A FRAMEWORK TO INVESTIGATE KEY CHARACTERISTICS OF DIGITAL TWINS AND THEIR IMPACT ON PERFORMANCE

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This dissertation is dedicated in memory of my grandpas.

I miss you both and wish you were still here.

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ABSTRACT

The modern world of manufacturing is in the middle of an industrial revolution with the digital and physical worlds integrating through cyber-physical systems. Through a virtual model that is able to communicate with its physical system known as the Digital Twin, catered decisions can be made based on the current state of the system. The digital twin presents immense opportunities and challenges as there is a greater need to understand how these new technologies work together.

This thesis is an experimental investigation of the characteristics of the essential components of the Digital Twin. A Digital Twin Framework is developed to explore the impacts of model accuracy and update frequency on the system's performance measure. A simple inventory management system and a more complex manufacturing plant is modeled through the framework providing a method to study the interactions of the physical and digital systems with empirical data.

As the decision policies are affected by the state changes in the system, designing the Digital Twin must account for the direct and indirect impact of its components. Furthermore, we show the importance of communication and information exchange between the Digital Twin and its physical system. A key characteristic for developing and applying a digital twin is to monitor the update frequency and its impact on performance. Through the study there are implications of optimal combinations of the digital twin components and how the physical system responds. There are also limits to how effective the Digital Twin can be in certain instances and is an area of research that needs further investigation.

The goal of this work is to help practitioners and researchers implement and use the Digital Twin more effectively. Better understanding the interactions of the model components will help guide designing Digital Twins to be more effective as they become an integral part of the future of manufacturing.

1. INTRODUCTION

1.1 Background

One of the most promising enablers of Smart manufacturing is the Digital Twin [1]. From a manufacturing stand point, the Digital Twin (DT) is a virtual version of a physical system that is enabled with technologies to communicate, update, and provide decision support in real time. The DT can represent a range of systems from a single machine to a complex network of manufacturing plants with potential benefits including reduction in cost, reduced errors, increased flexibility, and improved efficiency. From a systems standpoint, incorporating a system that can help forecast and utilize information in real time to make better decisions should be utilized in every manufacturing plant. However, the modern world of manufacturing has yet the ability to fully integrate smart manufacturing though a digital twin yielding the benefits that Industry 4.0 and next gen manufacturing promote to provide [2]. There are still major hurdles in order to implement the DT into modern day manufacturing due to potentially high costs and a lack of empirical research showing its benefits [3] [4]. Although the computing power and technologies to support the DT are improving at an incredible rate, those alone will not make up the gap that exists.

1.2 Motivation

The motivation for this thesis is to better understand the characteristics of the Digital Twin in order to bridge the gap that exists in the research. Due to the potential costs of implementing a DT in an industrial context the research and evidence of the benefits of the DT must be sound [4]. Not only will this thesis give empirical evidence to the interactions of the DT components and their impact on performance, this research is being conducted with hopes to assist designing effective DT of the future. Due to this research area still being in its infancy [5], prominent work can help accelerate Digital Twin application methods and potentially change the future of manufacturing systems forever. Understanding the details of the Digital Twin and how it communicates with its physical counterpart is motivating in hopes to show the true value of a Digital Twin and its potential place in manufacturing systems as an industry standard.

An experimental investigation of the characteristics of the Digital Twin is needed to show the interconnections of DT components and their impact on performance. As models grow in complexity, the ability to understand results become increasingly difficult. Simplification of systems is one method to see how the Digital Twin can be used and applied to systems while better understanding its characteristics.

The research goal is to show a methodology to not only use the Digital Twin for different systems, but to study its components and their interactions to show the areas that are critical to building such DT systems. This research is a building block to understanding and applying Digital Twins for the future of manufacturing.

1.3 Thesis

In order to bridge the gap that exists in the Digital Twin research area, a Digital Twin Framework was developed. This framework allows the analysis of the DT model and its interactions with its physical system. The approach to this research is an experimental one, where different models of different complexities were built using the framework that allows the study of the interconnections of the DT components and their impacts. The framework combines simulation modeling, digital twins, and a unique model logic which incorporates different time frames to have different systems running simultaneously.

