strategies. Here, first 4 scenarios are explained with case studies and suggested control strategies. Based on cost and performance, suitable improvement method can be selected by the user.

5.4.1 Scenario 1

In this scenario, shiftiness and BN ratio are low. All other BN characteristics are high. This shows clear indication of presence of dominant BN machines in the system. To mitigate the impact of BN, control strategies such as additional capacity to dominant BN machines and optimal buffer before each machine are considered. A case study is conducted to demonstrate the occurrence of this scenario and a best control strategy is implemented to improve the system performance.

Consider a production line as shown in Figure 5.1. Processing time for each machine is listed in Table 5.2. Inactive duration method is used to identify BN for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 5.4. The control strategies are implemented and compared on the basis of renovation cost and performance of the system.

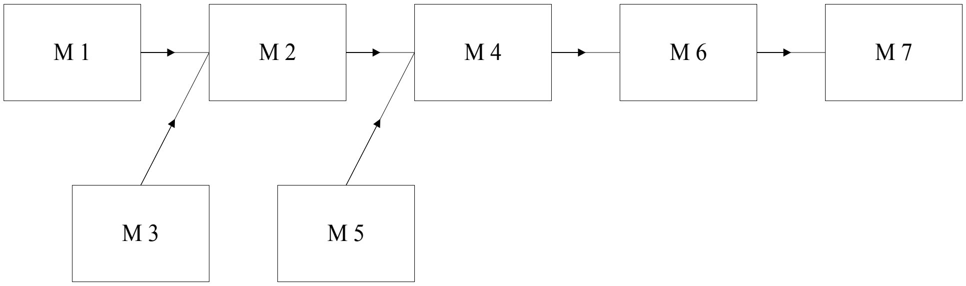


Figure 5.1. Case study model for scenario 1.

Table 5.2. Processing time of each machine in case study for scenario 1

Machine	1	2	3	4	5	6	7
Processing time in minutes	40	40	40	40	40	40	40

5.4.1.1 Control Strategy 1

From simulation results, machine 3 and 4 found to be dominant BN machines in the system. Increase in capacity of dominant BN machines will improve the system performance. Cost of additional capacity of each machine has been listed in the Table 5.3. Therefore, additional capacity of machine 3 and 4 costs $840,000. Results show that there is 36% increase in the throughput of the system.

Table 5.3. Additional capacity of each machine in case study for scenario 1

Machine	1	2	3	4	5	6	7
Additional Capacity Cost	350,000	400,000	520,000	320,000	700,000	375,000	400,000

5.4.1.2 Control Strategy 2

Optimal buffer for each machine is found using proposed optimal buffer determination procedure. Placement of optimal buffer before each machine will improve the system performance. Inclusion of optimal buffer before each machine costs $1,000,000. Results show that there is 4% increase in the throughput of the system.

User can choose the best suitable control strategy based on cost and performance from the discussed control strategies. In this case, method 1 is more efficient on the basis of cost and performance. The results are listed in the Table 5.4.

Table 5.4. Case study results for scenario 1

	Initial Model	**Additional Capacity**	**Optimal Buffer**
# of Machines	7	9	7
# of BN Machines	3	1	1
Run Time	1000	1000	1000
BN Time	1523.69	5.71923	6.647269
# of Inactive Durations	144	2	3
# of BN Shifts	54	1	1
β	0.448	0	0
α	1	0.005719	0.006647
τ	0.429	0.111111	0.142857
φ	0.944	0	0
χ	1.000	1	1
Throughput	25	34	26

5.4.2 Scenario 2

In this scenario, shiftiness, BN ratio and BN shifting frequency are low. All other BN characteristics are high. This shows clear indication of presence of dominant BN machines in the system. To mitigate the impact of BN, control strategies such as additional capacity to dominant BN machines and optimal buffer before each machine are considered. A case study is conducted to demonstrate the occurrence of this scenario and a best control strategy is implemented to improve the system performance.

Consider a production line as shown in Figure 5.2. Processing time for each machine is listed in Table 5.5. Inactive duration method is used to identify BN for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 5.7. The control strategies are implemented and compared on the basis of renovation cost and performance of the system.

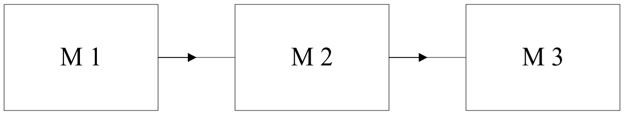


Figure 5.2. Case study model for scenario 2.

Table 5.5. Processing time of each machine in case study for scenario 2

Machine	**1**	**2**	**3**
Processing time in minutes	30	35	30

5.4.2.1 Control Strategy 1

From simulation results, machine 2 found to be a dominant BN machine in the system. Cost of additional capacity of each machine has been listed in the Table 5.6. Therefore, additional capacity of machine 2 costs $650,000. Results show that there is 26% increase in the throughput of the system.

Table 5.6. Additional capacity of each machine in case study for scenario 2

Machine	**1**	**2**	**3**
Additional Capacity Cost	400,000	650,000	325,000

5.4.2.2 Control Strategy 2

Optimal buffer for each machine is found using proposed optimal buffer determination procedure. Inclusion of optimal buffer before each machine costs $500,000. Results show that there is a 4% increase in the throughput of the system.

User can choose the best suitable control strategy based on cost and performance from the discussed control strategies. In this case, method 1 is more efficient on the basis of cost and performance. The results are listed in the Table 5.7.

Table 5.7. Case study results for scenario 2

	Initial Model	**Additional Capacity**	**Optimal Buffer**
# of Machines	3	4	3
# of BN Machines	1	0	1
Run Time	1000	1000	1000
BN Time	536.116	0	208.0322
# of Inactive Durations	144	0	25
# of BN Shifts	1	0	1
β	0	1	0
α	0.5361	0	0.208032
τ	0.3333	0	0.333333
φ	0	0	0
χ	1	0	1
Throughput	27	34	28

5.4.3 Scenario 3

In this scenario, all BN characteristics are high. This shows clear indication of presence of multiple BN machines in the system. This is the most severe case in a manufacturing setting based on bottlenecks. To mitigate the impact of BN, control strategies such as additional capacity to BN machines and optimal buffer before each machine are considered. A case study is conducted to demonstrate the occurrence of this scenario and a best control strategy is implemented to improve the system performance.

Consider a production line as shown in Figure 5.3. Processing time for each machine is listed in Table 5.8. Inactive duration method is used to identify BN for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 5.10. The control strategies are implemented and compared on the basis of renovation cost and performance of the system.

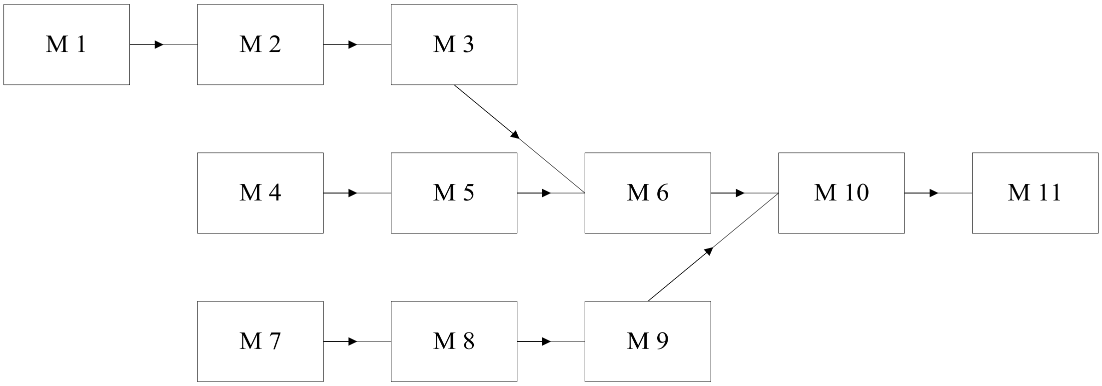


Figure 5.3. Case study model for scenario 3.

Table 5.8. Processing time of each machine in case study for scenario 3

Machine	1	2	3	4	5	6	7	8	9	10	11
Processing time in minutes	40	40	40	40	40	40	40	40	40	40	40

5.4.3.1 Control Strategy 1

From simulation results, machine 3,5,6,9 and 10 found to be dominant BN machines in the system. Cost of additional capacity of each machine has been listed in the Table 5.9. Therefore, additional capacity of these machines cost $2,280,000. Results show that there is 55% increase in the throughput of the system.

Table 5.9. Additional capacity of each machine in case study for scenario 3

Machine	1	2	3	4	5	6	7	8	9	10	11
Additional Capacity Cost (million $)	0.35	0.4	0.52	0.32	0.7	0.38	0.4	0.4	0.35	0.33	0.5

5.4.3.2 Control Strategy 2

Optimal buffer for each machine is found using proposed optimal buffer determination procedure. Inclusion of optimal buffer before each machine costs $3,000,000. Results show that there is 144% increase in the throughput of the system. User can choose the best suitable control strategy based on cost and performance from the discussed control strategies. In this case, method 2 is more efficient on the basis of cost and performance. The results are listed in the Table 5.10.

Table 5.10. Case study results for scenario 3

	Initial Model	Additional Capacity	Optimal Buffer
# of Machines	11	17	11
# of BN Machines	11	7	8
Run Time	1000	1000	1000
BN Time	1000	957.1732	1000
# of Inactive Durations	153	57	76
# of BN Shifts	51	21	54
β	0.8278	0.628746	0.5746
α	1	0.957173	1
τ	1	0.636364	0.7272
φ	0.7843	0.666667	0.8518
χ	1	1	1
Throughput	9	22	14

5.4.4 Scenario 4

In this scenario, shiftiness is low. All other BN characteristics are high. This shows clear indication of presence of dominant BN machines in the system. To mitigate the impact of BN, control strategies such as additional capacity to dominant BN machines and optimal buffer before each machine are considered. A case study is conducted to demonstrate the occurrence of this scenario and a best control strategy is implemented to improve the system performance.

Consider a production line as shown in Figure 5.4. Processing time for each machine is listed in Table 5.11. Inactive duration method is used to identify BN for a run length of 1000 minutes. BN characteristics are calculated and listed in Table 5.13. The control strategies are implemented and compared on the basis of renovation cost and performance of the system.

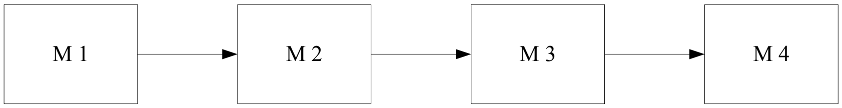


Figure 5.4. Case study model for scenario 4.

Table 5.11. Processing time of each machine in case study for scenario 4

Machine	**1**	**2**	**3**	**4**
Processing time in minutes	35	30	31	30

5.4.4.1 Control Strategy 1

From simulation results, machine 1 and 3 found to be dominant BN machines in the system. Cost of additional capacity of each machine has been listed in the Table 5.12. Therefore, additional capacity of machine 3 and 4 costs $825,000. Results show that there is 36% increase in the throughput of the system.

Table 5.12. Additional capacity of each machine in case study for scenario 4

Machine	**1**	**2**	**3**	**4**
Additional Capacity Cost	400,000	350,000	325,000	500,000

5.4.4.2 Control Strategy 2

Optimal buffer for each machine is found using proposed optimal buffer determination procedure. Inclusion of optimal buffer before each machine costs $500,000. Results show that there is 4% increase in the throughput of the system.

User can choose the best suitable control strategy based on cost and performance from the discussed control strategies. In this case, method 1 is more efficient on the basis of cost and performance. The results are listed in the Table 5.13.

Table 5.13. Case study results for scenario 4

	Initial Model	**Additional Capacity**	**Optimal Buffer**
# of Machines	4	5	4
# of BN Machines	1	1	3
Run Time	1000	1000	1000
BN Time	536.116	65	345.87
# of Inactive Durations	144	65	125
# of BN Shifts	1	1	54
β	0	0	0.664224
α	0.5361	0.065	0.34587
τ	0.3333	0.2	0.75
φ	0	0	0.944444
χ	1	1	1
Throughput	25	34	26

5.5 Conclusion

In this chapter, different possible combinations of BN characteristics and feasible scenarios in the manufacturing setting are discussed. Case studies were conducted for different possible scenarios and control strategies. The results from the case studies proved that control strategies implemented is effective in reducing the impact of BN and increasing the throughput of the system. User can select the efficient control strategy from the different options based on cost, performance and application. The following chapter presents the conclusion of this thesis and the scope of possible future work.

CHAPTER 6

CONCLUSION AND FUTURE RESEARCH

Bottlenecks in manufacturing systems contribute to loss of efficiency. Previous attempts to determine BN"s have focused on identifying them for the long-term. There is a need to identify momentary bottlenecks and to use them for controlling the manufacturing system which in turn can lead to improved production efficiency. In addition to identifying BNs, the appropriate type of actions to be taken for controlling the impact of BNs also have to researched.

6.1 Conclusion

This research work can be divided into four phases: a) BN identification for production lines with and without buffer, b) BN characteristics to identify the current state of the production system, c) optimal buffer size determination heuristic, and d) control strategies to mitigate bottlenecking effect in the production line.

Past research in BN identification have focused on generic method for determining long-term BNs. Active duration method proposed by Roser, Nakano and Tanaka (2002) is the only existing method in the literature for determining momentary BN and average BN. But this method failed to identify BN shifting between different machines. It also fails to identify the criticality of BN machines in the system. Therefore, a new method called the inactive duration method has been developed to determine momentary BNs, average BNs, and BN shifting in production lines with and without buffer. This method finds the root causes of BN through a back tracking process. Case studies performed in this research shows that the new method is more effective than active duration method. The BN determination for different types of production lines with three levels of variability is analyzed. Case studies are conducted for production lines with and without buffer. From the case study results, it is evident that increase in variability increases the BN time of the production lines.

In the literature, shiftiness proposed by Lawrence and Buss (1995) is the existing characteristic to analyze BNs. But this characteristic failed to identify shifting BNs between different machines and severity of BNs in production system. Therefore, to capture the BN shifting in production lines and severity of bottleneck machines in production lines, four new BN characteristics are proposed. These characteristics are - a) Bottleneck time ratio, b) Bottleneck ratio, c) Bottleneck shifting frequency, and d) Bottleneck Severity ratio. Increase in bottleneck characteristics indicate increase in bottleneck time and shifting of bottlenecks between different machines in the system. Case studies have shown that the characteristics are useful in explaining the behavior of the manufacturing system.

In production lines with buffer, optimal buffer before each machine is the critical factor in the system. There are different types of buffer determination techniques mentioned in literature. None of them addressed the buffer problem from a BN perspective. A new method for determining optimal buffer size before each machine in the system while considering root causes of BN has been developed. Inclusion of buffers reduces the BN time and BN shifting. Simultaneously, increase in buffer space increases the WIP inventory. Hence, an optimal buffer is determined for each case as a tradeoff point between BN time and WIP. Inclusion of optimal buffer in the production lines reduced the BN time in all the case studies conducted. The reason for the reduction of BN time is due to elimination of buffer bottlenecks in the production lines. Starving and blocking time due to buffer has been eliminated due to optimal buffer inclusion. Case study results show that addition of optimal buffer spaces decreases BN time. It is also observed that inclusion of buffer spaces decreases bottleneck characteristics of the production lines with buffer.

Based on the determination of BN and BN characteristics, control strategies have been developed for different scenarios. Each BN characteristic is considered at two levels (low and high) which lead to 120 scenarios. Unrealistic and infeasible scenarios are eliminated, which reduced the total number of possible scenarios to twelve. Two control strategies – increase in buffer and increase in capacity of BN machines -have been used to study the scenarios. The cases studies provide insight into the appropriate action to be taken while considering the reduction of the impact of BNs. It gives the user an idea to select the appropriate option based on their system performance, target level, application, and profit margin of the product.

Therefore, in this research work BN identification for production lines with and without buffer, BN characteristics to identify the current state of the production system, optimal buffer size determination heuristic, and control strategies to mitigate bottlenecking effect in the production line are developed. This research also proved that increase in variability increases the BN characteristics in production lines with no buffer and with optimal buffer.

6.2 Future Research

Decrease in BN time has been observed after inclusion of optimal buffers in production line. In some cases, addition of optimal buffers before each machine is not possible due to space constraint in a manufacturing plant. So, number of buffers can be reduced by having common storage areas (buffer) at optimal locations for a group of workstations. In this research, the focus was on single product assembly lines. Research in multiple product line has to be undertaken. BN identification methods, buffer size determination, and buffer allocation point can be determined for multiple product manufacturing lines. The scope of this problem may be expanded with alternate routing strategies in multiple product production lines. Thus, this research forms a platform to extend towards different practical conditions in production lines.

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APPENDICES

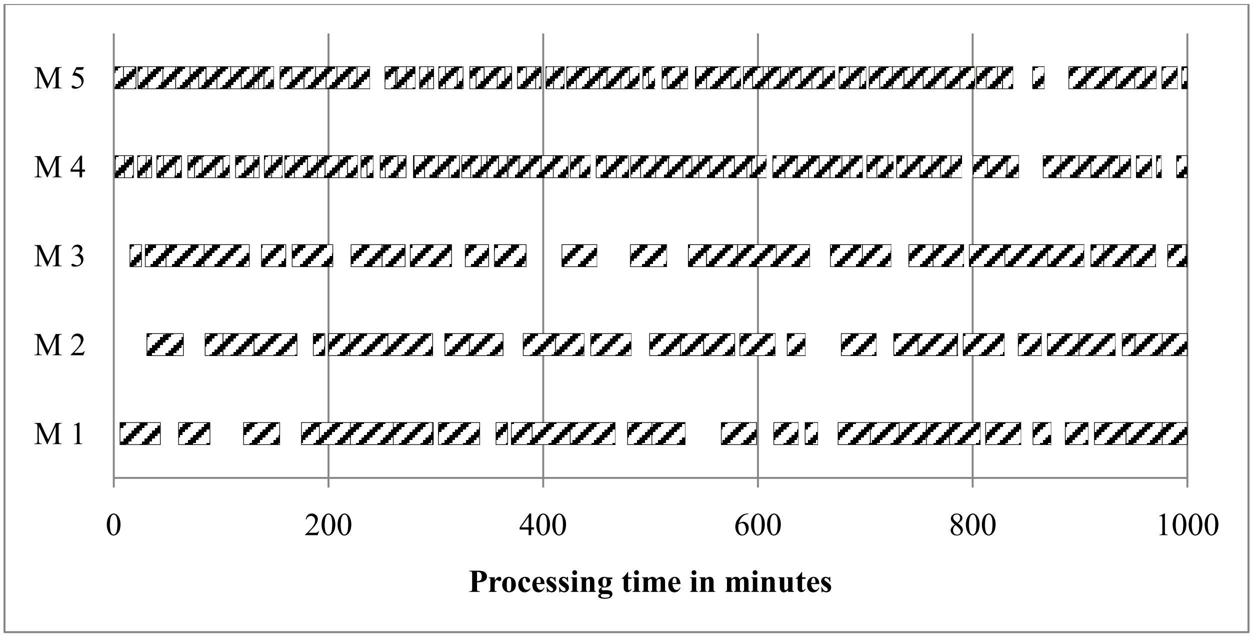
APPENDIX A

PROCESSING TIMES OF EACH MACHINE IN ALL CASE STUDIES

Machine	**Processing Time In Minutes**						
	Case Study 2	**Case Study 3**	**Case Study 4**	**Case Study 5**	**Case Study 6**	**Case Study 7**	**Case Study 8**
M 1	30	40	70	40	40	40	40
M 2	30	40	70	40	40	40	40
M 3	30	40	70	40	40	40	40
M 4	10	40	70	40	40	40	40
M 5	10	40	70	40	20	40	20
M 6	N/A	40	70	40	40	40	40
M 7	N/A	40	70	40	40	40	40
M 8	N/A	N/A	10	40	40	40	20
M 9	N/A	N/A	10	40	40	40	40
M 10	N/A	N/A	10	40	N/A	40	40
M 11	N/A	N/A	10	N/A	N/A	40	40
M 12	N/A	N/A	N/A	N/A	N/A	40	N/A