A simulation and modeling approach is taken in this thesis and is used throughout each of the chapters. Simulation modeling has become popular in its sheer ability to represent a wide variety of systems compared to any mathematical model[6]. There are certain limitations to such techniques like queuing theory that can be relaxed and be represented using simulation modeling. However, it's not to say that simulation and modeling doesn't come with its disadvantages, like being unable to find closed form optimal solutions. However, if we use simulation to just be better than before, and to find added value, an unlimited range of systems can be explored. Adding details that are too difficult to mathematically model shows the capabilities of using simulation modeling, and its impact in understanding complex systems.

There also seems to be a fine line between the amount of information gained and the amount of time, energy and work that is put into a simulation model. Modelers as well as from personal experience often add as much ”detail” into a model in hopes of satisfying the model's objectives. Jones et. al [4] found from their systematic review of the DT that most papers advocate the highest feasible fidelity levels due to the fact that higher fidelity levels offer more accurate models due to the virtual and physical systems being closer aligned. However, they also mentioned the need for further research in understanding fidelity levels of the DT and finding appropriate and realistic levels. In ways this is the crux of the problem in simulation and modeling, looking at the current objectives and rarely setting up the model to be easily updated, especially when the objectives change. Sometimes, there is too much detail in a model where updates become very difficult or become too expensive to complete. Sometimes it is cheaper to scrap a model and start over. As the complexity of a model grows, so does the model's behavior, and it becomes harder to understand and explain, what many call emergent. In order to effectively understand a model, there must be a better way to understand how details in a model convey information and affect model behaviors through simplification. Even for the study of the Digital Twin, a key component is to understand how information is being used by both the digital twin and its physical system.

Models are a simplification of a ”real” system, no matter how much detail is included, it is near impossible to fully create a carbon image of reality. The complexities of real systems can be difficult to model and there are factors that won't be included that could potentially affect the outcome of a model. Information is lost as details are lost, and this idea is prevalent in model building and is no different with Digital Twins. Modeling correctly is synonymous to understanding and managing the amount of information lost in a simplified version of reality and what kinds of bounds it places on the model. Knowing how details are lost and understanding its effects minimizes the amount of information lost during the model building process.

There are many benefits to a well developed model to see potential issues as well as alternative unknown results. The usefulness of a model is only as good as the model, so it is crucial to have the right amount of details that mimic the interaction of parts in the ”real” system. Creating this framework allows the study of these interactions where there is enough detail to see the impact DT components have on performance.

Model behavior is a result of the interactions of the models components and input parameters. As the detail of the model increases, the model's complexity does as well. In order to have a better understanding of how the model behaves it is important to fully understand what drives it. The difficulty of using a model effectively depends not only on understanding how the model is driven, but also showing that the model reflects the real system's behavior.

The developed Digital Twin Framework provides an experimental investigation of DT components and their impact on performance through a modeling perspective. Different performance measures and system policies are used to see the impacts the DT has to better understand the potential benefits of the DT for the future of manufacturing.

1.4 Thesis Overview

This Thesis is structured as follows:

Chapter 2 is a literature review of the major concepts regarding the Digital Twin, Modeling and Simulation, Decision making and Manufacturing

Chapter 3 mainly looks into the modeling perspective of the Digital Twin discussing the conceptual and functional requirements. The chapter breaks down the components required to not only build a DT model but also describes the method to measure information exchange. The developed Digital Twin Framework is introduced and the concept of the Pseudo-Physical Real System. This chapter lays down the foundation for this research and is critical for understanding the latter chapters.

Chapter 4 Showcases the simple inventory model. This chapter shows how the DT can be used in a simple case highlighting beyond just conceptually how each component of the DT interacts with a pseudo-real physical system.

Chapter 5 Presents a more complex Digital Twin Manufacturing System and discusses the integration of the Digital Twin Framework.