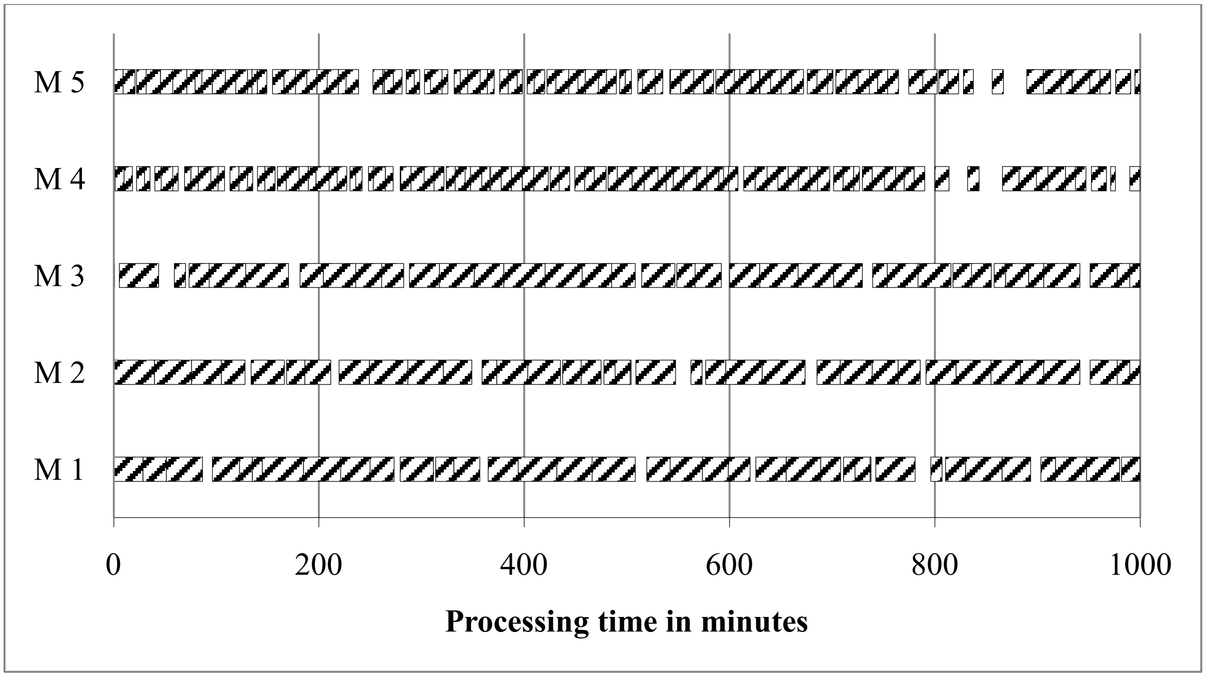
APPENDIX B

PROCESSING TIME CHART OF CASE STUDY 2 WITH HIGH VARIABILITY - NO BUFFER CASE



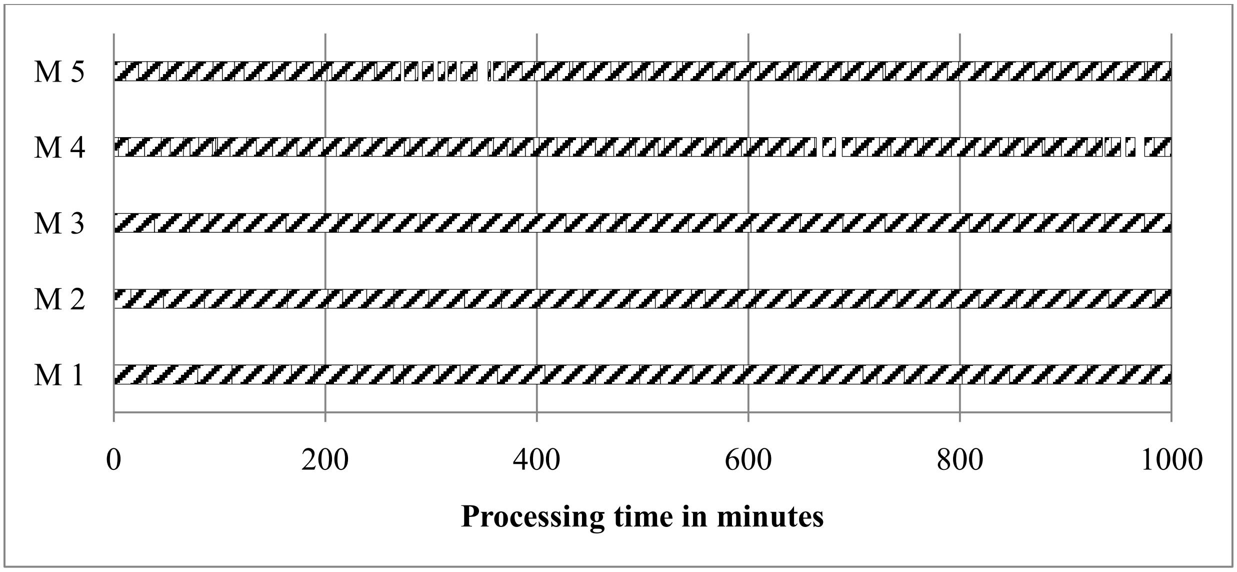
APPENDIX C

PROCESSING TIME CHART OF CASE STUDY 2 WITH MEDIUM VARIABILITY - NO BUFFER CASE



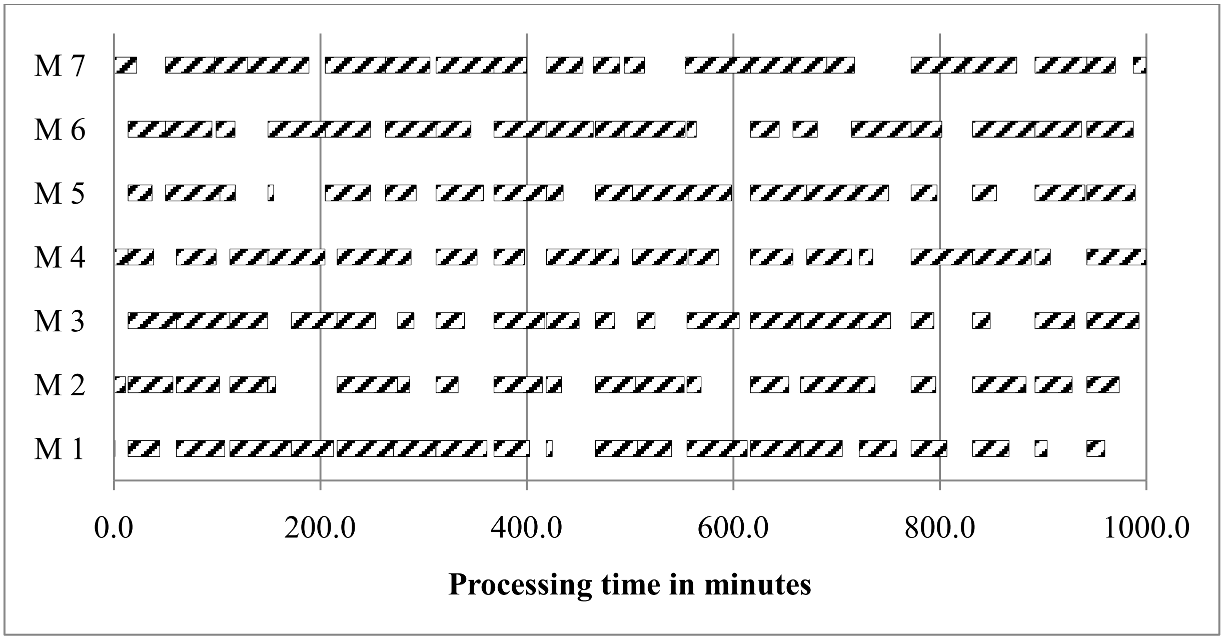
APPENDIX D

PROCESSING TIME CHART OF CASE STUDY 2 WITH LOW VARIABILITY - NO BUFFER CASE



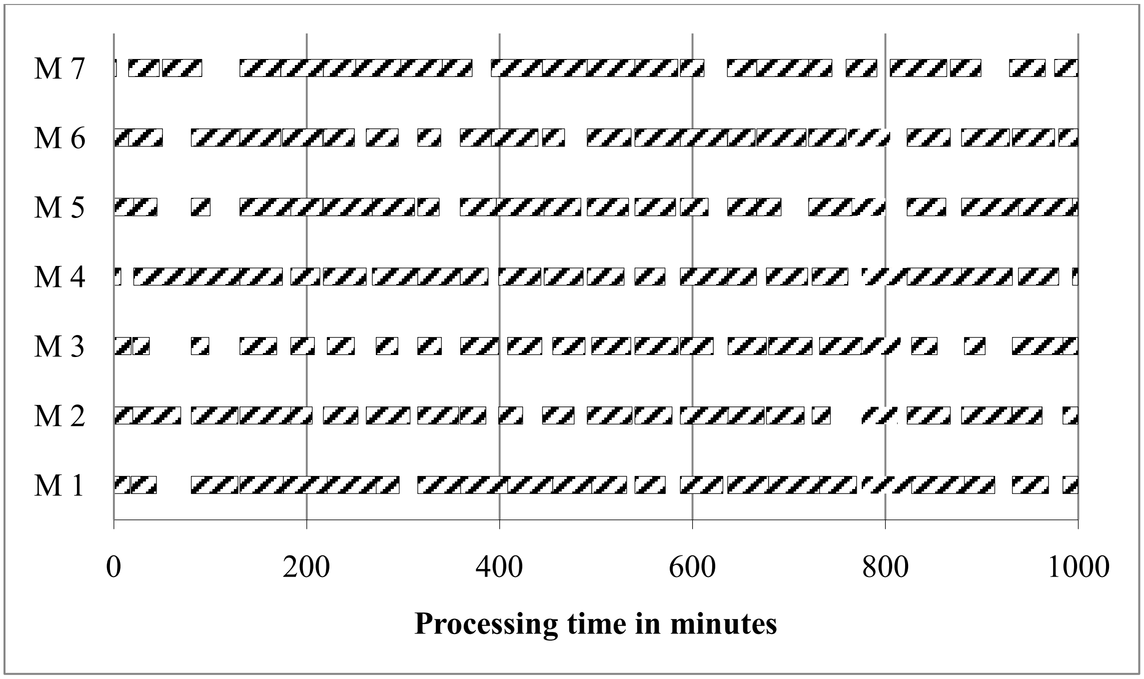
APPENDIX E

PROCESSING TIME CHART OF CASE STUDY 3 WITH HIGH VARIABILITY - NO BUFFER CASE



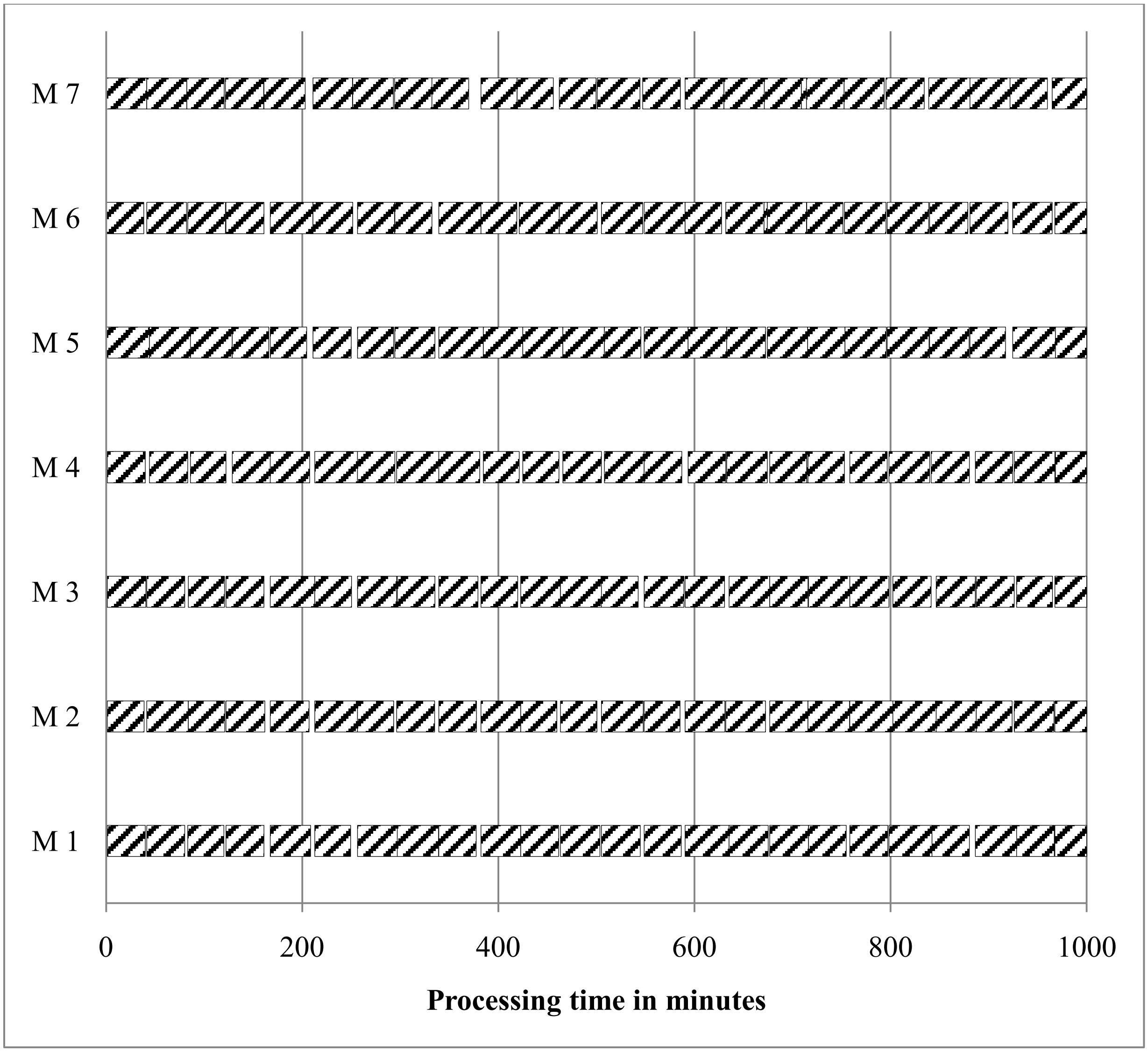
APPENDIX F

PROCESSING TIME CHART OF CASE STUDY 3 WITH MEDIUM VARIABILITY - NO BUFFER CASE



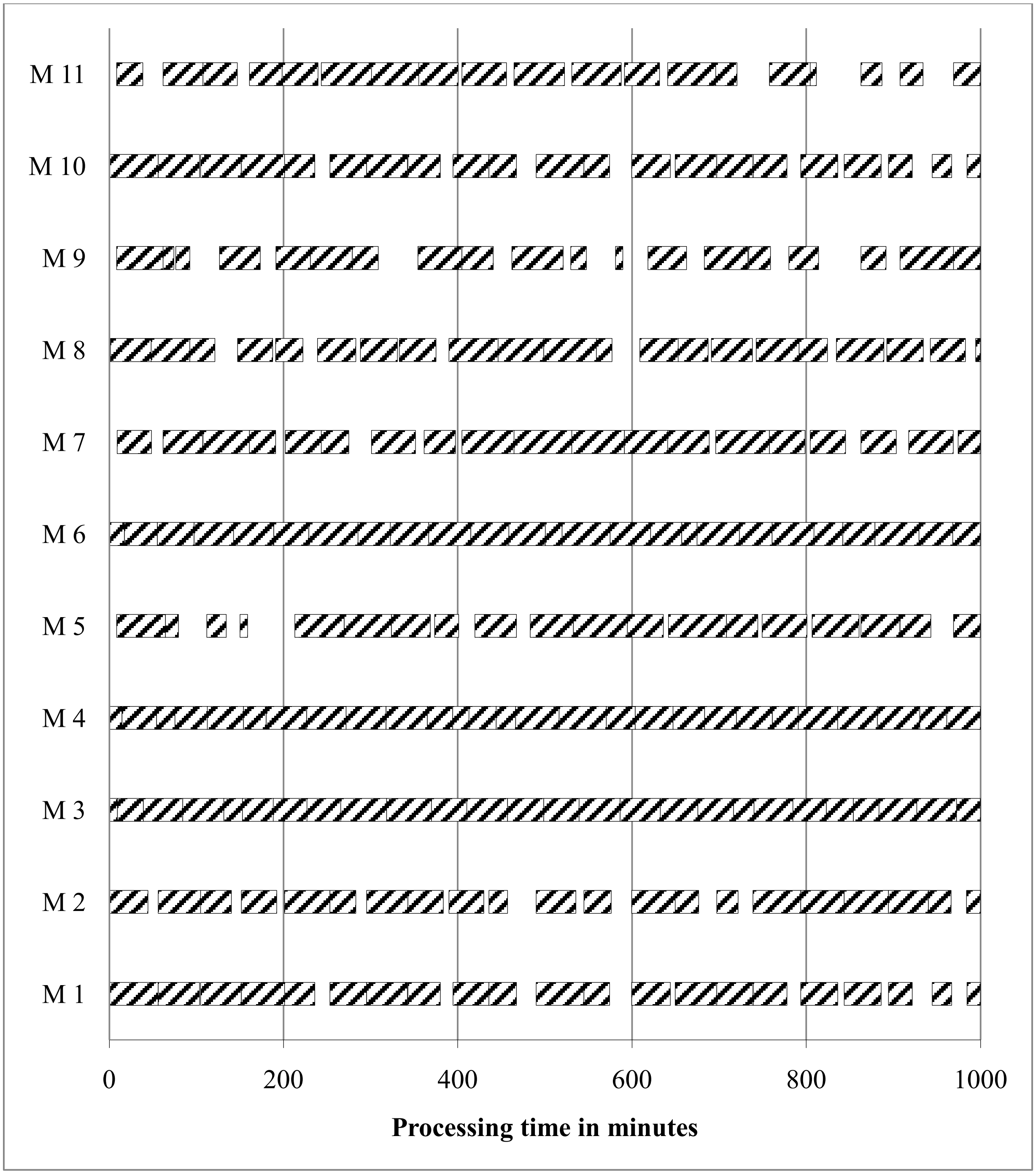
APPENDIX G

PROCESSING TIME CHART OF CASE STUDY 3 WITH LOW VARIABILITY - NO BUFFER CASE



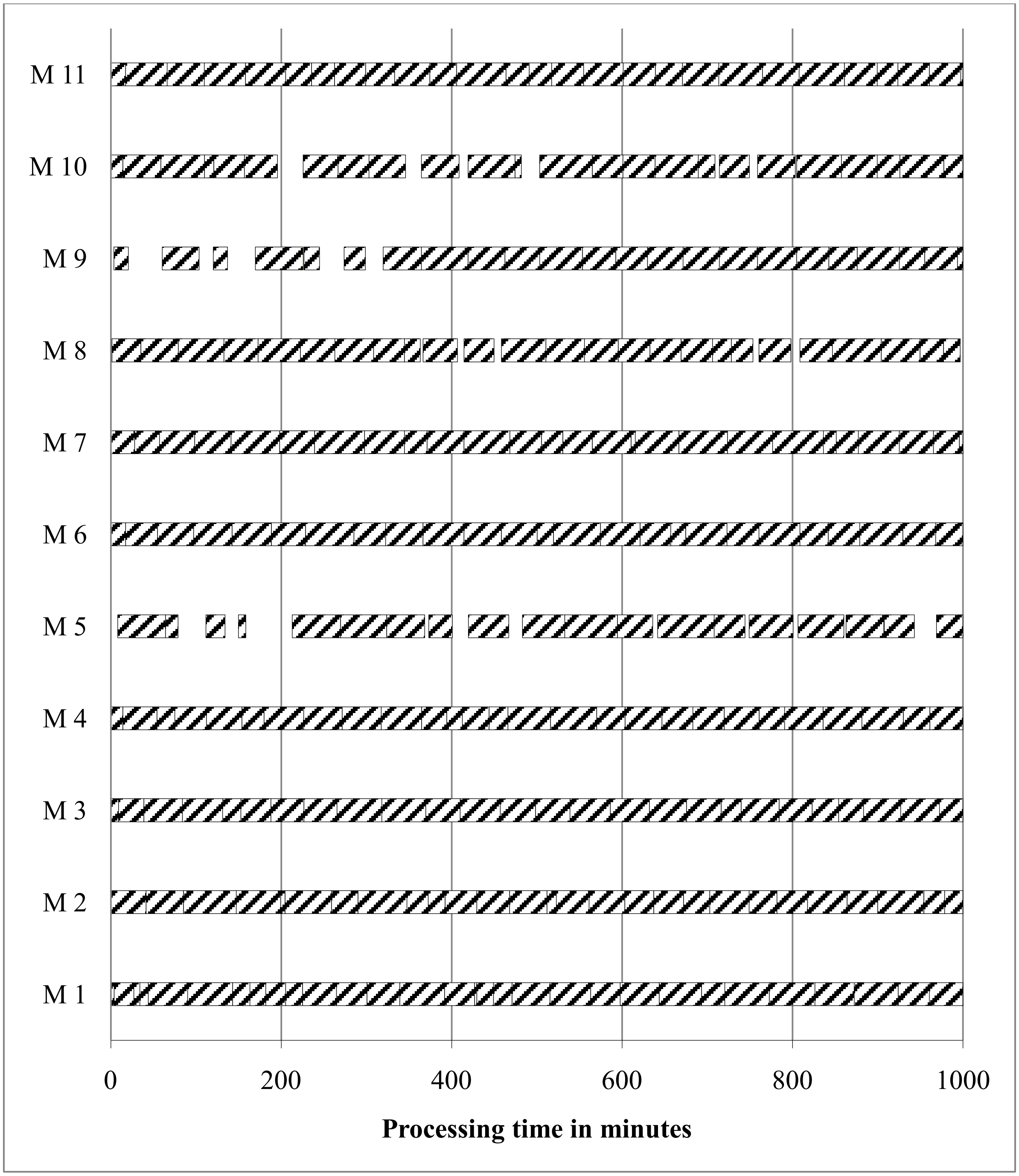
APPENDIX H

PROCESSING TIME CHART OF CASE STUDY 4 WITH HIGH VARIABILITY - NO BUFFER CASE



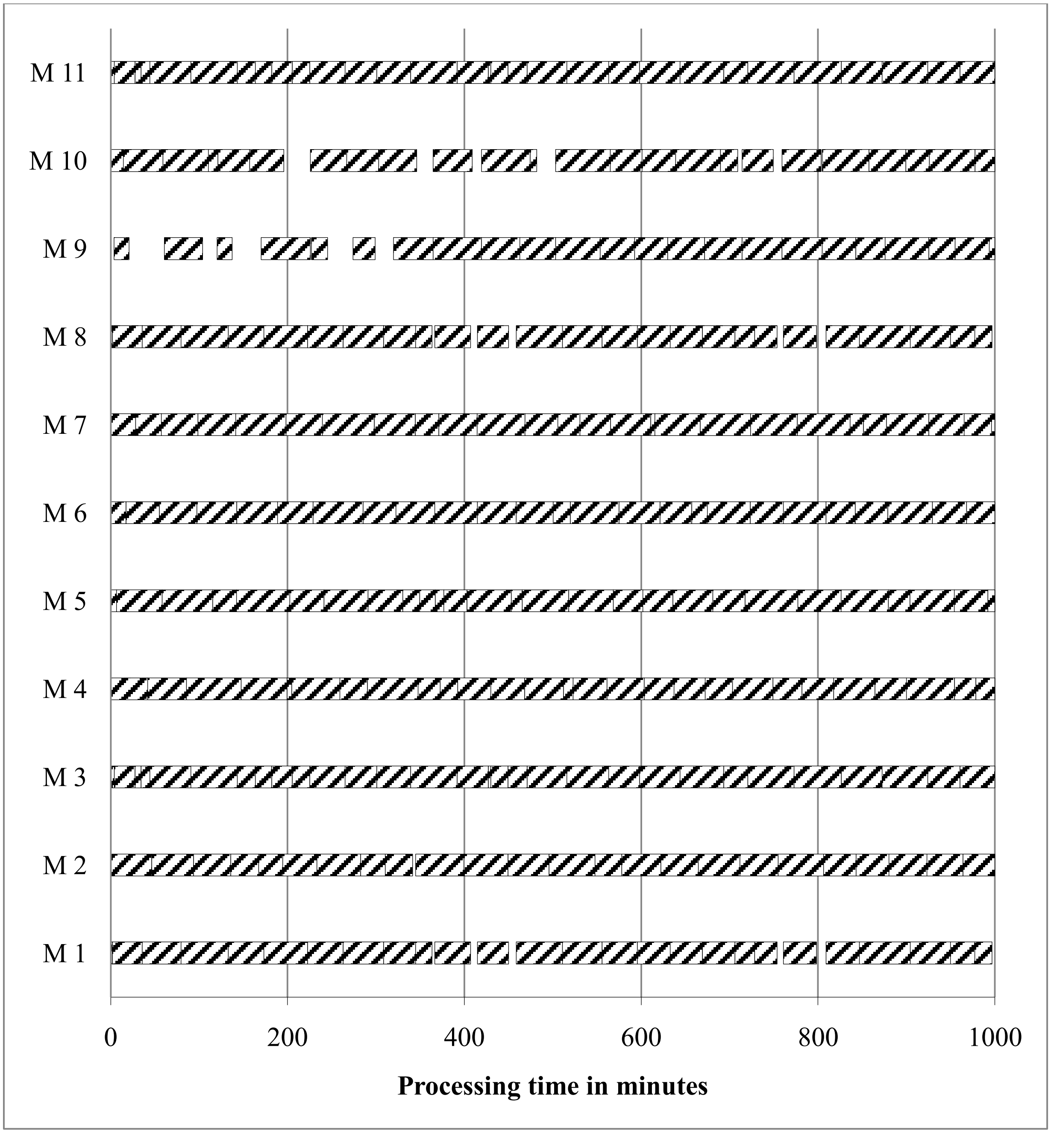
APPENDIX I

PROCESSING TIME CHART OF CASE STUDY 4 WITH MEDIUM VARIABILITY - NO BUFFER CASE