Chapter 6 Presents the analysis of using the DT framework in a more complex manufacturing system. Shows the empirical data and results from the different studies using the Digital Twin Framework. Model accuracy and update frequency are some variables that are considered.

Chapter 7 A brief summary of the findings of this thesis with closing remarks.

References

Appendix Comprehensive results from each of the studies

2. LITERATURE REVIEW

In the modern manufacturing industry, cyber-physical system-based manufacturing and service innovations are leading trends in how smart factories are able to analyze data from an ever connected communicative system of machines [7]. Smart manufacturing is the application of networked information based technologies resulting in a fundamental transformation of demand-dynamic economics throughout the manufacturing and supply chain enterprise [8]. More than ever, a greater need to shorten time to market is desired with increasing product development performance [9]. A digitized value chain supporting ”flexibility, modularity, adaptability and automated assembly systems” is an essential component of the industrial future [10]. A literature review of the materials related to the Digital Twin was conducted and presented in this chapter.

2.1 Future of Manufacturing

2.1.1 Research State of Manufacturing

Research on the Digital Twin is still early and in need for research to show the potential benefits of the DT and its effects on relevant industrial applications [3]. A dependable two-way mapping between physical and virtual systems is considered a highly important aspect of the DT for a successful decision making outcome for the decision maker [11]. There is a greater increase in interest from both academia and industry in the development of the Digital Twin [4], with a steady increase in the number of publications in both journals and conference papers over the past years [11].

However, more empirical research on the DT showing the improvements and potential return on investment of the DT concept must be studied due to the potential costs of implementing the DT in an industrial context [4]. Other reviews found majority of papers categorized as “concepts” with at most a minimal case-study, which still shows that the DT is in its infancy with a need to emphasize application methods of the DT [12].

One of the challenges is still understanding how to converge the physical and virtual worlds of manufacturing [5] [13] due to the difficulty in combining all the necessary components of the Digital Twin. Not only does the system need cyber-physical systems that are able to communicate with data, a well built virtual world is also required.

The Digital Twin is about managing information[14]. The technologies must allow the communication between its parts, with a system to exchange information and make decisions provided by the system components such as cyber-physical systems. Using the DT through modeling and simulation will allow for the better understanding of emergent behavior of systems and even potentially forecast these behaviors before they happen [14]. Enabling modelers and managers with real time system behaviour provides invaluable information and one of the true reasons why there is so much effort researching this field.

The future of manufacturing in this modern era will continue to produce data generated by sensors embedded in machines where modern solutions of dealing with big data will help create a system known as smart manufacturing. [15]. IoT paradigm allows manufacturing to be flexible, adaptive and more aware of the production conditions due to the network of connected resources [15]. The Digital Twin is considered to be an integral tool to better understand how systems/products are able to communicate with its digital twin and will be a major factor in smart manufacturing.

2.1.2 Integration Challenges in Manufacturing

There are still many concerns in how to fully implement the Digital Twin either as an image for a product or to look more in detail as a system. One of the difficulties to implementing a Digital Twin is that users often have minimal knowledge either in the product/system or the Digital Twin technologies [5]. Incorporating a full team to manage and enable the Digital Twin is a factor that can't be overlooked.

Another major challenge is using the data available to make the right decision effectively. The information available comes from data that is collected and deciding which data is considered useful information can be difficult. The challenge rests on using the data to make the right decisions, while using the information available to learn new patterns and being able to respond in real time [16]. When dealing with a large amount of generated data from a network of connected sensors, one challenge is gathering the most important data that has an impact on decisions that are made [15]. As systems become more complex, the need to distinguish and effectively find useful data will be a critical step in implementing an effective Digital Twin model.

Complex systems can often fail abruptly with minor issues developing into major problems highlight the importance of having capabilities to mitigate/eliminate serious issues into the behavior of such systems [14]. The task of incorporating the Digital Twin is deemed difficult due to the complex nature of predicting complex systems and the challenges of processing and analyzing big data. There is a need for sound conceptual frameworks and comprehensive reference models for the Digital Twin [9].

U.S. smart manufacturing infrastructure also remains limited with uncoordinated investments in information technologies, modeling and simulation to fully realize the benefits of a highly connected system [8]. Necessary technologies are not yet widely implemented in all manufacturing operations such as SME enterprises, making horizontal integration difficult to realize the full advantages of systems utilizing Digital Twin models [10].

2.2 Decision Making In Manufacturing

Although the Digital Twin has many application areas and its use can be applied to any system, our research's focus stayed in manufacturing systems. Here we present background research in decision making to help better understand the potential impacts of the Digital Twin. Decision making is a key characteristic of the DT enabled by technologies that enable communication between the physical and digital worlds.

2.2.1 Decision Support Systems

Flexibility has been a topic of interest for manufacturing systems to improve productivity. Computer based decision support systems provides a way to help manage high cost and low productive systems but with an emphasis on integrated hardware and software components [17]. Decision support systems can better react to changing environments through the combination of human skills, big data, analytics and planning. [18] Although decision support technologies such as manufacturing execution systems (MES), Enterprise Resource Planning

(ERP), Advanced Planning Systems (APS) and Big Data/Business Intelligence (BI) exist, there is a need to develop more adaptive decision support systems [18].

Integration of advanced technologies such as Artificial Intelligence with DSS can help eliminate the need for human expertise and run manufacturing systems through DSS [19]. Sustainability focused DSS with economic, environmental, and social implications have shown a trend in the literature [20].

Materials and Resources are always in need of being used in a order that takes into account multiple objectives and criteria. Decisions that occur in manufacturing environments include the proper selection of materials and even designing multi-attribute decision making models [21]. Simulation based decision support systems can also be used to organize production more efficiently [22]

2.2.2 Scheduling

Scheduling problems are considered important to manufacturing with multiple solution approaches ranging from traditional/advanced techniques to using simulation and artificial intelligence [23]. With the introduction of cyber physical systems and Industry 4.0, scheduling is still a mainstay for problems within job-shop manufacturing systems [24]. Generally, scheduling problems are NP-hard, where proofs exist for simple problems however realistic manufacturing problems are even more complex [25].

Recent interest in scheduling problems using DT technologies to enable real time action, automation and autonomy has grown significantly based on the number of research journals in the past decade [26]. Scheduling problems in manufacturing have always gone hand in hand with problems relating to supply chains, production systems, flexible job shop, capacity changes, multi-resource constrained production and much more [27]. Although a vast majority of literature in scheduling problems deal with finding optimal solutions to simple models, dynamic scheduling is one area of research being pushed to tackle real-world scheduling systems [28]

Kemppainen [29] presented a thesis document on job shop scheduling and discussed finding dominant priority rules comparing existing policies such as tardiness cost, variation of due dates, weighted processing times against different performance measures including holding cost, and tardiness. The experiment was designed to look at different loads of the system, order types, due date settings, and shop types. The best performing policies depends on the performance measures and the system rules. The methodology to test some of the policies against performance measure was used in this thesis, like having different system loads.

First in First Out (FIFO), equal probability, and dissimilarity maximization method was used to test different methods of routing selection through a simulation of a flexible manufacturing system [30]. Machine selection rules can help improve scheduling performance depending on job shop conditions [31]. Non FIFO dispatching rules have also been studied for manufacturing systems although there are advantages and disadvantages of different approaches [32].

One of the most widely used policies is FIFO which is used to study the stability of packet-switch networks based on queue build up [33]. FIFO is a popular decision policy often used for inventory management problems [34] and a common decision policy for any manufacturing system. Genetic algorithms have also been used as an approach to solve scheduling problems [35] [36].

Another simulation model choosing between different machine selection and dispatching rules for a partial flexible job shop used an action table with state probabilities for the results to converge towards an optimal behaviour through reinforcement Q-learning [37]. Different scheduling algorithms and heuristics to minimize makespan of deterministic job shop scheduling problems was conducted to show the overview of this research area [38]. Many of the literature in scheduling for smart manufacturing are still concentrated on simple objectives with one of the main challenges or gaps being the reliance on assumptions that are not always true for real manufacturing systems [39].