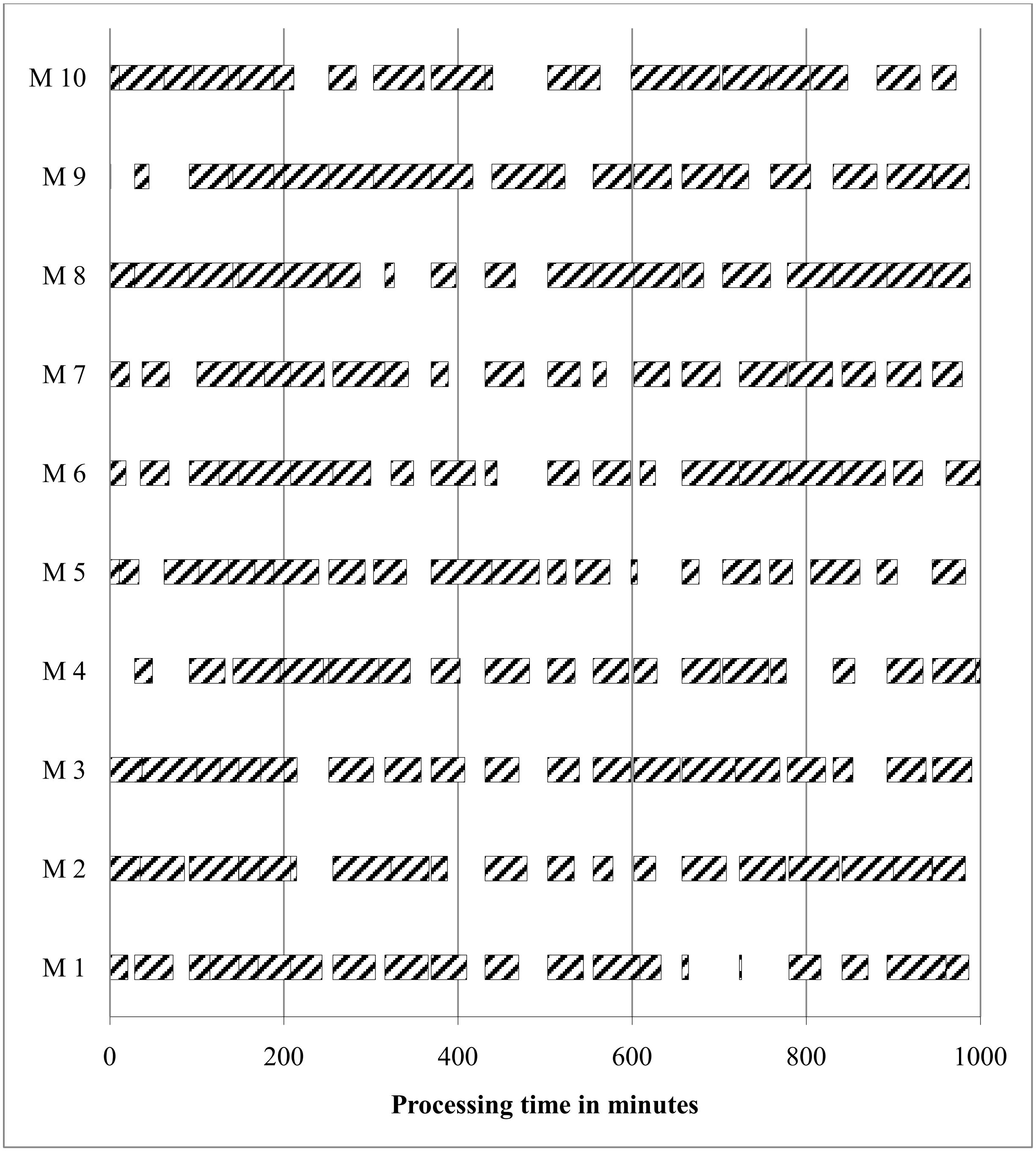
APPENDIX J

PROCESSING TIME CHART OF CASE STUDY 4 WITH LOW VARIABILITY - NO BUFFER CASE



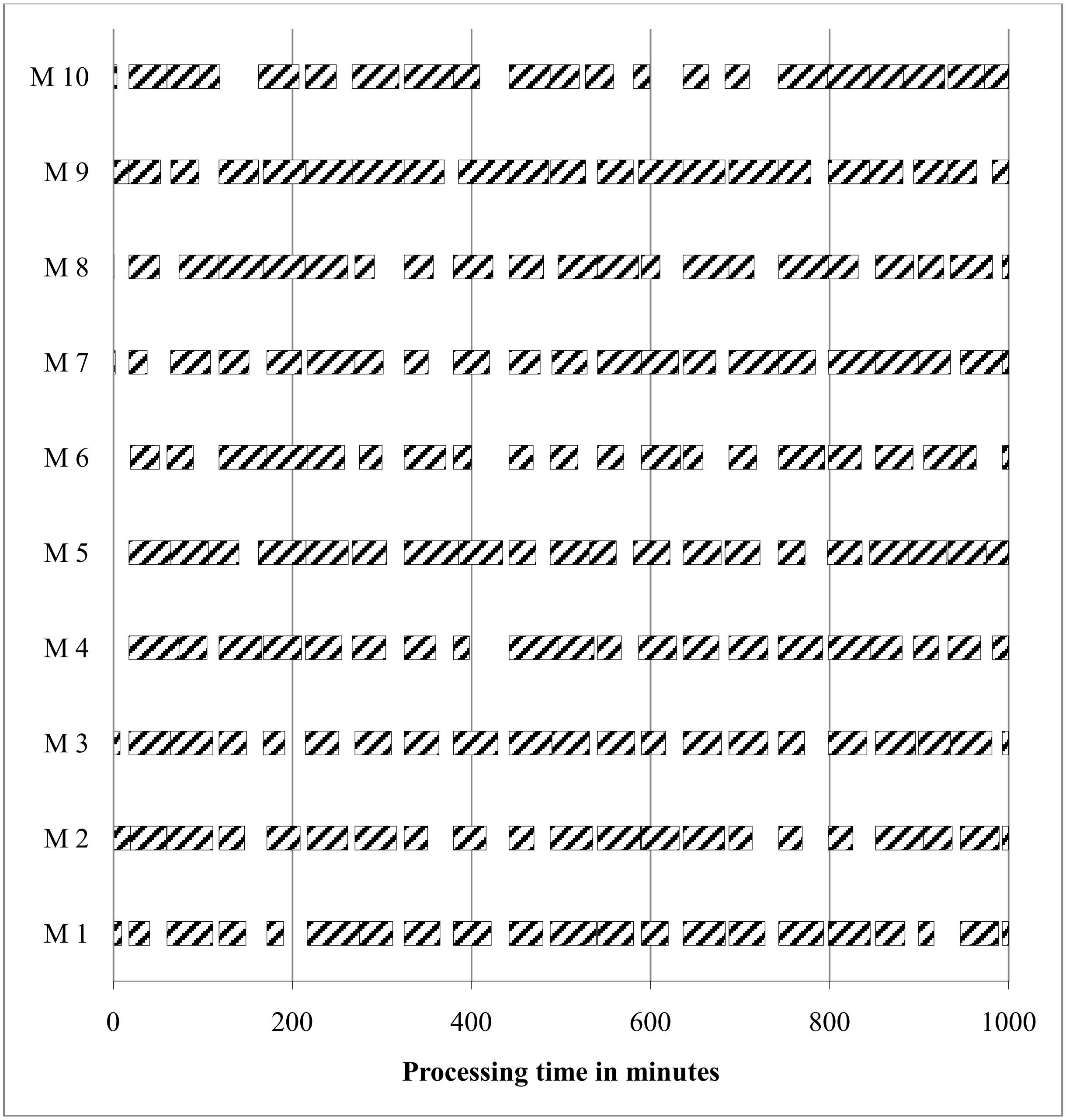
APPENDIX K

PROCESSING TIME CHART OF CASE STUDY 5 WITH HIGH VARIABILITY - NO BUFFER CASE



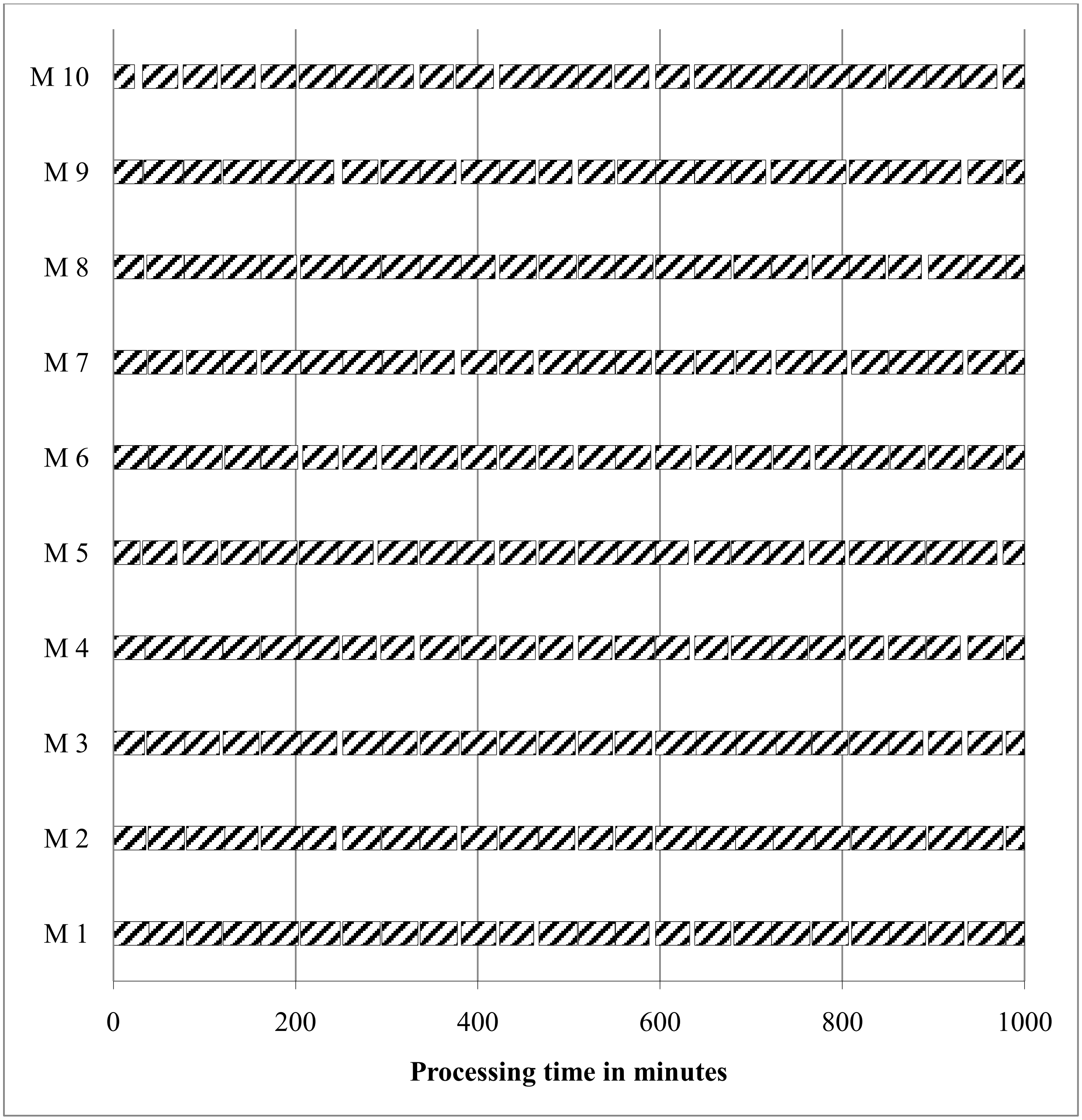
APPENDIX L

PROCESSING TIME CHART OF CASE STUDY 5 WITH MEDIUM VARIABILITY - NO BUFFER CASE



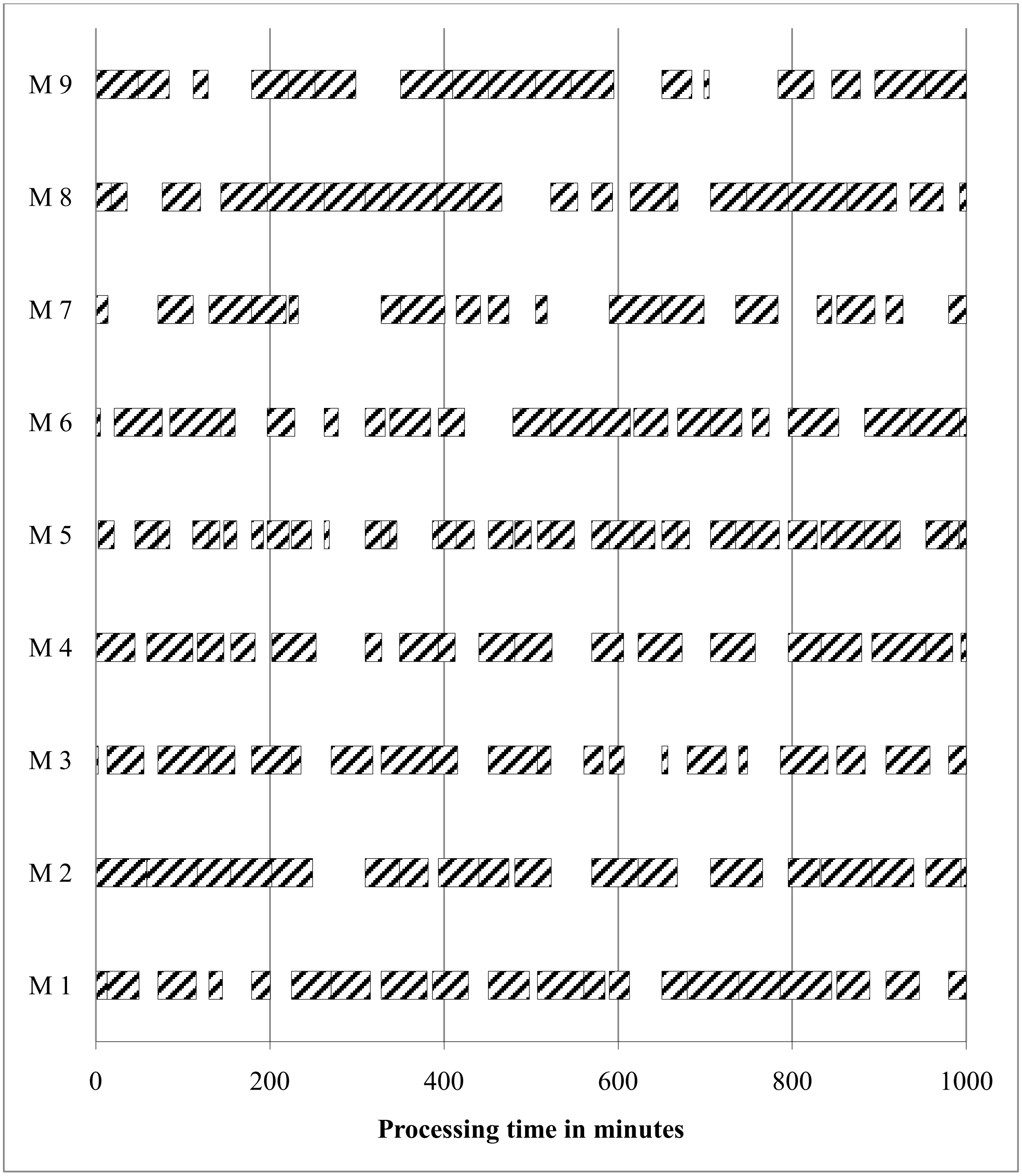
APPENDIX M

PROCESSING TIME CHART OF CASE STUDY 5 WITH LOW VARIABILITY - NO BUFFER CASE



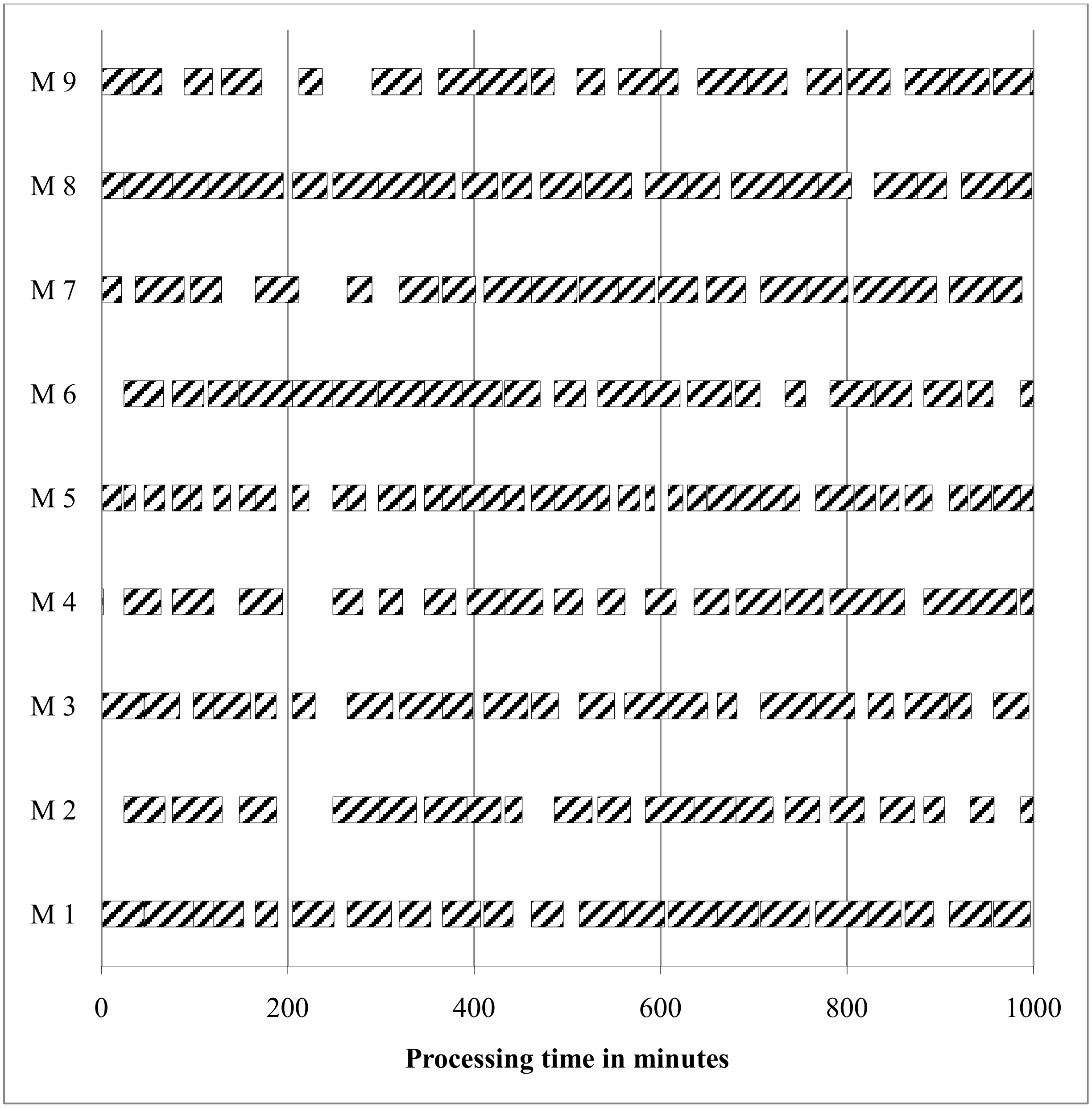
APPENDIX N

PROCESSING TIME CHART OF CASE STUDY 6 WITH HIGH VARIABILITY - NO BUFFER CASE



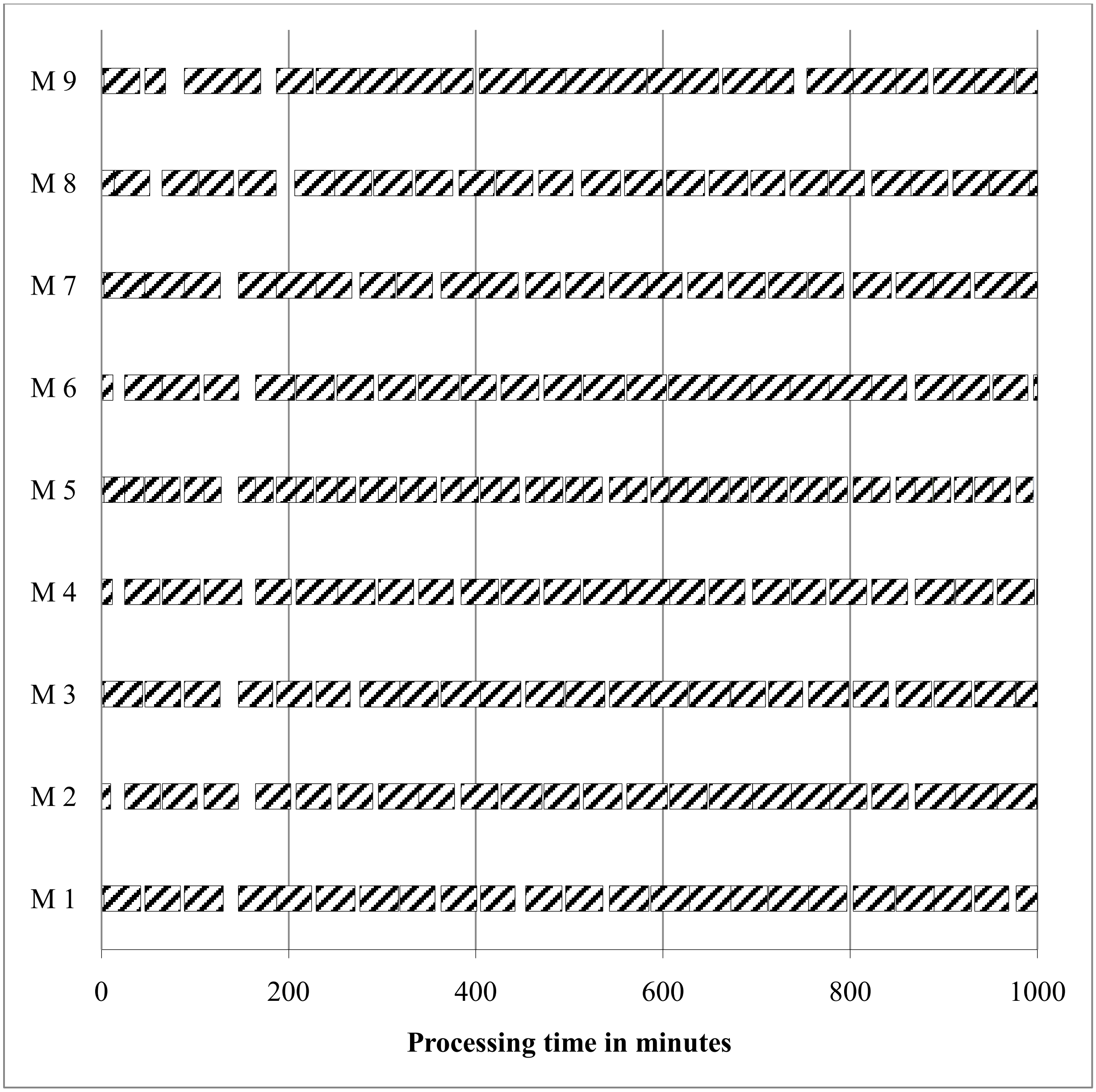
APPENDIX O

PROCESSING TIME CHART OF CASE STUDY 6 WITH MEDIUM VARIABILITY - NO BUFFER CASE



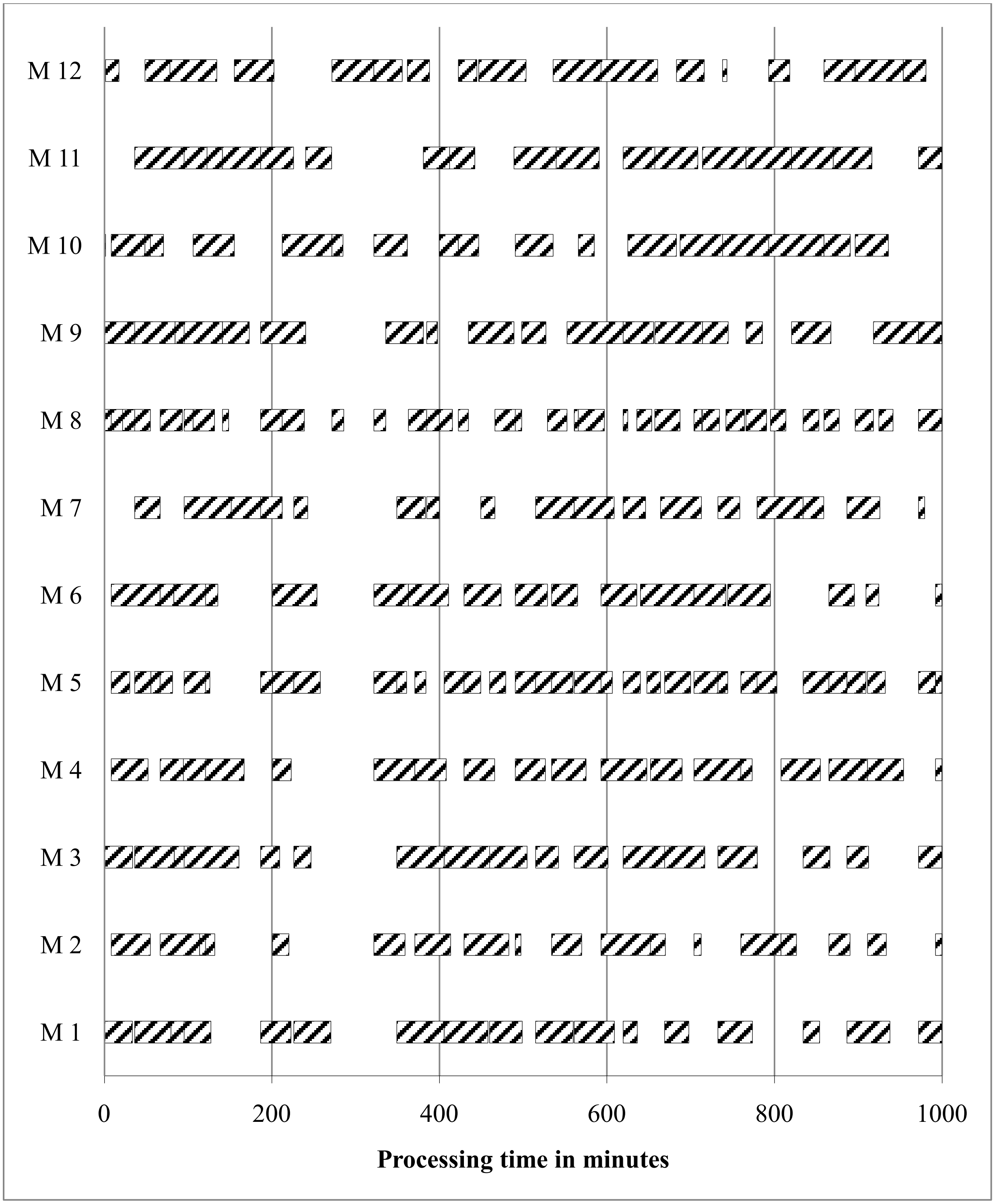
APPENDIX P

PROCESSING TIME CHART OF CASE STUDY 6 WITH LOW VARIABILITY - NO BUFFER CASE



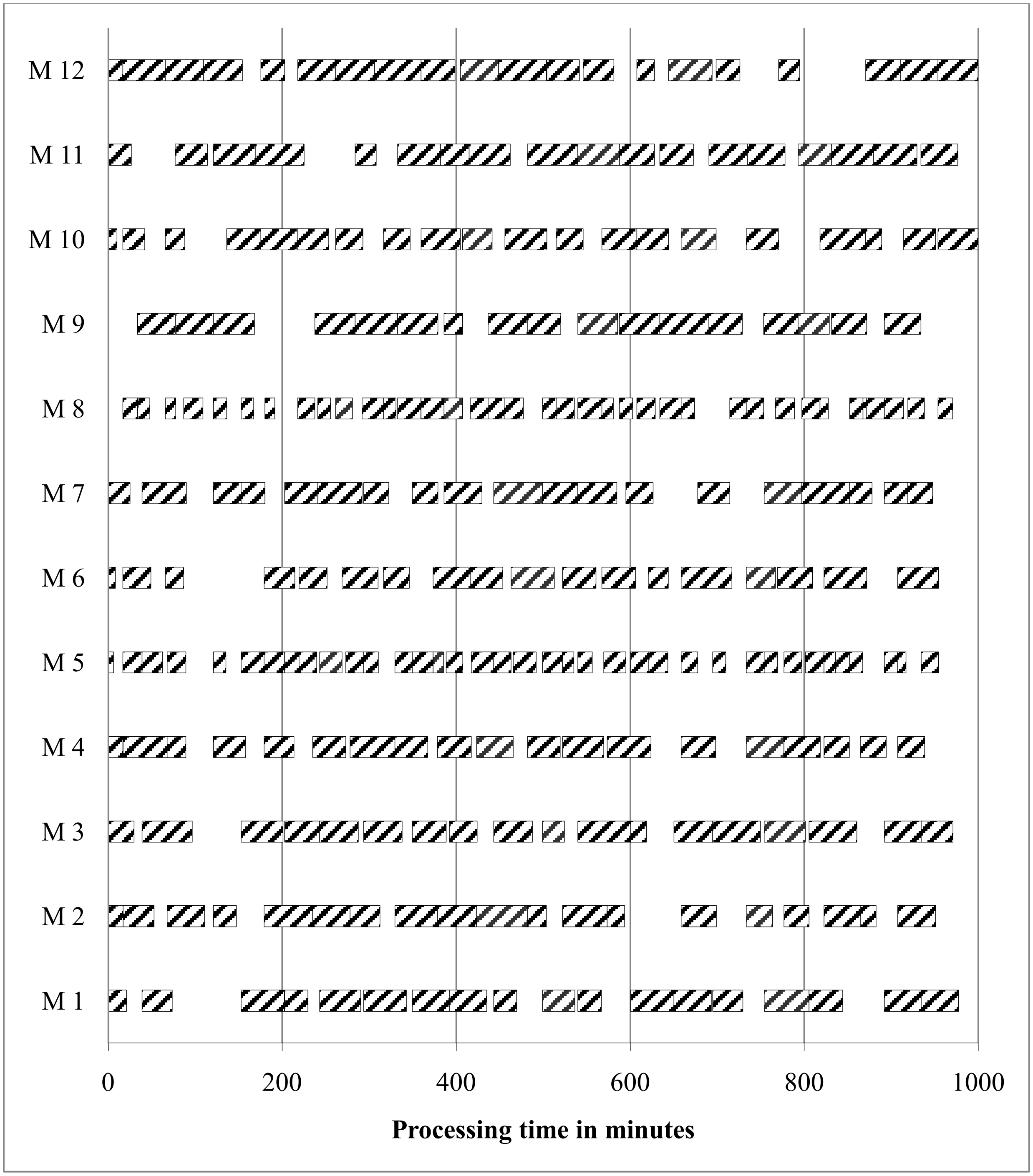
APPENDIX Q