2.2.3 Data

In order to properly frame the Digital Twin using simulation models and its interaction with its physical system, there is a need to ensure the information or data exchange is properly executed. Decisions support systems are an integral part to support manufacturing systems that can be flexible [17], a clear area that would help building DT models. Key decision support system applications are around data, model building, AI, and information exchange [18]. Data integration, model creation/upkeep, and visualization for effective decisions are major challenges simulation based decision support systems face [22]. Many interdependent variables impact manufacturing systems and decision making and as the complexity of systems grow, simulation based models is a viable method to approach such tasks [22]

2.3 Modeling and Simulation

2.3.1 Digital Twin Modeling

The virtual world of the Digital Twin can be represented in some cases as a simulation model as used in this research. The Digital Twin approach is deemed the next wave in modeling, simulation and optimization technology by anticipating the benefits of an autonomous system in manufacturing [40]. This change from automated to autonomous systems will be a further improvement in the capabilities of the DT and will require detailed virtual worlds.

Building a Digital Twin has to consider the geometry, physics, behavior, and rules of the physical system [13]. A benefit of using a model, the Digital Twin allows for vivid simulation scenarios to better predict actual performance of physical products and more effective application of results on physical prototypes [41]. With the increase in computing power, more realistic virtual models will help better mirror the real and virtual worlds through modeling and simulation of the system [9]. However, small and medium size enterprises have a steeper barrier to entry due to the difficulty of having enough resources to implement effective modeling and simulation tools [8].

Ideas of virtual factories that are integrated simulation models with advanced decision support capabilities have been around and been studied from a holistic point of view [42]. The Digital Twin is in the process of using the model in real time, and making decisions as the physical world changes.

Digital Twin research is ongoing in all types of fields, ie. waste electrical and electronic equipment are hopping to use DT and Industry 4.0 technologies to support remanufacturing [43]. DT product design frameworks have also guided manufacturers to support and help the design process using a digital twin [16]. A preliminary extension of a service oriented framework of a digital twin driven product design in manufacturing was conducted as a part of a product's life-cycle management[41]. Digital Twin also allows for "what if" scenarios and analyze how processes are affected in the future [44].

Cloud servers have been highlighted to play an important role of aggregating data from connected cyber-physical systems [15]. Digitization of manufacturing by cyber-physical production systems, combined with model-based system engineering, models are more than ever able to predict systems behaviour [9]. Another example of the Digital Twin was used in a process model method which studied integrating process design data and on-site processing parameters in marine diesel engine pistons to study the effects of real-time visual simulation and decision making [45].

2.3.2 Conceptual Modeling

Model complexity can lead to difficulties discerning the cause and effects in models. The idea of conceptual modeling is creating a framework during the simulation development process to better understand the model [46]. Taking the time to conceptually plan out how the model is built is believed to help minimize errors and help researchers, practitioners and stakeholders understand the model [47]. Conceptual Modeling is regarded by Robinson [48] as a one of the most vital steps in a simulation study due to the design of the model having many impacts throughout the simulation study. The conceptual model is in essence the link between the real system and the simplified simulation model and is an important idea for when building a digital twin. A conceptual model is described as a living and growing document, developed from an informal to formal description of the model and are concepts that will be used to developing the digital twin framework [49].

2.4 Digital Twin

The concept of the Digital Twin was first coined by Grieves in 2003 through an executive course on Product Life cycle management, defined "as a virtual representation of what has been produced" [50]. Although the definition of the Digital Twin has changed since then, one of the earlier concepts of the Digital Twin was proposed in 2012 to monitor future NASA and U.S Air Force vehicles under higher stresses over their lifetime by integrating higher fidelity models allowing to monitor the vehicle's health in hopes to enable unprecedented levels of safety and reliability [51].

Conceptually, the Digital Twin was a digital duplicate of the physical entity [44]. The idea of the digital twin was to have a working virtual copy of the physical product to understand and investigate the effects of actual forces in order to understand its behavior at a fraction of the actual cost of physically building a duplicate. [14] So, the DT was most often seen as a virtual twin to a physical product [52] and the concept of the Digital Twin was the convergence between product's physical and virtual space, and understanding how to generate and apply cyber-physical data to better serve a product's life-cycle through improvement in product design, manufacturing, and service [41].

The Digital Twin concept has been growing as a tool to combine the physical and cyber worlds, not just products together and has been growing exponentially [11]. The DT is considered to be a "critical milestone" in the world of smart manufacturing [16] by providing real-time monitoring capabilities to analyze and help make system decisions [53]. This virtual copy of the physical system where its digital information would be a "twin" of the information embedded within the physical system throughout its entire life cycle [14].

Some of the potential benefits of the DT include reduction in cost, higher efficiency, better decision making, enhanced flexibility, and a more competitive manufacturing system, however, there are few examples validating and quantifying such benefits [4]. By integrating the physical and digital worlds, the Digital Twin provides a promising opportunity to implement smart manufacturing [5]. Smart manufacturing enabled by a combination of new information technologies, big data, Internet of Things (IoT), artificial intelligence, advanced computing make this possible [5].

Digital Twin in the way we see in our research is a method to incorporate cyber-physical systems into manufacturing, which is a critical step to develop systems that are considered smart manufacturing [54]. Connecting the two worlds provides manufacturers new methods to carry out decisions through the use of simulation, data analysis, and optimization and provides manufacturers a greater level of productivity [40]

More than ever, not only does the digital system contain information about the physical system [14], but the Digital Twin emphasizes the interaction and communication between the physical and digital systems [16]. A manufacturing shop-floor is an area where new information technologies (big data, AI, autonomous decision making) can be applied using the Digital Twin [13].

The following are some examples of definitions found on the Digital Twin:

> "A Digital Twin is an integrated multiphysics, multiscale, probabilistic simulation of an as-built vehicle or system that uses the best available physical models, sensor updates, fleet history, etc, to mirror the life of its corresponding flying twin."[51].

> "Concept of a virtual, digital equivalent of a physical product." [53]

> "The Digital Twin posits that the flow of data, process and decision is captured in a software avatar that mimics the operation." [44].

> "The Digital Twin is a comprehensive digital representation of an individual product. It includes the properties, condition and behavior of the real-life object through models and data. The digital twin is a set of realistic models that can simulate its actual behavior in the deployed environment." [52]

> "Digital Twin is a set of virtual information constructs that fully describes a potential or actual physical manufactured product from the level of micro atomic level to the macro geometrical level" where its elements are the "real space, virtual space, the link for data flow from real space to virtual space, the link for information flow from virtual space to real space and virtual sub-spaces" [14]

2.4.1 Internet of Things (IoT)

One of the main objectives of Internet of Things (IoT) from a manufacturing standpoint is to realize smart factories, where physical machines and resources are communicating and connected to a network that is able to make better decisions [15]. A relatively new paradigm for universal connectivity with the use of tools and technologies known as Internet of Things, a "digital-by-design metaphor" which brings together the digital world [44]. Internet of Things (IoT) benefit the manufacturing plant through automation, accuracy, efficiency, and productivity though the use of IoT technologies such as sensors that connect physical resources in real-time [16]. Internet of Things (IoT) is also described as a network of interconnected objects that allow for a smart environment, a modern digitized manufacturing system [15]. In order for IoT to be more fully realized, establishing factories with self-awareness, self-prediction, self-comparison, self-maintenance capabilities are required [7].

The Digital Twin fits into the IoT paradigm in that the physical and virtual worlds are able to communicate through IoT technologies. Internet of Things (IoT) used in an industrial level proposes higher efficiency, accuracy, and economic benefits through an infrastructure of devices with sensors allowing for the integration of both physical and virtual systems[3]. These technologies enable the Digital Twin to be effective and have both physical and virtual worlds connected together.