PROCESSING TIME CHART OF CASE STUDY 7 WITH HIGH VARIABILITY - NO BUFFER CASE



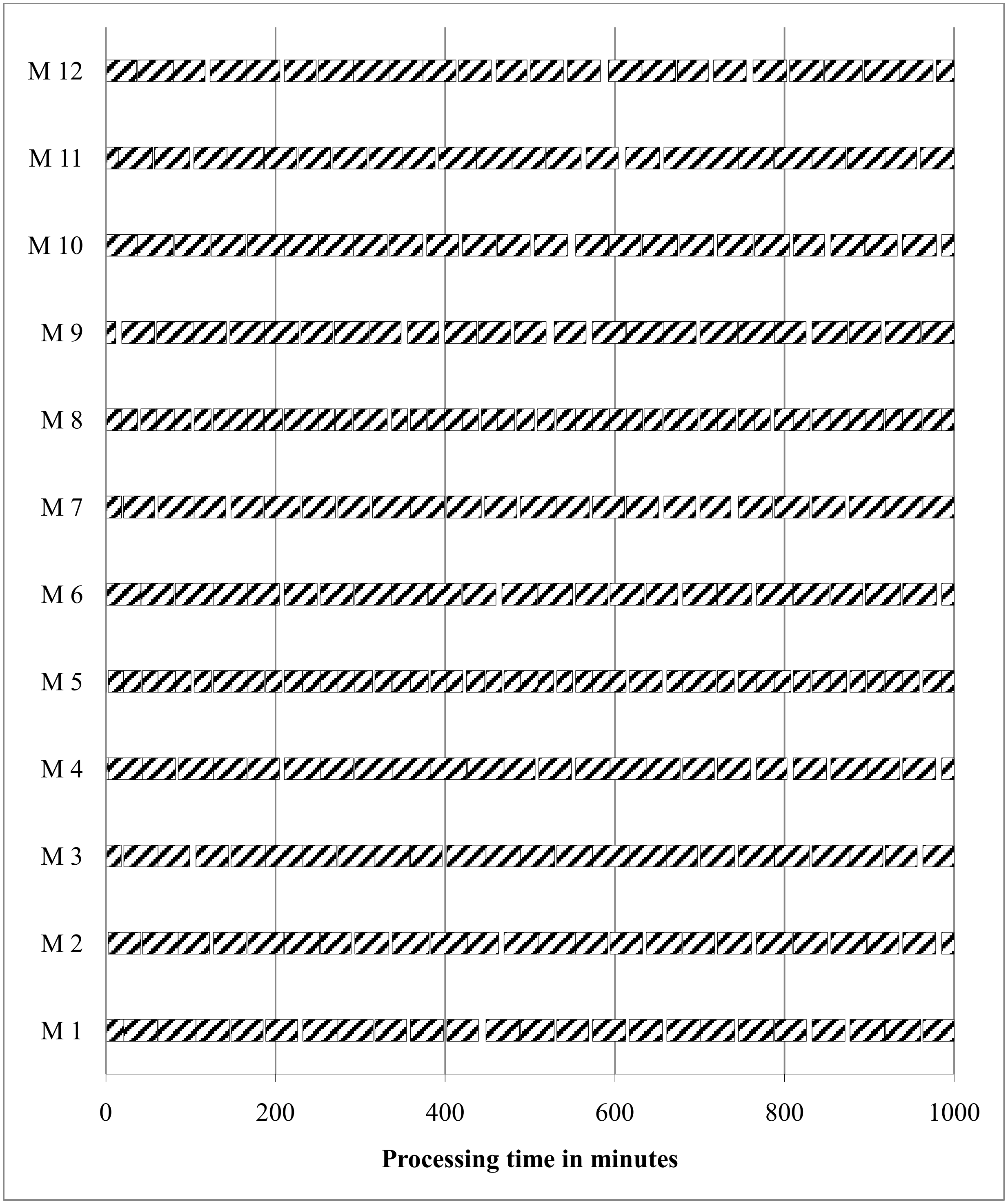
APPENDIX R

PROCESSING TIME CHART OF CASE STUDY 7 WITH MEDIUM VARIABILITY - NO BUFFER CASE



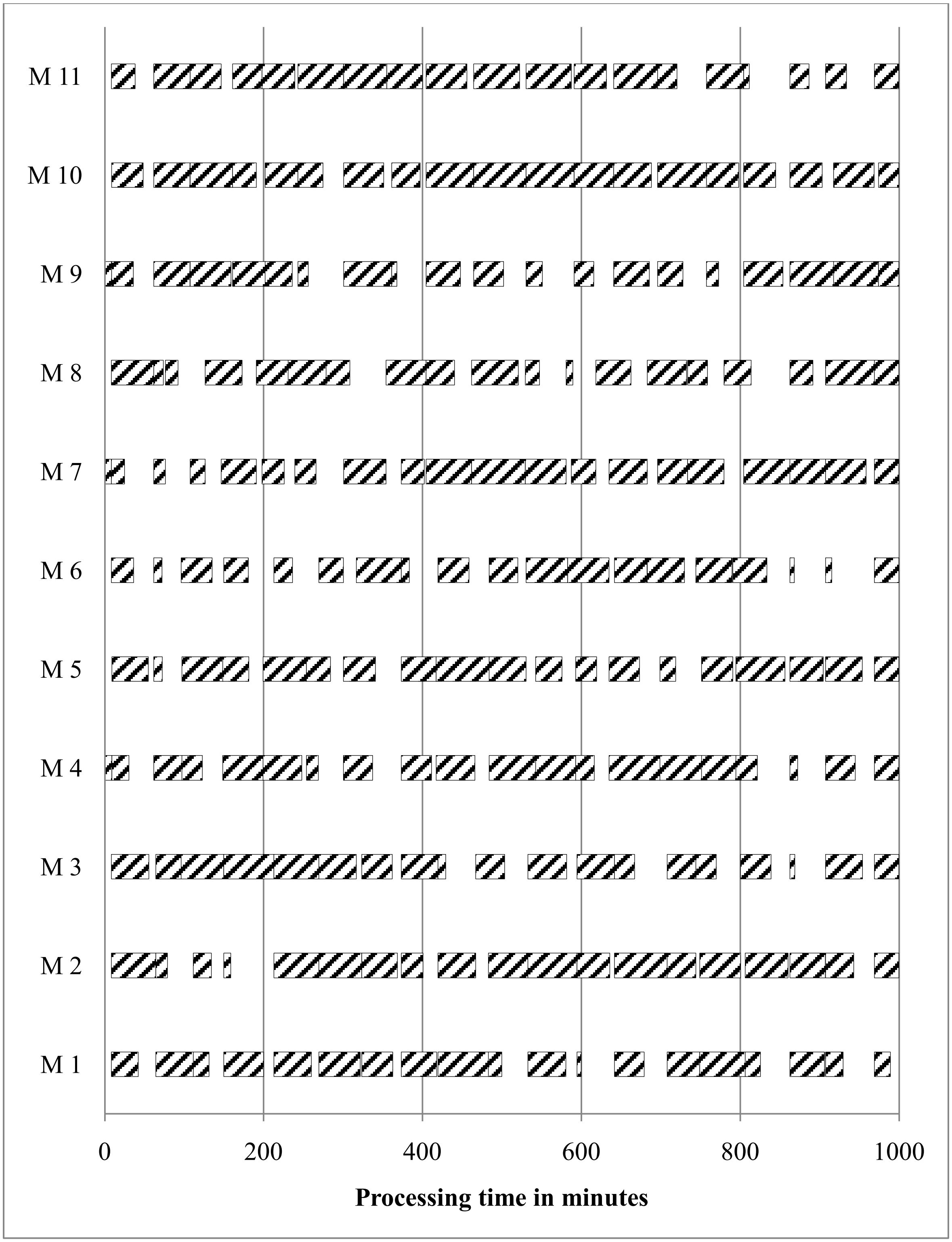
APPENDIX S

PROCESSING TIME CHART OF CASE STUDY 7 WITH LOW VARIABILITY - NO BUFFER CASE



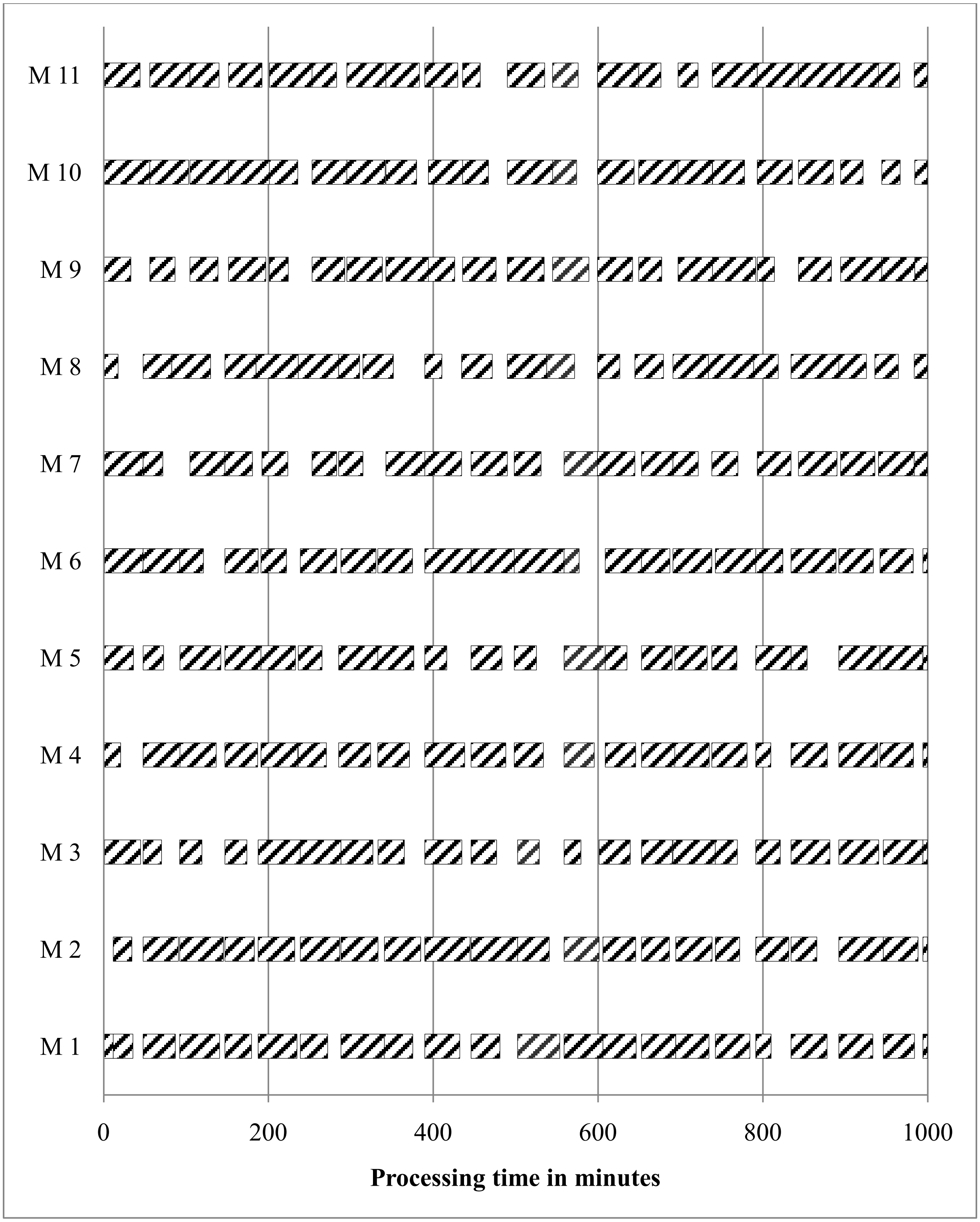
APPENDIX T

PROCESSING TIME CHART OF CASE STUDY 8 WITH HIGH VARIABILITY - NO BUFFER CASE



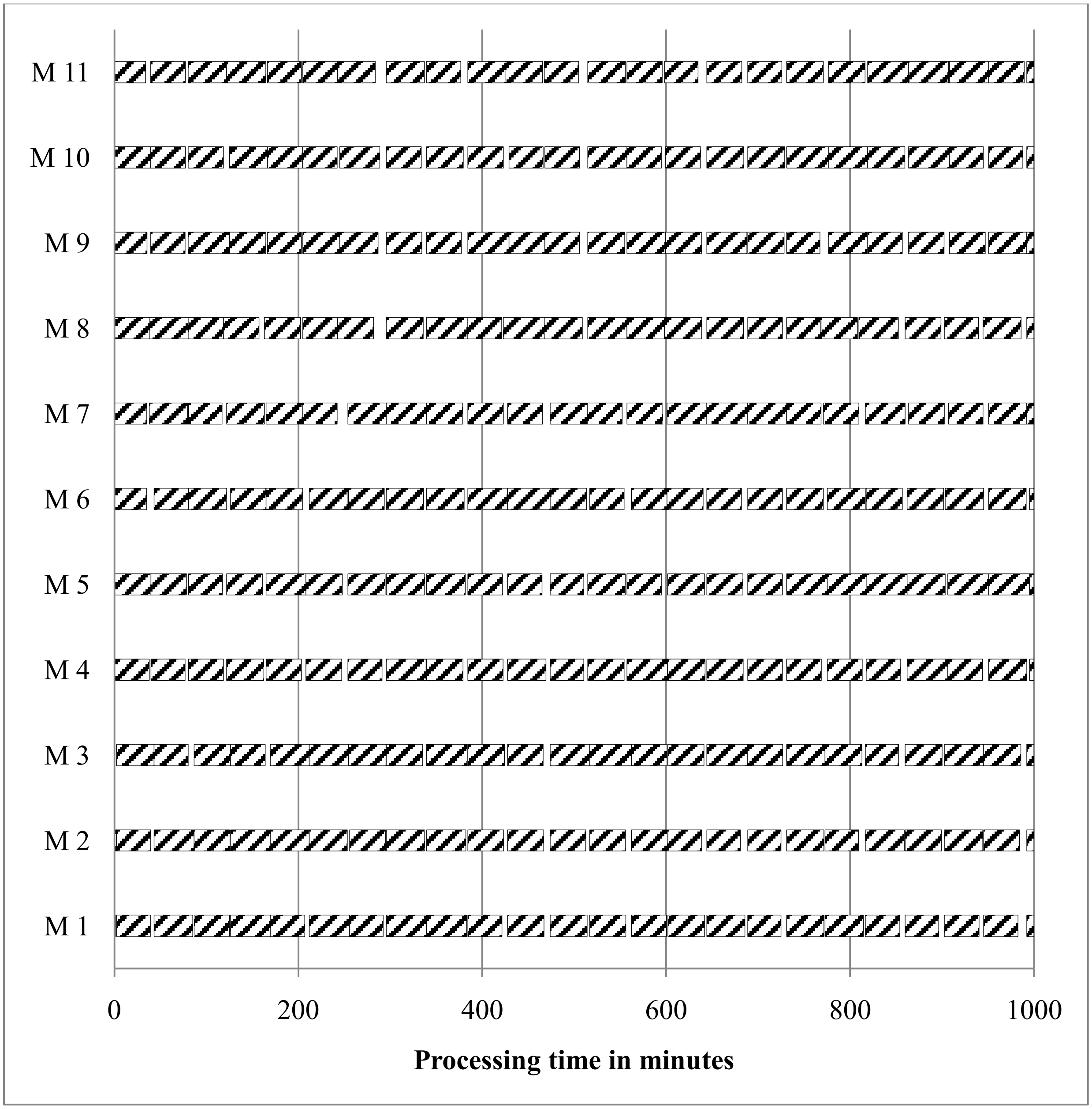
APPENDIX U

PROCESSING TIME CHART OF CASE STUDY 8 WITH MEDIUM VARIABILITY - NO BUFFER CASE



APPENDIX V

PROCESSING TIME CHART OF CASE STUDY 8 WITH LOW VARIABILITY - NO BUFFER CASE



APPENDIX W

BN TIME OF EACH MACHINE IN CASE STUDY 2 - NO BUFFER CASE

Machine	**BN Time in Minutes**		
	High Variability	**Medium Variability**	**Low Variability**
M 1	86.3899	67.3899	26.3899
M 2	71.1033	51.1033	31.1033
M 3	143.57	72.5696	28.5696
M 4	112.342	69.3423	24.3423
M 5	92.2345	38.2345	11.2345
Total BN time	505.64	298.64	121.64