2.4.2 Cyber-Physical Systems (CPS)

Cyber-Physical-Systems have two main components, having the ability to communicate real-time information with the physical and digital worlds and secondly, an intelligent data management system to make decisions within the cyber space [55]. This function is a critical part of allowing the Digital Twin to communicate between its physical world and its virtual model. An integral component of integrating a Digital Twin requires the use of Cyber-Physical Systems, a technology to manage interconnected physical assets with its computational capabilities [55].

As Cyber-Physical-Systems is a combination of physical and computational capabilities which allow for physical resources to gather information, make decisions and communicate,

[13], the full realization of the Digital Twin is still seen as a major challenge [13]. CPS links the physical world with the virtual world through data as information that need to be analyzed in order to provide value [15]. There are still many concerns with implementing a Digital Twin ranging from manual acquisitions of data, high costs for new information technology environments, and a need for simulations and optimization models to better take advantage of real time information especially for small and medium sized enterprises [2].

3. DIGITAL TWIN FRAMEWORK: A MODELING PERSPECTIVE

The journey to uncovering the true potential of the Digital Twin (DT) starts with understanding the DT from a modeling perspective. There have not been many papers that explore in detail how the benefits of the DT are realized. It is a common idea that cyber-physical systems coupled with real time data and computing power should help decisions makers make better decisions but the question is how? Far too often authors leave readers with only a broad overview of the concepts of the DT and how the data from both the physical and virtual worlds will be used to spit out an optimized solution.

In this chapter, we will explore the general concepts of Digital Twins and introduce a framework to study its key characteristics.

3.1 Digital Twin Concepts

In its simplest form, the main components of a Digital Twin model includes a physical world, it's digital or virtual counterpart, sensors that are able to track information, and the ability to communicate between each world. Given these components, it is reasonable to believe that the system can reap the benefits of using a DT and make better decisions. It is believed that in order for future manufacturing companies to stay competitive, adopting technologies that enable DT characteristics will be of critical importance. Developing a method to analyze performance benefits of the DT is an important step we hope to study through this research.

Typically, when a simulation is made of a system, the model is built hoping to find the answer to a question. What is the utilization of a specific machine if we add a new product? How many more parts can we make if we change and upgrade a machine? What savings can we achieve if we move around the location of products? Months are devoted to building a model which in turn is used to finding answers to the questions at hand. With the completion of a project models are sometimes recycled and used in future projects but more often become unused. Factors ranging from model complexity to staff unfamiliarity can lead to the difficulty of extending a models life cycle.

Although the DT consists of a simulation model, it is very different to the typical simulation project. The method to how you answer/ask questions make the use of the DT more unique compared to a typical simulation. One key characteristic is the continual integration of the physical system's current state through the use of sensors and relaying the information as parameters to the DT. The mirroring of the physical world has benefits such as increasing the accuracy of the simulation while not requiring a ramp up time to reach steady state. Due to the relationship between the physical world and the DT, the most effective questions to study are those which affect repetitive decisions.

There is a delicate balance between the update frequency of the DT and the value gained from the simulation run time. If your update is frequent, the DT will be closer to the real system throughout the simulation process, however, the value of information gained from the simulation is only as good as the increment of the update period. If the update of the DT is rare, the DT results will be more like a typical simulation run as discussed earlier. The relationship of the update frequency of the DT and the value of information will be explored more thoroughly in later sections of this thesis.

The DT's role in a manufacturing plant is one of continuous cycle of updates and decisions using the most current state of the physical system. This is a massive benefit where the decisions are no longer made generally but catered to exactly what the current physical system is experiencing. As models become more accurate and the technology required to use the DT are better understood, the benefits are believed to heavily outweigh the costs of setting up the DT system.

A Digital Twin framework will be developed to explore the behaviour of the DT's interaction with the physical system and to provide empirical research to assist in designing DT systems.