APPENDIX X

BN TIME OF EACH MACHINE IN CASE STUDY 3 - NO BUFFER CASE

Machine	BN Time in Minutes		
	High Variability	Medium Variability	Low Variability
M 1	22.91	133.2	8.12
M 2	21.41	31.6646	23.18
M 3	188.8	110.145	36.36
M 4	218.89	170.661	63.56
M 5	1.23	52.1685	35.73
M 6	310.97	186.815	56.55
M 7	125.65	97.2941	3.08
Total BN time	889.86	781.948	226.58

APPENDIX Y

BN TIME OF EACH MACHINE IN CASE STUDY 4 - NO BUFFER CASE

Machine	**BN Time in Minutes**		
	High Variability	**Medium Variability**	**Low Variability**
M 1	0	0	0
M 2	0	0	0
M 3	300.345	178.568	98.457
M 4	198.459	94.67	56.789
M 5	0	0	0
M 6	129.567	98.432	45.78
M 7	189.64	56.89	11.789
M 8	34.789	67.543	34.789
M 9	45.89	0	0
M 10	67.568	12.789	0
M 11	0	0	0
Total BN time	966.258	508.892	247.604

APPENDIX Z

BN TIME OF EACH MACHINE IN CASE STUDY 5 - NO BUFFER CASE

Machine	**BN Time in Minutes**		
	High Variability	**Medium Variability**	**Low Variability**
M 1	0	0	0
M 2	0	0	0
M 3	300.345	178.568	98.457
M 4	198.459	94.67	56.789
M 5	0	0	0
M 6	129.567	98.432	45.78
M 7	189.64	56.89	11.789
M 8	34.789	67.543	34.789
M 9	45.89	0	0
M 10	67.568	12.789	0
Total BN time	966.258	508.892	247.604

APPENDIX AA

BN TIME OF EACH MACHINE IN CASE STUDY 6 - NO BUFFER CASE

Machine	**BN Time in Minutes**		
	High Variability	**Medium Variability**	**Low Variability**
M 1	143.14	35.8746	5.44139
M 2	105.173	56.6454	28.1145
M 3	78.0067	70.7368	19.536
M 4	96.8183	49.4069	14.5567
M 5	580.638	399.507	122.275
M 6	257.753	200.823	102.243
M 7	347.915	295.48	84.5119
M 8	169.054	90.0102	11.5703
M 9	53.7934	22.4037	88.8371
Total BN time	1832.29	1220.89	477.086

APPENDIX AB

BN TIME OF EACH MACHINE IN CASE STUDY 7 - NO BUFFER CASE

Machine	**BN Time in Minutes**		
	High Variability	**Medium Variability**	**Low Variability**
M 1	24.23	40.1011	23.4391
M 2	38.7933	138.333	9.25285
M 3	65.2327	134.126	37.5235
M 4	87.2144	76.7166	30.8933
M 5	676.945	418.952	109.381
M 6	154.981	88.2651	18.6723
M 7	111.217	201.682	26.9847
M 8	485.453	555.343	128.256
M 9	245.277	296.55	62.5926
M 10	351.724	226.049	73.1425
M 11	148.796	226.049	16.452
M 12	120.682	106.243	1.85874
Total BN time	2510.54	2508.41	538.449

APPENDIX AC

BN TIME OF EACH MACHINE IN CASE STUDY 8 - NO BUFFER CASE

Machine	**BN Time In Minutes**		
	High Variability	**Medium Variability**	**Low Variability**
M 1	59.3618	32.3986	4.57398
M 2	196.276	66.2101	20.7166
M 3	238.409	53.4855	38.1264
M 4	143.203	22.9934	9.38121
M 5	74.6555	64.3614	36.969
M 6	85.9027	198.494	51.7393
M 7	333.518	268.521	93.1669
M 8	127.111	77.011	23.0749
M 9	50.0975	55.0151	21.6353
M 10	168.256	115.004	27.3427
M 11	167.588	177.096	19.8063
Total BN time	1644.38	1130.59	346.532

APPENDIX AD

UNIFORM BUFFER SIZE FOR ALL CASE STUDIES

Case Study	**High Variability**	**Medium Variability**	**Low Variability**
Case study 2	5	4	3
Case study 3	5	4	3
Case study 4	5	5	4
Case study 5	6	5	3
Case study 6	9	7	3
Case study 7	8	6	4
Case study 8	8	5	4

APPENDIX AE

OPTIMAL BUFFER SIZES OF EACH MACHINE IN CASE STUDY 2

Machine	**High Variability**	**Medium Variability**	**Low Variability**
M 1	1	1	1
M 2	2	2	1
M 3	5	4	3
M 4	4	3	3
M 5	1	1	1

APPENDIX AF

OPTIMAL BUFFER SIZES OF EACH MACHINE IN CASE STUDY 3

Machine	**High Variability**	**Medium Variability**	**Low Variability**
M 1	1	1	1
M 2	2	2	2
M 3	3	3	2
M 4	4	3	2
M 5	5	4	3
M 6	3	2	2
M 7	2	1	1

APPENDIX AG

OPTIMAL BUFFER SIZES OF EACH MACHINE IN CASE STUDY 4

Machine	**High Variability**	**Medium Variability**	**Low Variability**
M 1	1	1	1
M 2	1	1	1
M 3	6	5	3
M 4	5	4	2
M 5	5	5	4
M 6	5	3	2
M 7	4	3	2
M 8	3	3	2
M 9	3	3	2
M 10	3	2	1
M 11	2	1	1

APPENDIX AH

OPTIMAL BUFFER SIZES OF EACH MACHINE IN CASE STUDY 5

Machine	**High Variability**	**Medium Variability**	**Low Variability**
M 1	1	1	1
M 2	3	3	2
M 3	3	2	2
M 4	4	3	2
M 5	5	4	3
M 6	4	3	2
M 7	6	5	2
M 8	6	5	3
M 9	5	4	2
M 10	2	1	1

APPENDIX AI

OPTIMAL BUFFER SIZES OF EACH MACHINE IN CASE STUDY 6

Machine	**High Variability**	**Medium Variability**	**Low Variability**
M 1	1	1	1
M 2	3	2	1
M 3	7	5	2
M 4	8	6	3
M 5	9	7	3
M 6	7	4	2
M 7	4	3	2
M 8	4	3	2
M 9	2	1	1

APPENDIX AJ

OPTIMAL BUFFER SIZES OF EACH MACHINE IN CASE STUDY 7

Machine	**High Variability**	**Medium Variability**	**Low Variability**
M 1	1	1	1
M 2	4	2	1
M 3	4	3	2
M 4	5	3	3
M 5	8	5	4
M 6	7	6	4
M 7	8	5	3
M 8	7	5	3
M 9	6	4	2
M 10	5	3	2
M 11	4	3	2
M 12	1	1	1

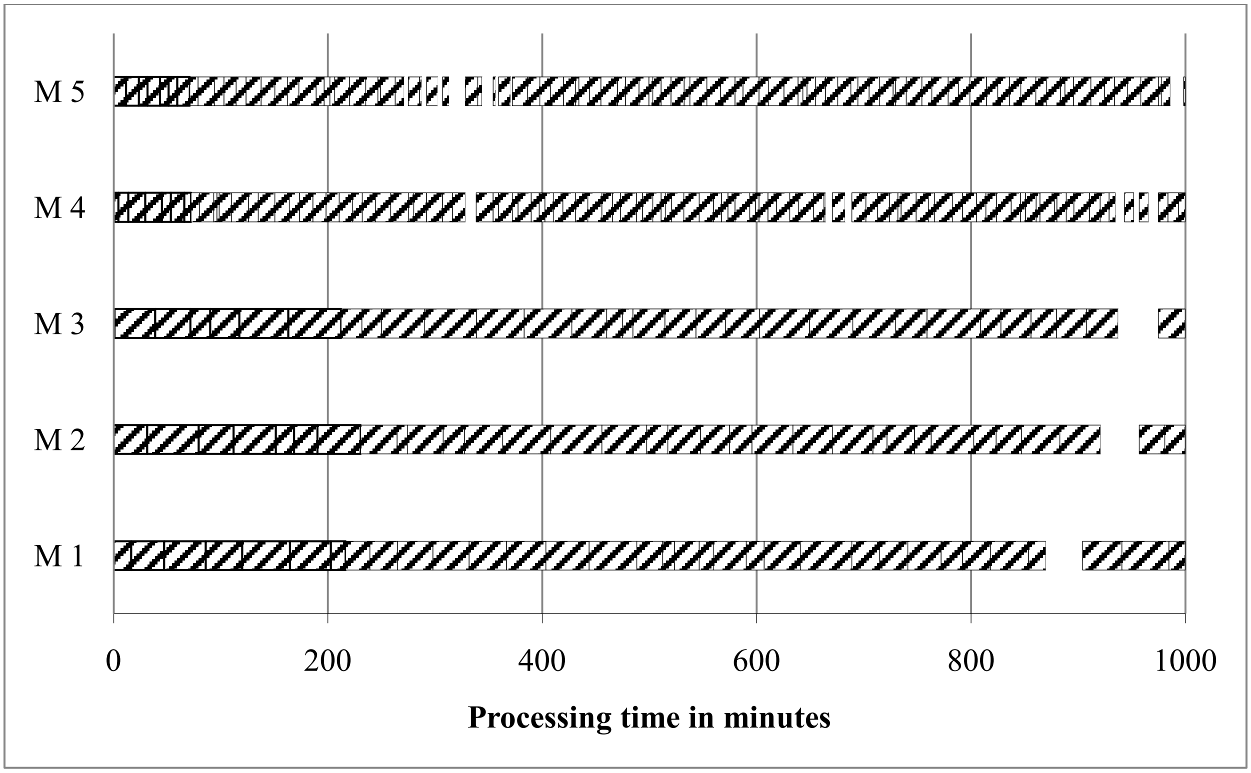
APPENDIX AK

OPTIMAL BUFFER SIZES OF EACH MACHINE IN CASE STUDY 8

Machine	High Variability	Medium Variability	Low Variability
M 1	1	1	1
M 2	4	2	2
M 3	5	3	2
M 4	6	3	2
M 5	6	4	3
M 6	7	5	3
M 7	8	5	4
M 8	7	4	4
M 9	6	3	2
M 10	4	2	2
M 11	1	1	1

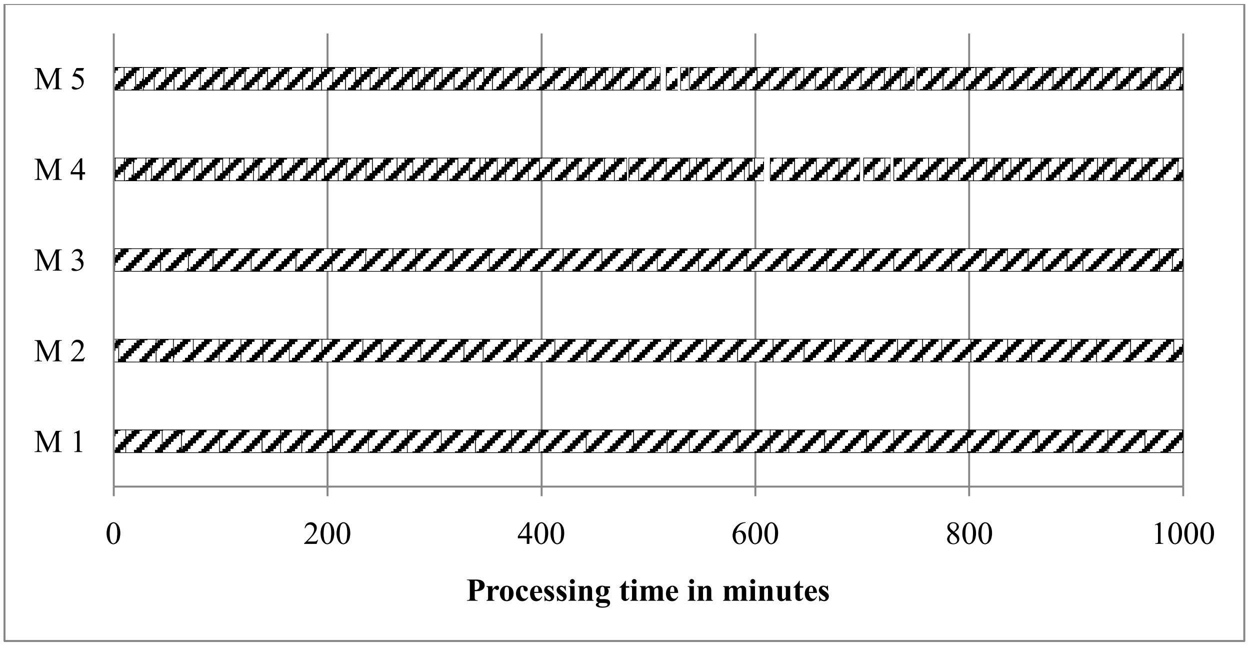
APPENDIX AL

PROCESSING TIME CHART OF CASE STUDY 2 WITH HIGH VARIABILITY - BUFFER CASE



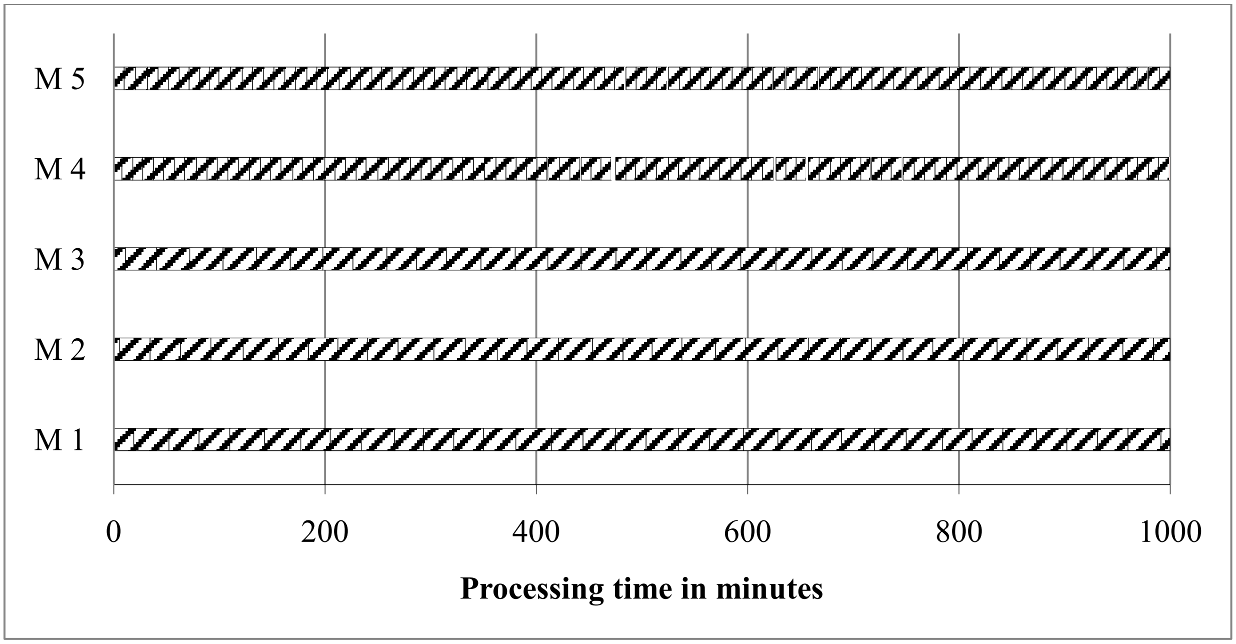
APPENDIX AM

PROCESSING TIME CHART OF CASE STUDY 2 WITH MEDIUM VARIABILITY - BUFFER CASE



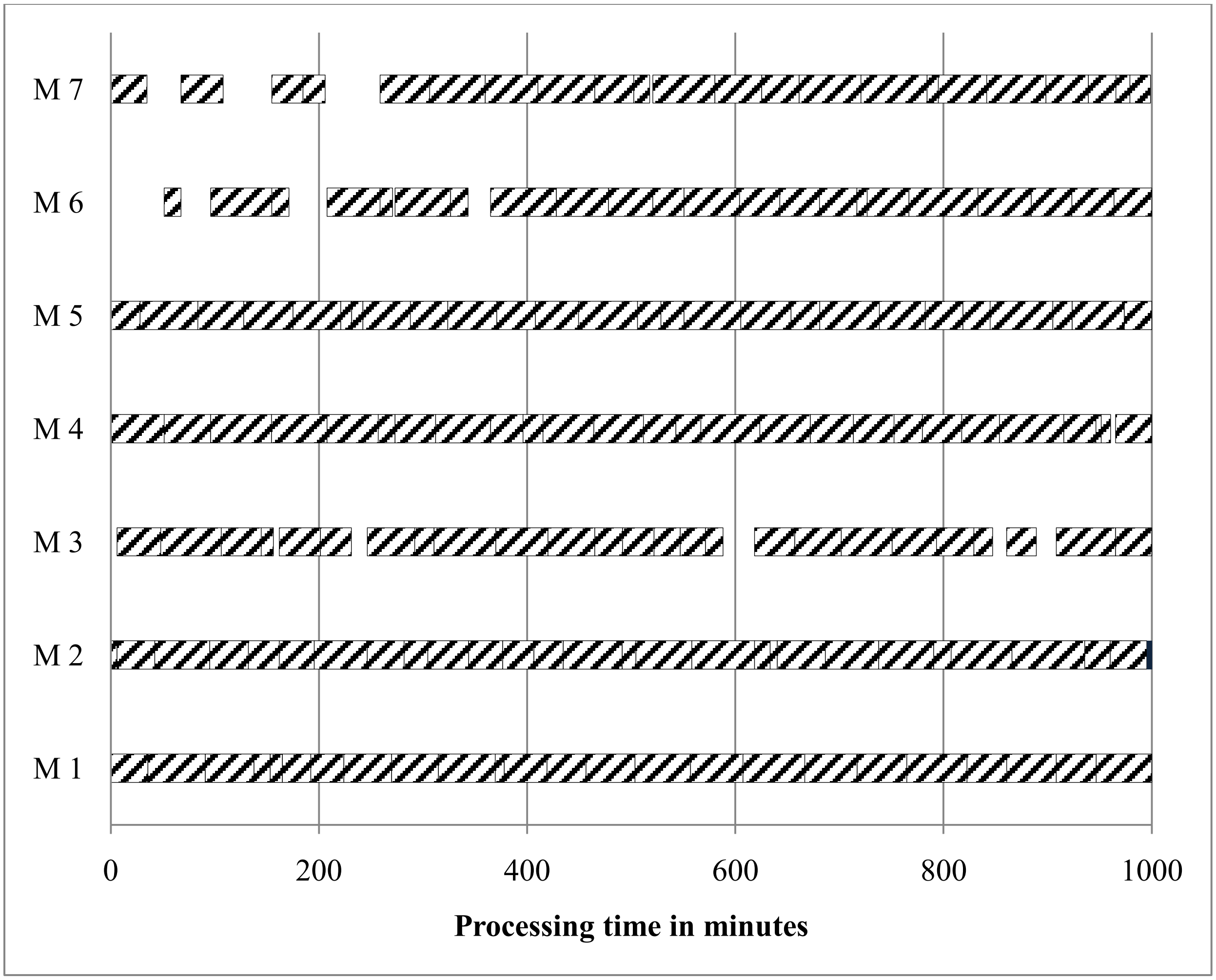
APPENDIX AN

PROCESSING TIME CHART OF CASE STUDY 2 WITH LOW VARIABILITY - BUFFER CASE



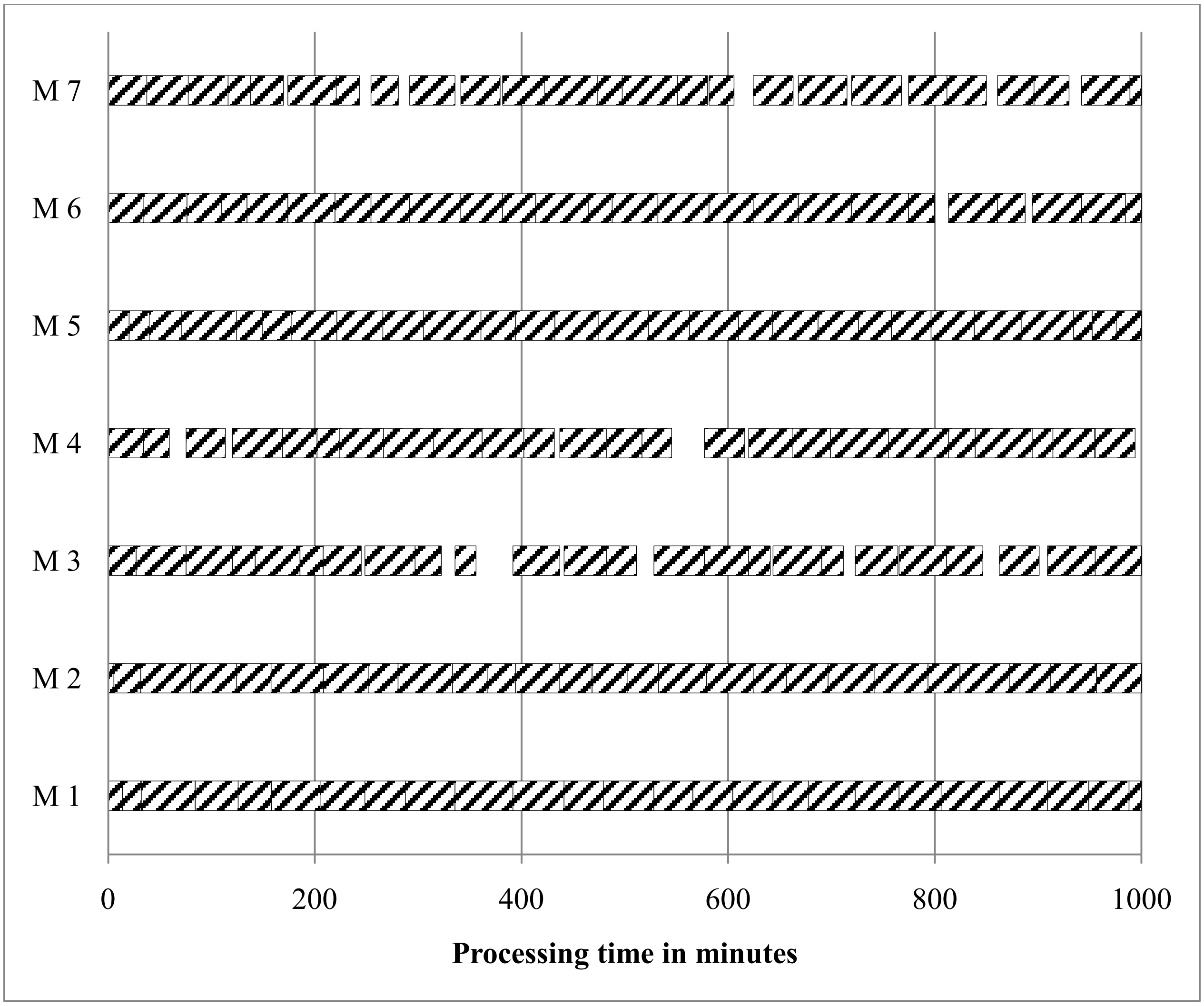
APPENDIX AO

PROCESSING TIME CHART OF CASE STUDY 3 WITH HIGH VARIABILITY - BUFFER CASE



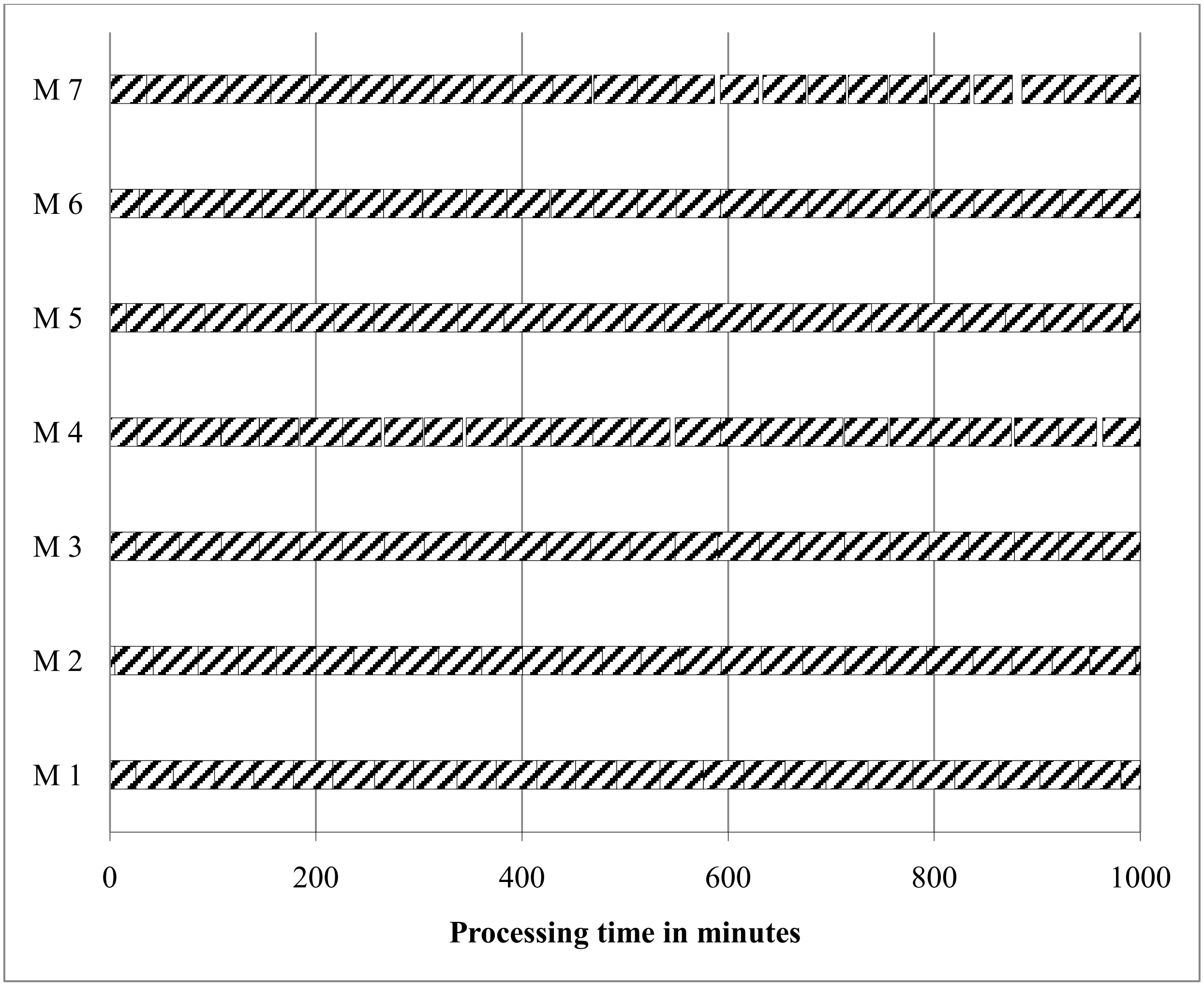
APPENDIX AP

PROCESSING TIME CHART OF CASE STUDY 3 WITH MEDIUM VARIABILITY - BUFFER CASE



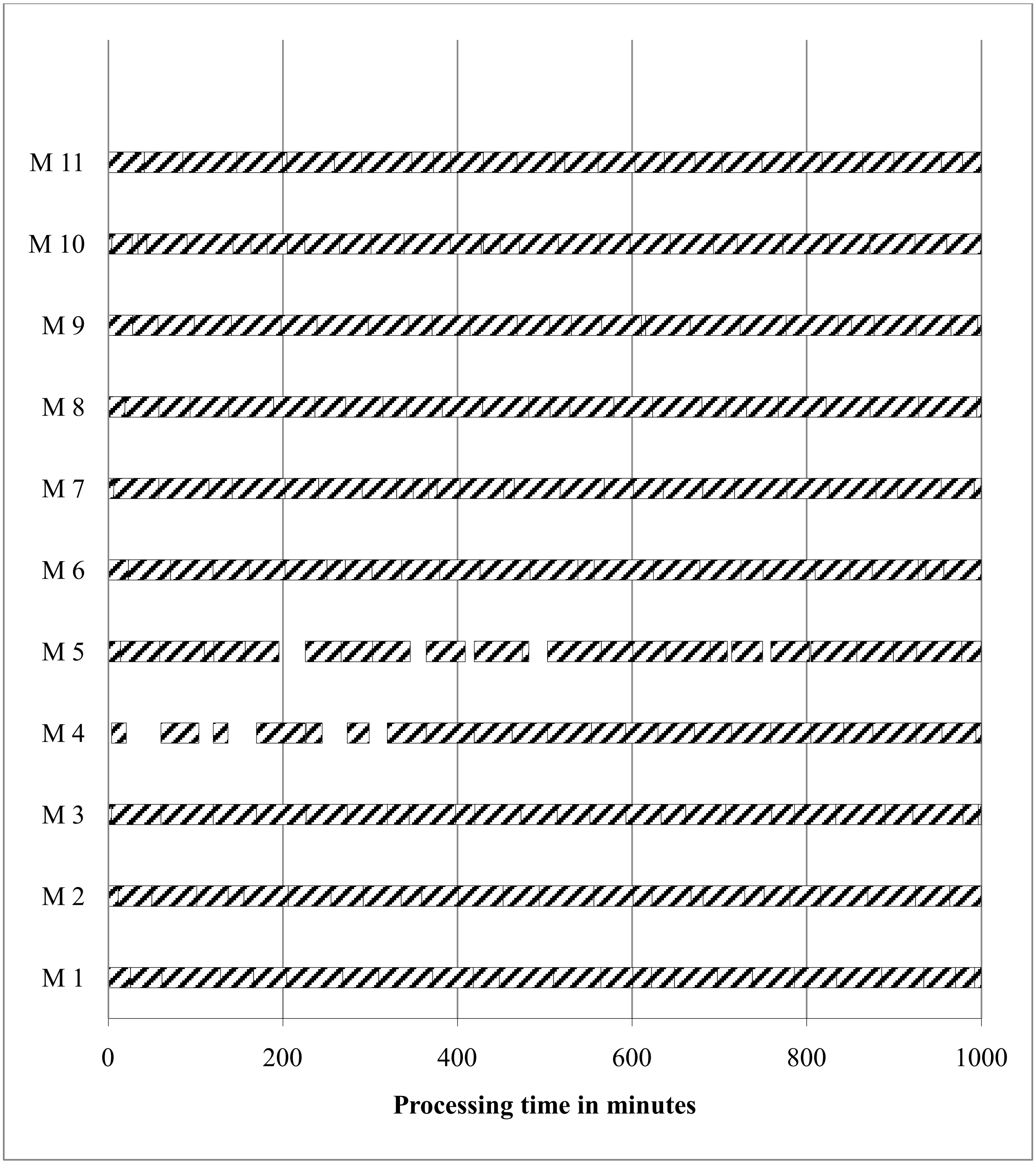
APPENDIX AQ

PROCESSING TIME CHART OF CASE STUDY 3 WITH LOW VARIABILITY - BUFFER CASE



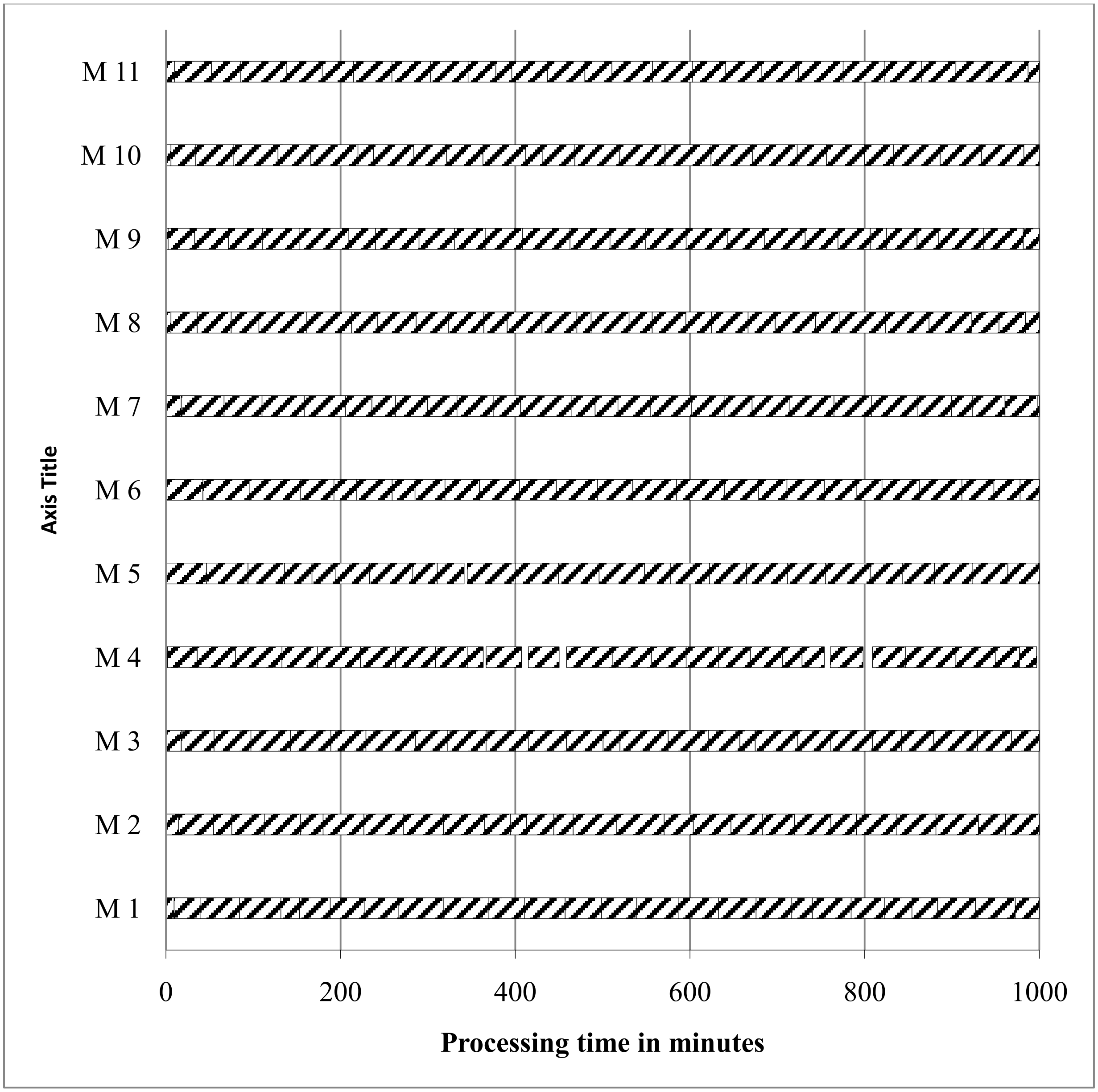
APPENDIX AR

PROCESSING TIME CHART OF CASE STUDY 4 WITH HIGH VARIABILITY - BUFFER CASE



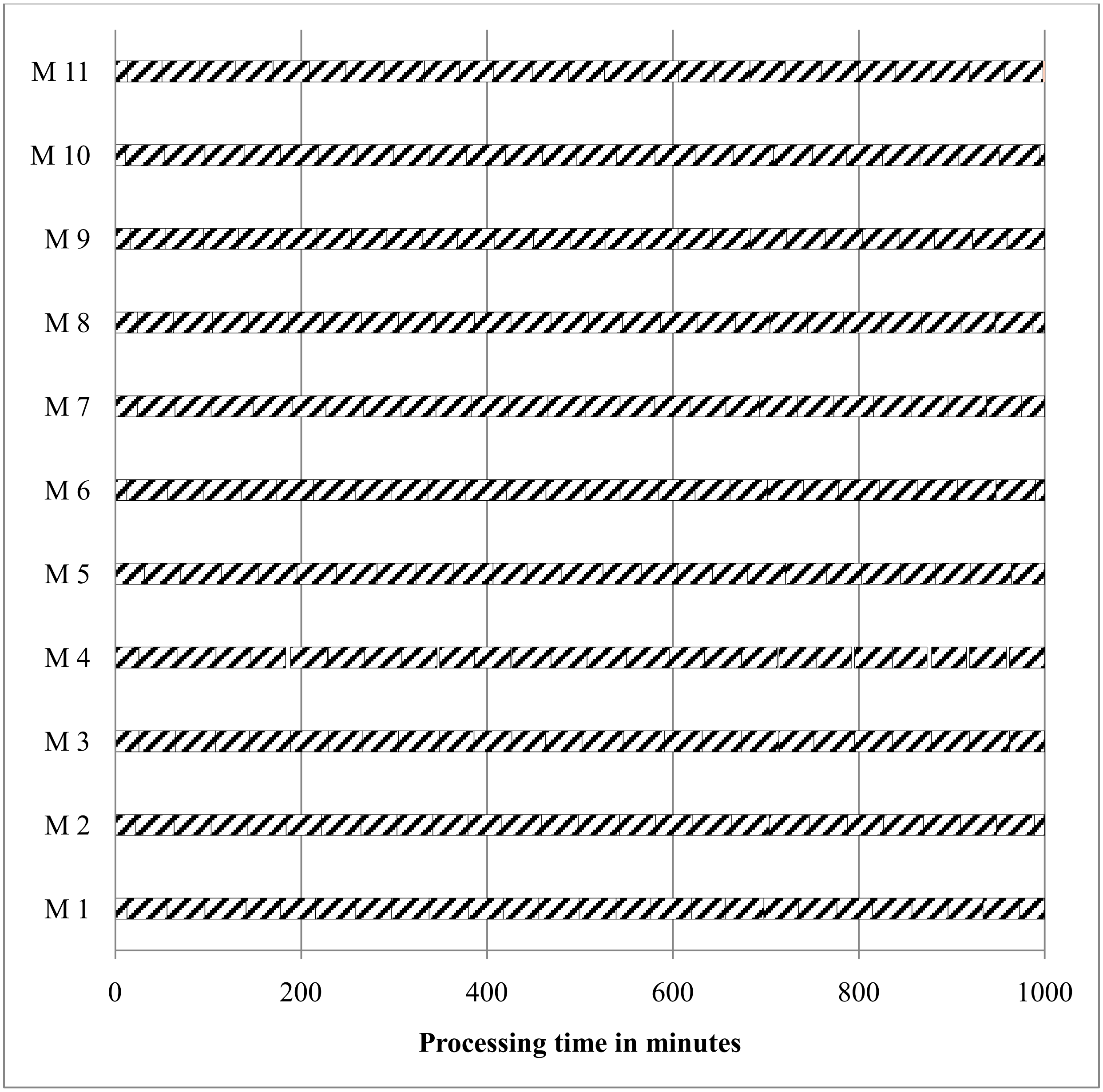
APPENDIX AS

PROCESSING TIME CHART OF CASE STUDY 4 WITH MEDIUM VARIABILITY - BUFFER CASE



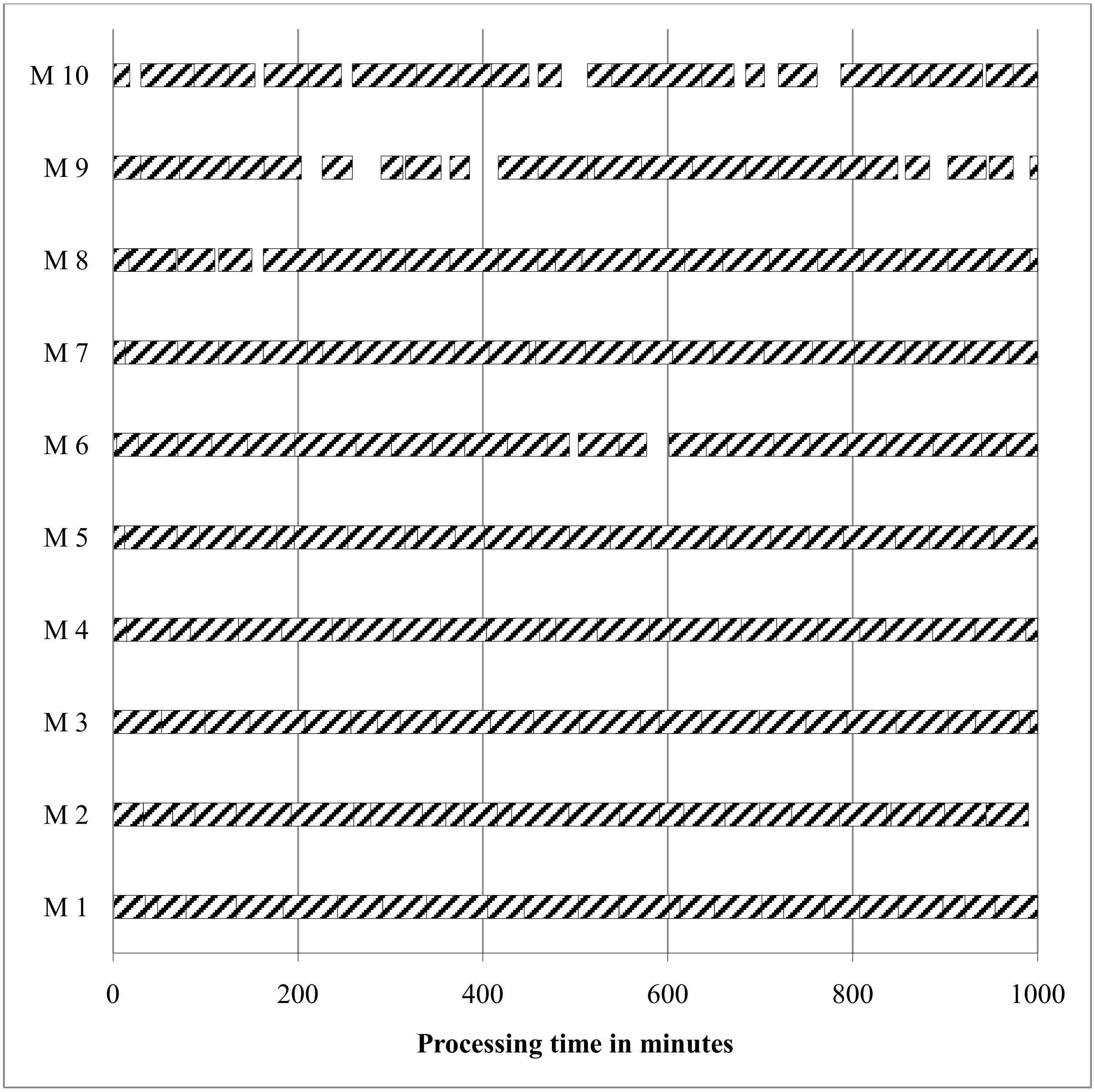
APPENDIX AT

PROCESSING TIME CHART OF CASE STUDY 4 WITH LOW VARIABILITY - BUFFER CASE



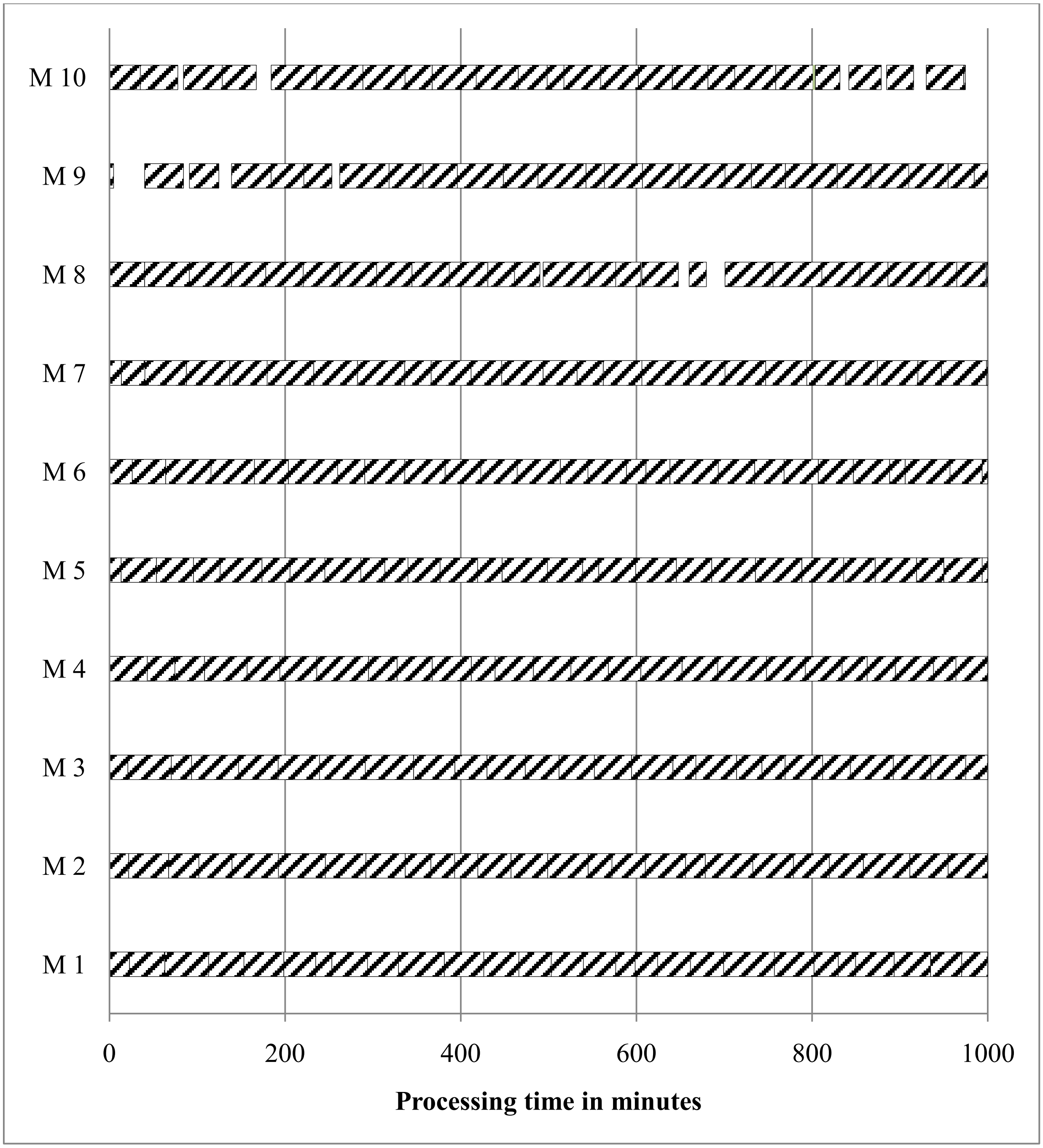
APPENDIX AU

PROCESSING TIME CHART OF CASE STUDY 5 WITH HIGH VARIABILITY - BUFFER CASE



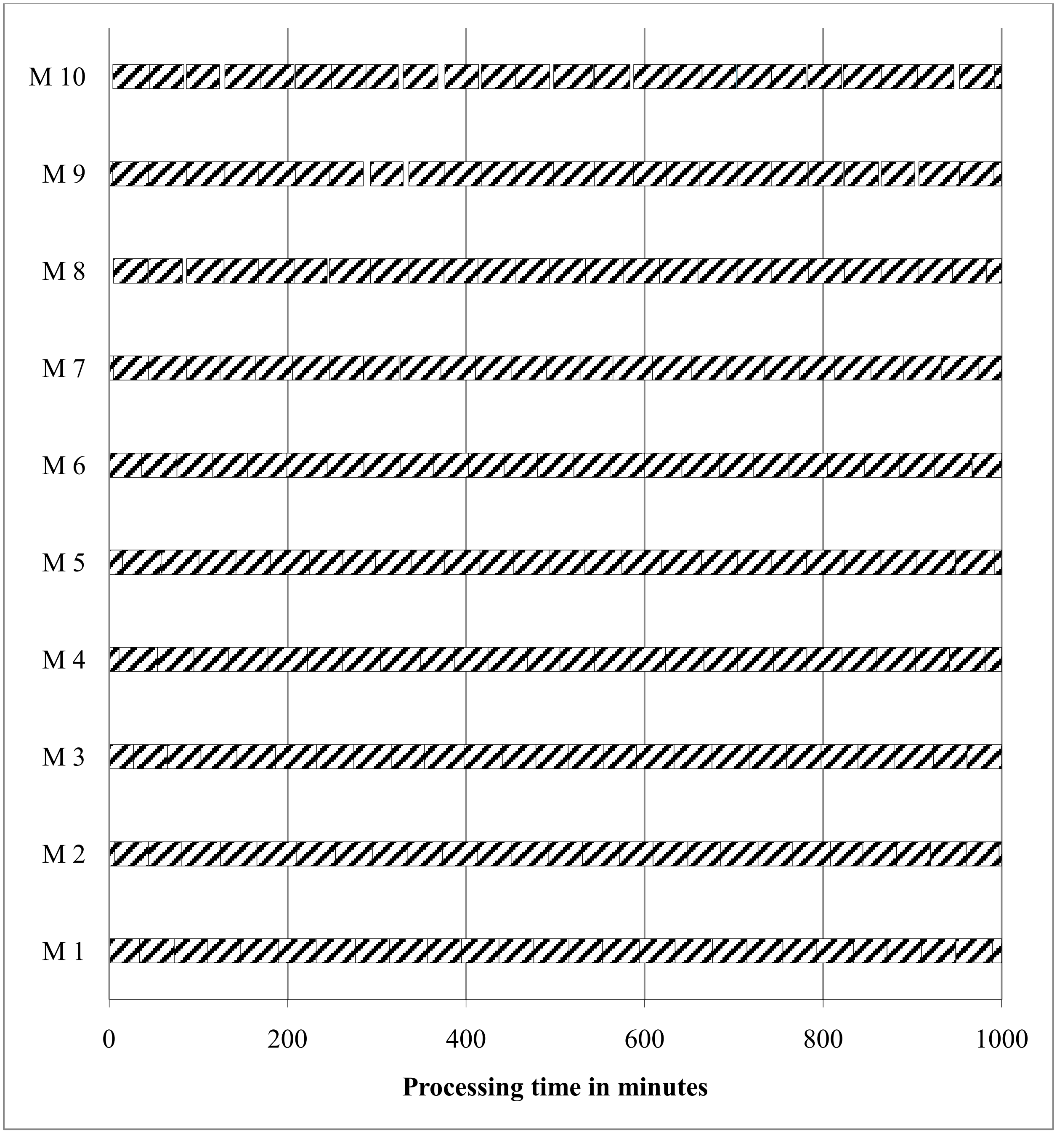
APPENDIX AV

PROCESSING TIME CHART OF CASE STUDY 5 WITH MEDIUM VARIABILITY - BUFFER CASE



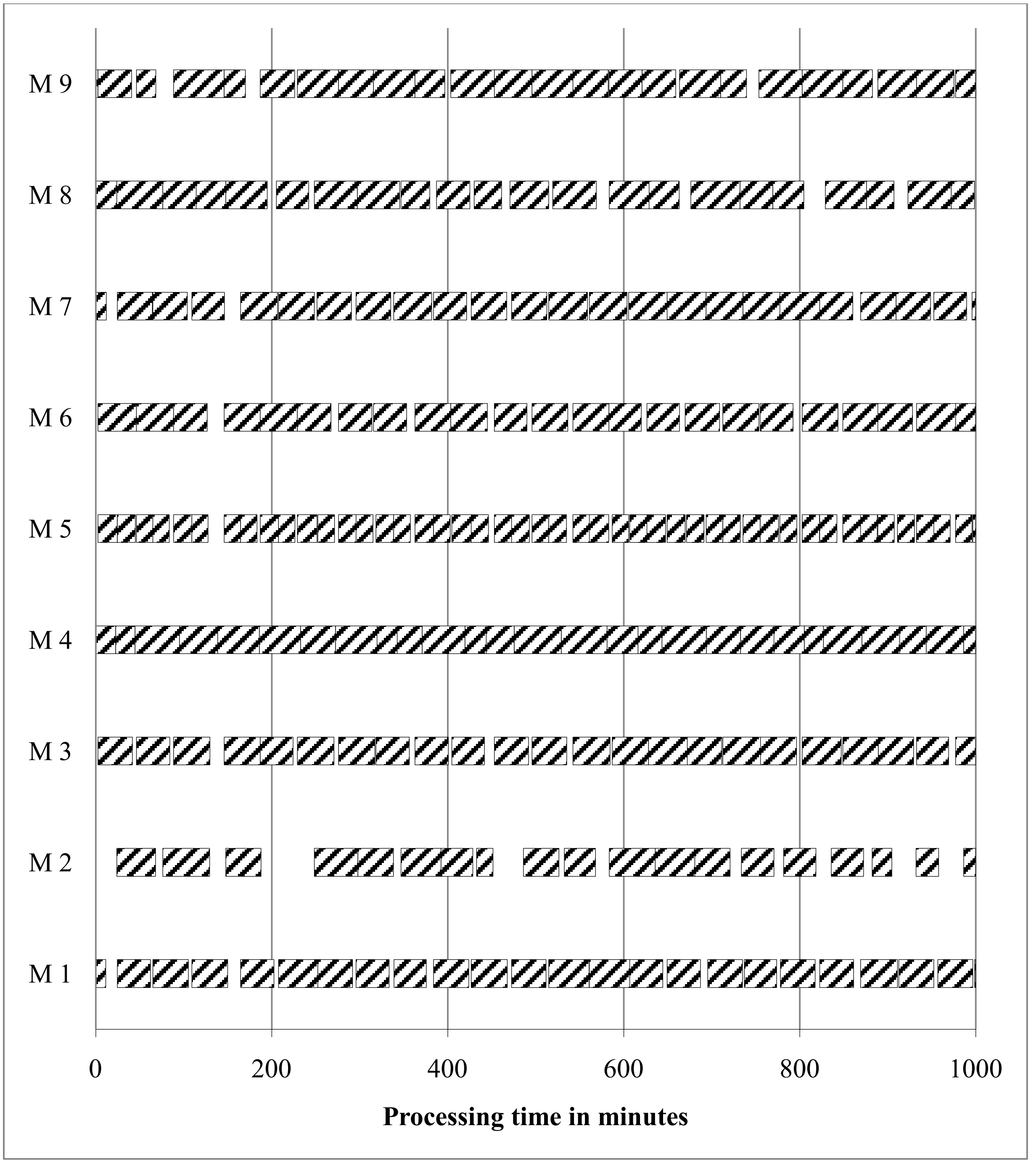
APPENDIX AW

PROCESSING TIME CHART OF CASE STUDY 5 WITH LOW VARIABILITY - BUFFER CASE



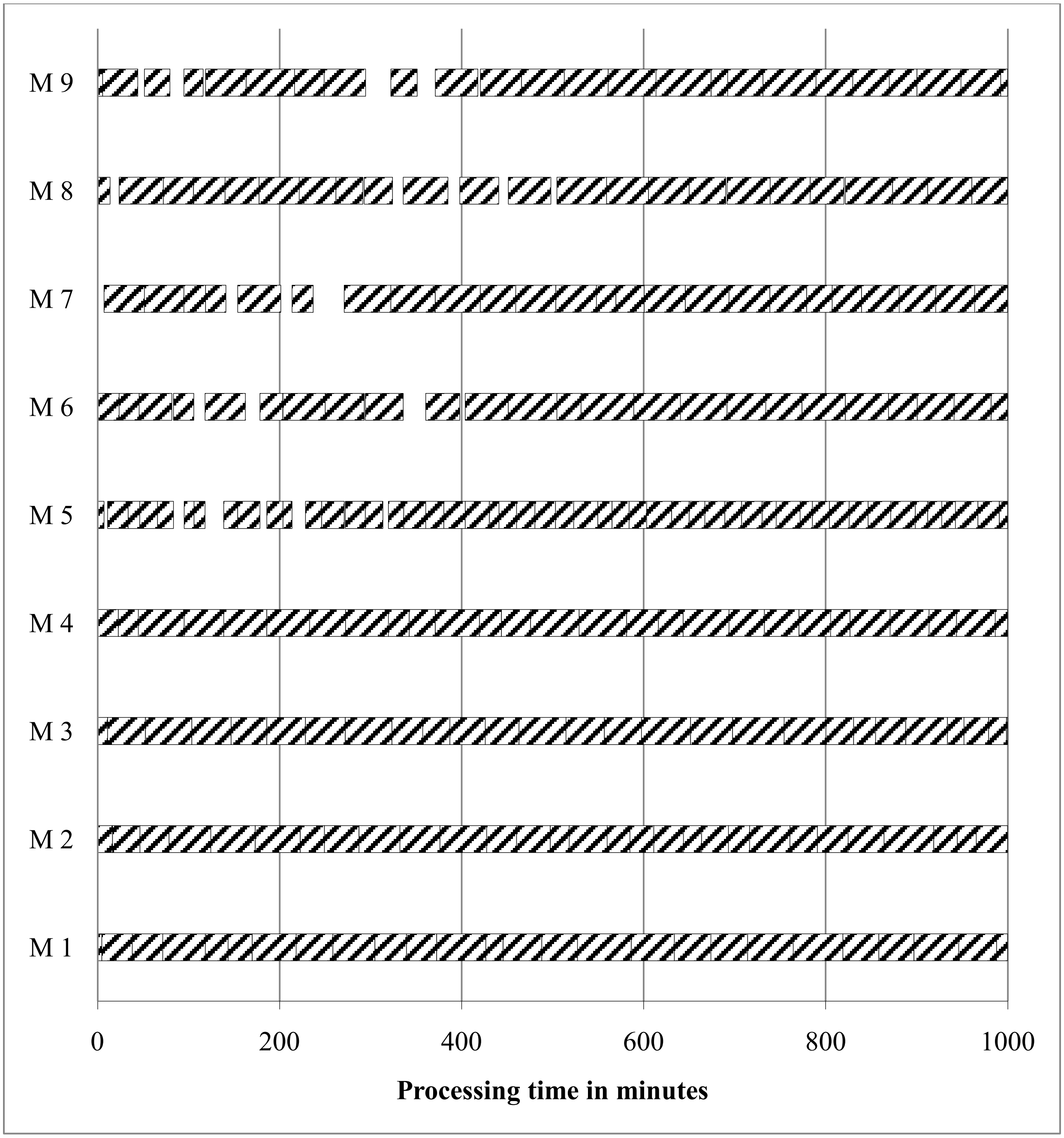
APPENDIX AX

PROCESSING TIME CHART OF CASE STUDY 6 WITH HIGH VARIABILITY - BUFFER CASE



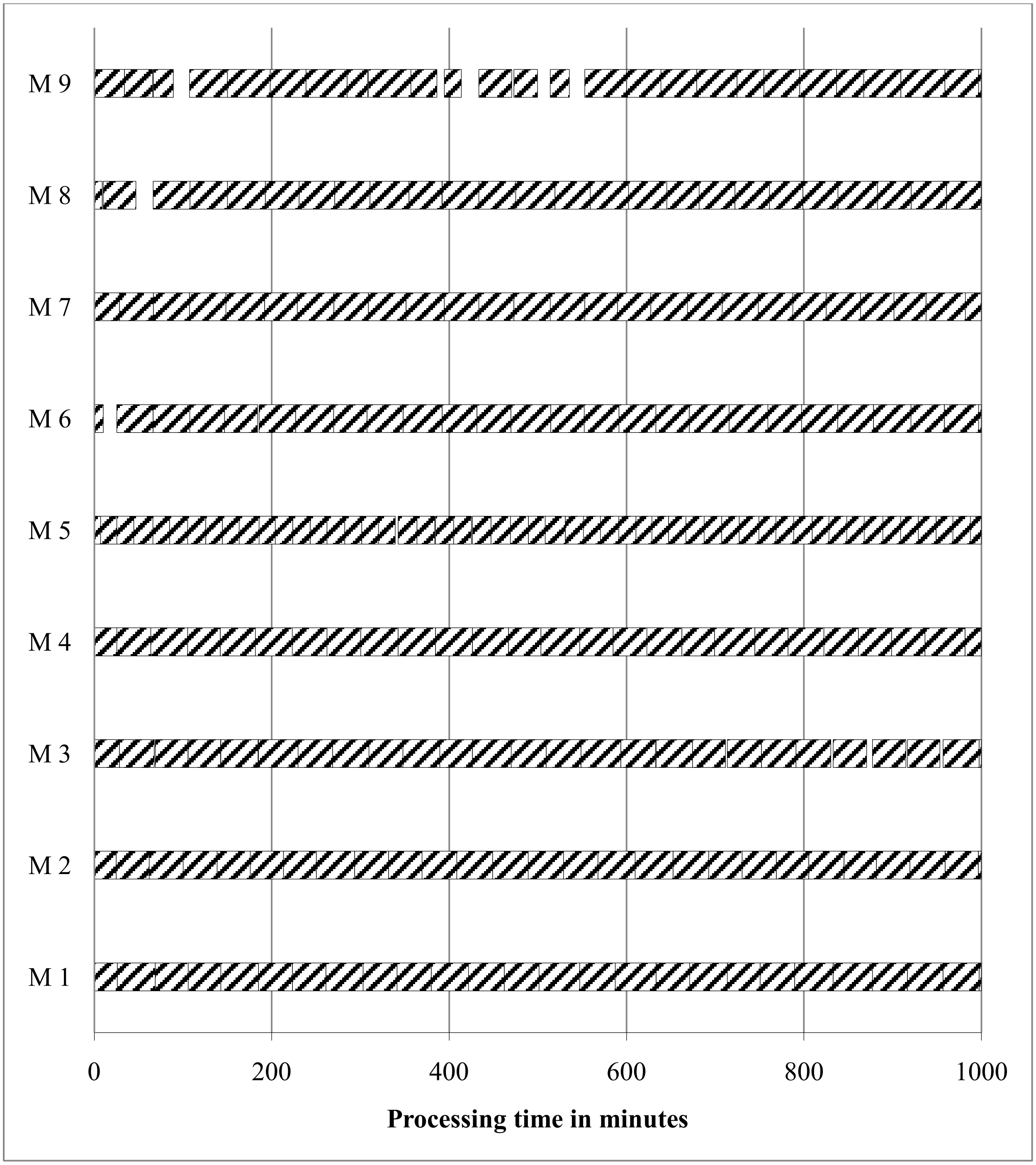
APPENDIX AY

PROCESSING TIME CHART OF CASE STUDY 6 WITH MEDIUM VARIABILITY - BUFFER CASE



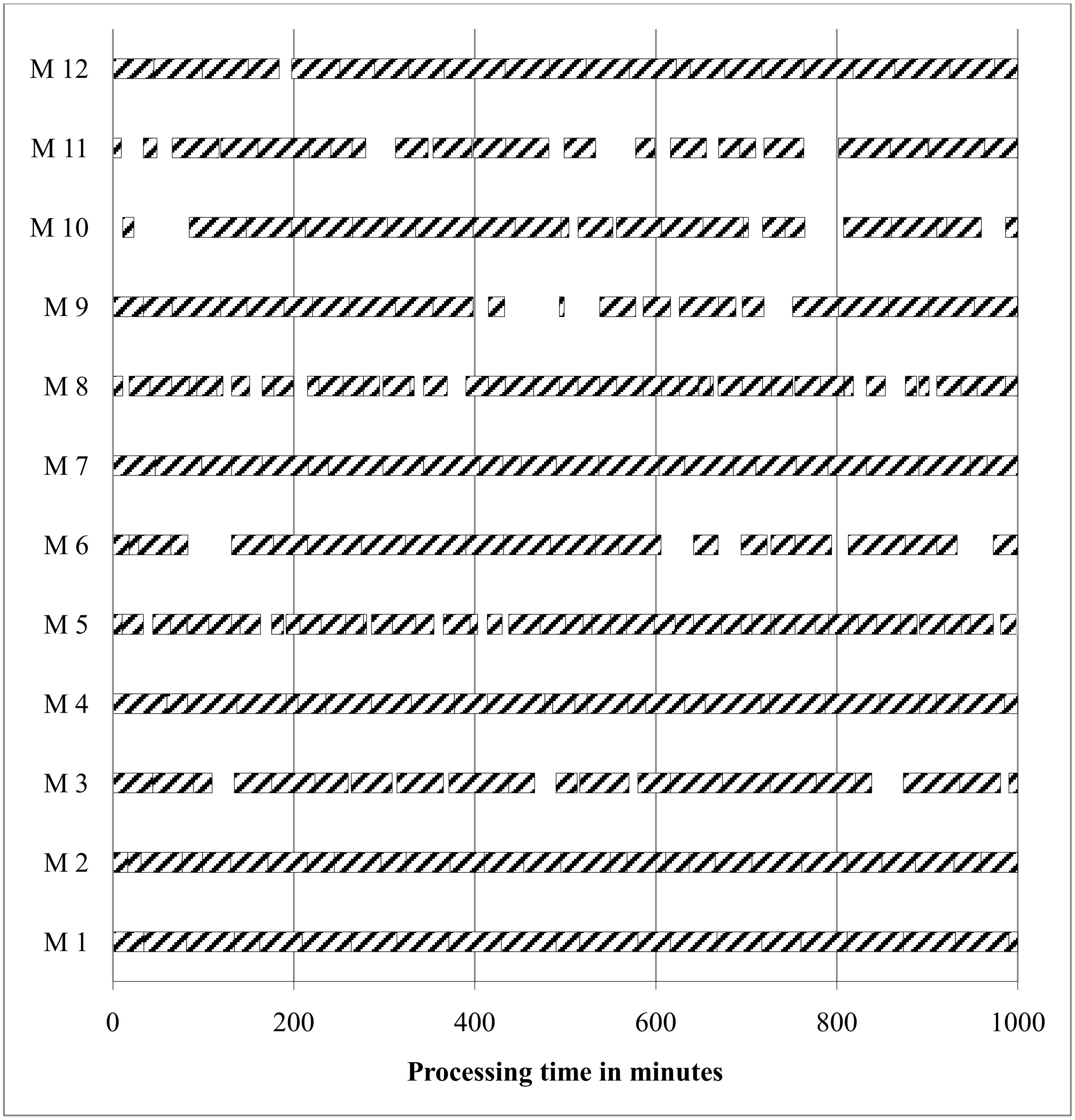
APPENDIX AZ

PROCESSING TIME CHART OF CASE STUDY 6 WITH LOW VARIABILITY - BUFFER CASE



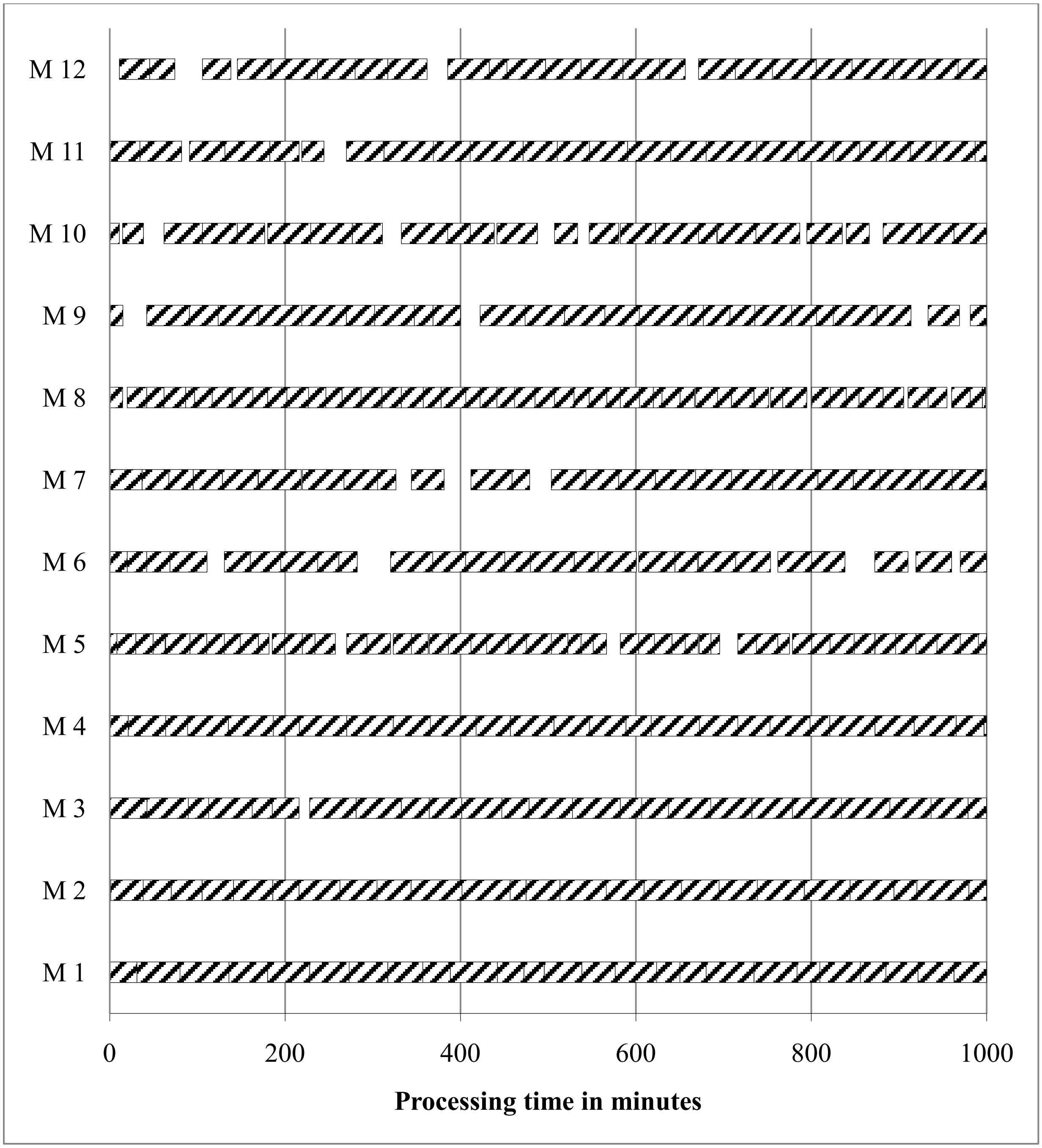
APPENDIX BA

PROCESSING TIME CHART OF CASE STUDY 7 WITH HIGH VARIABILITY - BUFFER CASE



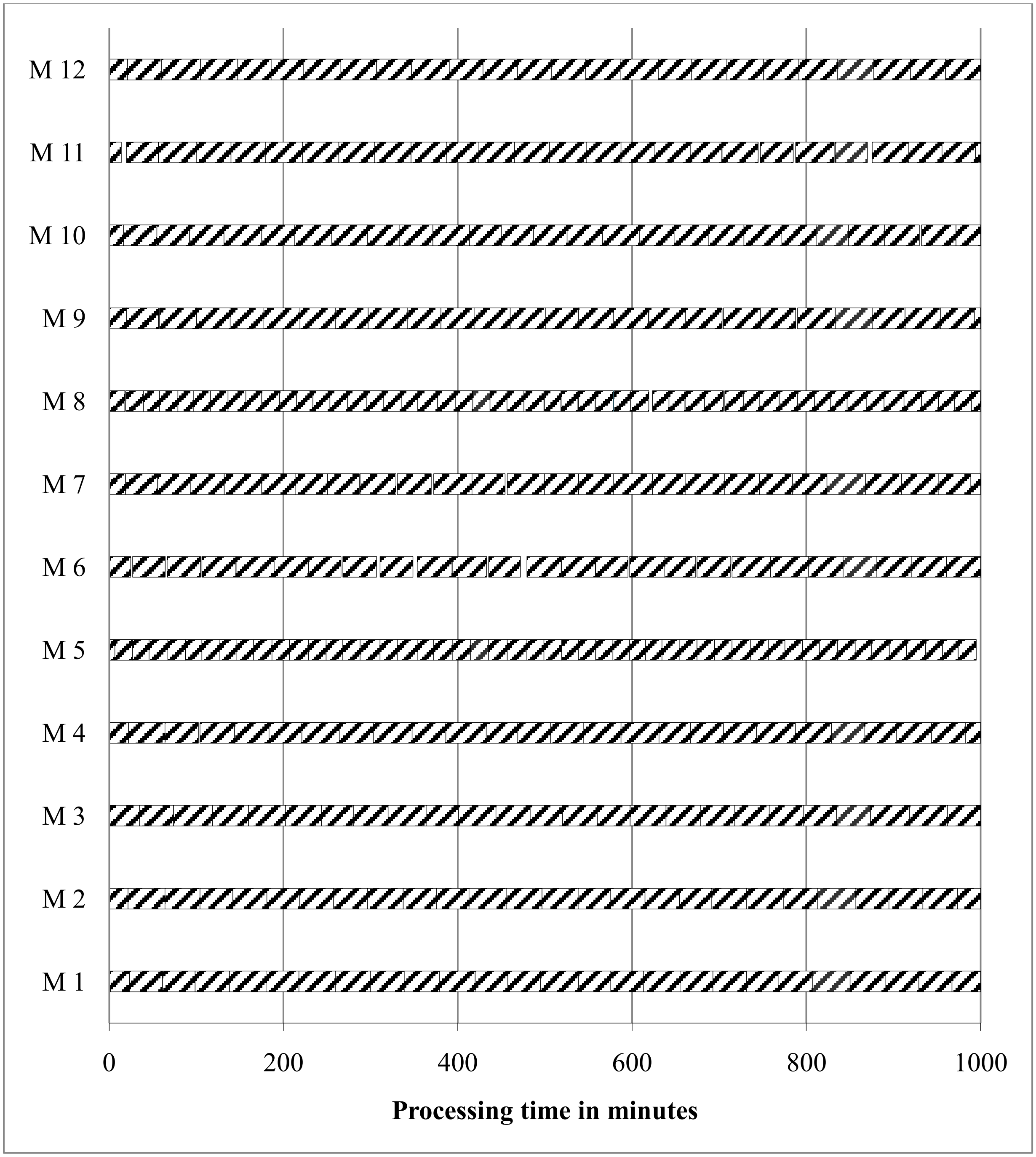
APPENDIX BB

PROCESSING TIME CHART OF CASE STUDY 7 WITH MEDIUM VARIABILITY - BUFFER CASE



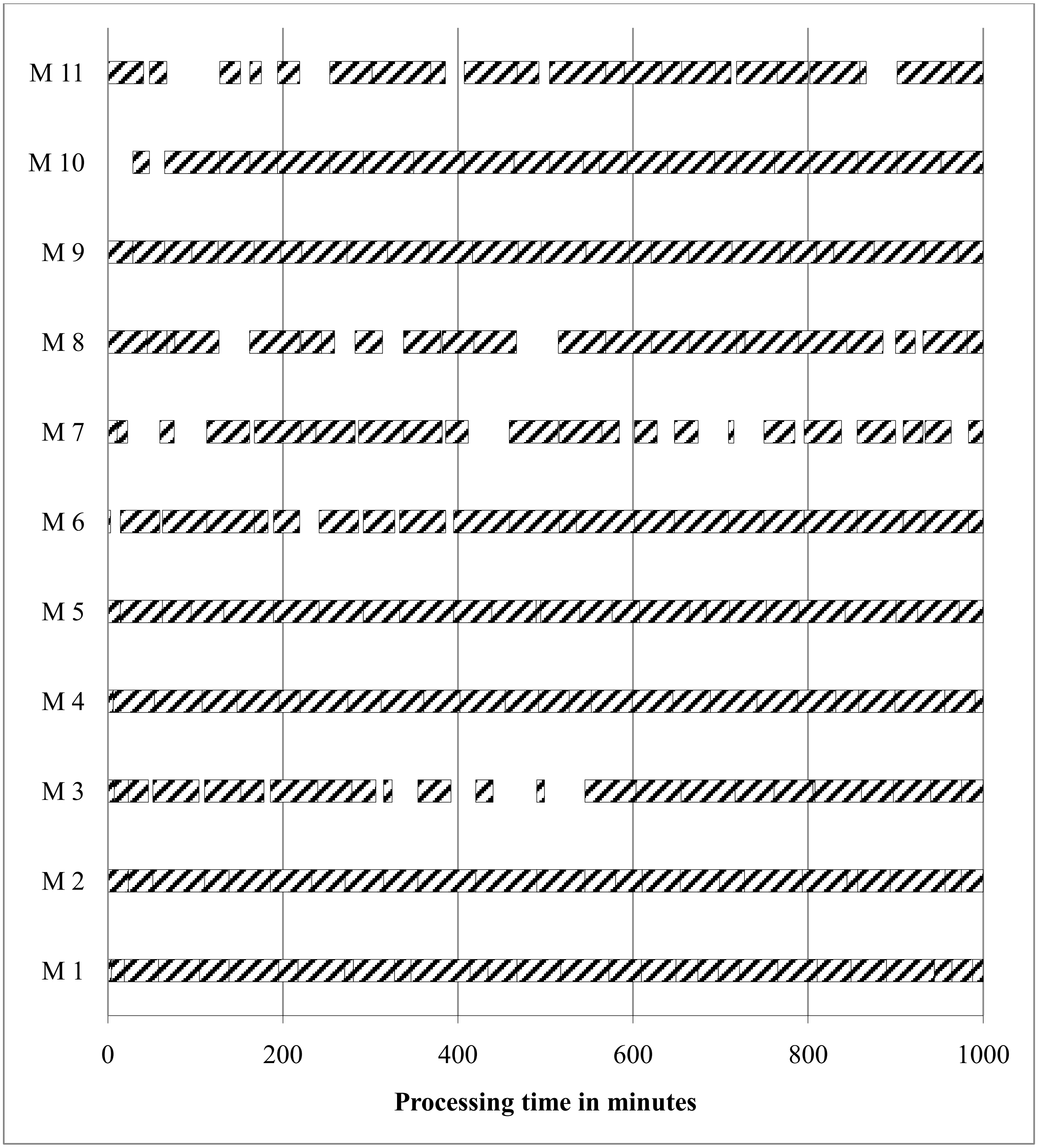
APPENDIX BC

PROCESSING TIME CHART OF CASE STUDY 7 WITH LOW VARIABILITY - BUFFER CASE



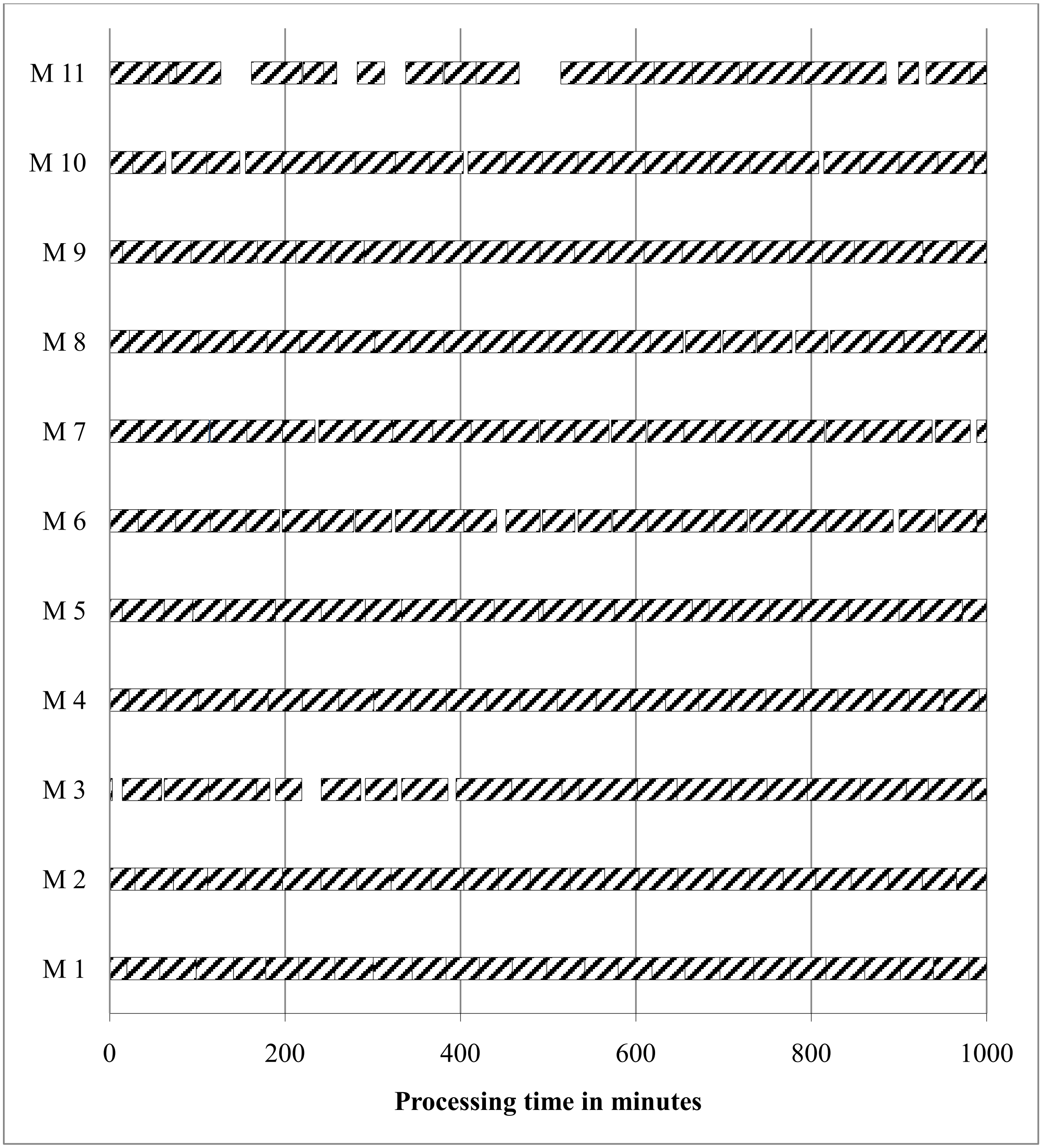
APPENDIX BD

PROCESSING TIME CHART OF CASE STUDY 8 WITH HIGH VARIABLITY - BUFFER CASE



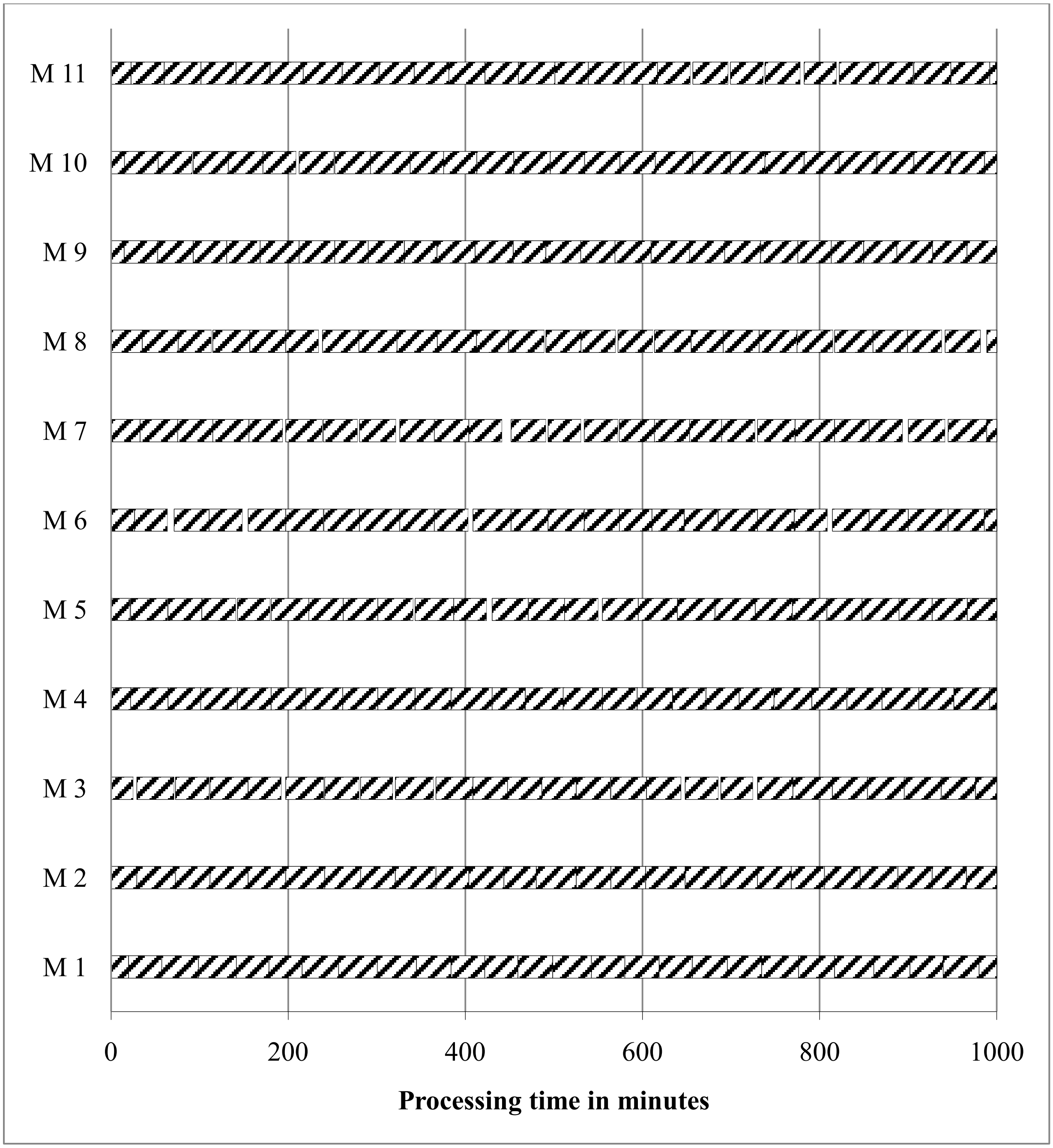
APPENDIX BE

PROCESSING TIME CHART OF CASE STUDY 8 WITH MEDIUM VARIABILITY - BUFFER CASE



APPENDIX BF

PROCESSING TIME CHART OF CASE STUDY 8 WITH LOW VARIABILITY - BUFFER CASE



APPENDIX BG

BN TIME OF EACH MACHINE IN CASE STUDY 2 - BUFFER CASE

Machine	**BN Time in Minutes**		
	High Variability	**Medium Variability**	**Low Variability**
M 1	6.38989	2.78137	2.63704
M 2	11.1033	8.72332	2.44025
M 3	11.5696	3.25056	2.35707
M 4	34.8509	5.72466	5.786
M 5	0	0	0
Total BN time	63.9137	20.4799	13.2204

APPENDIX BH

BN TIME OF EACH MACHINE IN CASE STUDY 3 - BUFFER CASE

Machine	**BN Time in Minutes**		
	High Variability	**Medium Variability**	**Low Variability**
M 1	32.6128	112.13	0
M 2	57.2655	0	0
M 3	5.02012	70.94	0
M 4	140.313	20.01	28.31
M 5	0	0	3.12
M 6	136.452	0	25.341
M 7	0	0	0
Total BN time	371.663	203.08	56.771

APPENDIX BI

BN TIME OF EACH MACHINE IN CASE STUDY 4 - BUFFER CASE

Machine	**BN Time in Minutes**		
	High Variability	**Medium Variability**	**Low Variability**
M 1	0	0	0
M 2	0	0	0
M 3	143.419	40.4979	22.6811
M 4	96.6226	3.43306	0
M 5	0	0	0
M 6	0	0	0
M 7	0	0	0
M 8	0	0	0
M 9	0	0	0
M 10	0	0	0
M 11	0	0	0
Total BN time	240.042	43.931	22.6811

APPENDIX BJ

BN TIME OF EACH MACHINE IN CASE STUDY 5 - BUFFER CASE

Machine	**BN Time in Minutes**		
	High Variability	**Medium Variability**	**Low Variability**
M 1	33.8557	0	0
M 2	0	0	0
M 3	0	0	0
M 4	0	0	0
M 5	0	0	0
M 6	0	0	1.98136
M 7	14.2584	39.341	13.247
M 8	119.378	65.6405	10.7605
M 9	159.903	81.9426	66.1729
M 10	0	0	0
Total BN time	327.395	186.924	92.1617

APPENDIX BK

BN TIME OF EACH MACHINE IN CASE STUDY 6 - BUFFER CASE

Machine	**BN Time In Minutes**		
	High Variability	**Medium Variability**	**Low Variability**
M 1	24.678	13.767	19.5795
M 2	0	0	0
M 3	32.9877	27.0461	1.2957
M 4	72.568	61.7482	4.54262
M 5	129.457	113.998	36.3231
M 6	48.1	44.9173	1.7084
M 7	57.8758	52.7849	82.5562
M 8	77.765	0	0
M 9	24.7308	13.1082	0
Total BN time	468.162	327.37	146.005

APPENDIX BL

BN TIME OF EACH MACHINE IN CASE STUDY 7 - BUFFER CASE

Machine	**BN Time in Minutes**		
	High Variability	**Medium Variability**	**Low Variability**
M 1	120.137	12.179	0
M 2	0	0	1.69335
M 3	48.6694	23.9699	0
M 4	22.4822	38.6279	0
M 5	172.738	197.171	41.3979
M 6	81.2584	23.3522	1.07931
M 7	40.0442	4.75575	7.39364
M 8	359.109	200.718	9.37204
M 9	190.369	37.5276	18.53
M 10	30.3788	88.7934	0
M 11	17.1071	0	0
M 12	0	0	0
Total BN time	1082.29	627.095	79.4662

APPENDIX BM

BN TIME OF EACH MACHINE IN CASE STUDY 8 - BUFFER CASE

Machine	**BN Time in Minutes**		
	High Variability	**Medium Variability**	**Low Variability**
M 1	0	0	0
M 2	181.846	94.234	31.7815
M 3	0	62.8768	25.7655
M 4	0	63.5678	17.0037
M 5	62.8768	0	0
M 6	301.804	71.2378	41.4354
M 7	155.845	155.845	25.3473
M 8	0	0	0
M 9	46.0692	23.456	5.4674
M 10	208.732	44.1245	14.2758
M 11	0	0	0
Total BN time	957.173	515.342	161.077