3.1.1 Building a Digital Twin Model

Creating an effective method to study the benefits of the DT requires a test bed to allow for the experimentation of DT components. As the development of the DT and it's potential impact are being discussed, it is still difficult to know the necessary requirements and how the DT needs to be built to effectively make better decisions. In order to better understand the DT, this research proposes using simulation modeling to test the DT by building both the physical system and virtual system congruently in the same model.

The physical model will be represented as the real system. All the randomness and decisions played out in the physical model's representation in the simulation is considered to be the actual changes in the real system's state. The state changes in the physical world portion of the simulation will then be replicated and pasted onto the virtual image as the physical system's DT. It is an important detail to understand that this virtual image of the real system can be as detailed as the physical model's representation, as in a perfect replica, an exact twin, or less detailed in terms of accuracy or aggregation of parts. Simulation models of physical systems often capture the main components and interactions, however, models never fully are able to incorporate all the complexities that real physical systems have. Likewise, one of the objectives of this thesis is to look at how the change in the model's representation of the real world affects the effectiveness of the DT.

There are many hurdles before a fully integrated DT can provide companies with its claimed benefits. There is a need to stress the importance of building the DT model and the amount of detail that is required in order to gain enough information to make the right decisions. Some say that building models is more of an art than science, and as much of the model building techniques will carry over into building the DT. This thesis will explore not only the model building process but also dive into the technical requirements of the DT.

3.1.2 Digital Twin Model Components

We propose the testing of the Digital Twin model be explored through creating the physical ”real” system as well as its DT or shadow counterpart both virtually in a simulation model. Modeling both systems in a single simulation will allow the study to find the benefits as well as the interactions between the pseudo-physical system with its DT. Much of the research seen so far has not shown quantitatively the interactions and impact of using the DT. Local and global variables become a way for the models to communicate representing the data that would be collected from sensors of cyber physical systems on a plant floor. There are other simulation techniques that will allow to represent the DT in a simulation along side it's pseudo-physical system. Simulating the interactions of the two systems will also help predict the benefits of the DT in a real world setting.

In the simulation model, in order to update the DT, there must be a way to manipulate the parameters in order for the DT to match the physical "real" world. For example, at certain points in time when the DT is updated, every parameter essentially gets discarded, such as the number of items in queue, where new entities are created to match the number of entities in queue in the pseudo-physical world. Since the pseudo-physical world is considered to be the real system, there is no need to have additional methods of adjusting, creating, or destroying parts due to the fact that the results are considered permanent as would be in the real world.

Theoretically, a perfect DT would be an exact copy of the real system, where the simulation of the two systems would differ only by the generated random numbers. However, models will always fall short of representing a real system due to its complexity and in essence lacks information compared to the real system. In order to test the benefits of the DT, many different representations of the pseudo-physical system must be tested. How to represent the DT and how much detail is required is a topic of concern in this research. When building a model, oftentimes there is a hierarchy of behaviors or logic deemed important while other mechanisms are considered unimportant and often left out or tuned as an assumption.

3.1.3 Digital Twin Update Frequency

One of the main concepts of the Digital Twin is the idea of the update frequency. The update frequency can be defined as how often you update your DT to mirror the physical system's state. At every update point, the DT takes all the parameters that it can in order to best match the physical system. The update frequency is defined as the number of times the

DT is updated between decision epochs or the frequency of each update. The time between each update can be measured as the time between each decision period t and the number of updates, n. Random numbers, or unforeseen occurrences, or inaccuracy in the model can all lead to the diversion of the DT and the real physical system. Update frequency can also be adjusted by changing the frequency of the decision period. Updating the DT allows the DT model to correct itself and be more aligned with the real system. However, the trade-off for increasing the update frequency is we lose information gained by the simulation of the DT. In the next section we will look at the effects of adjusting the update frequency. Simulation modeling has often been used to find long run averages with decisions based on the steady state of the system, however, using the DT enables a shift in the way we approach decision making. The simulation of the DT allows decisions to be based on the current state of the system, where adjustments are made to counteract errors of the model, miscellaneous events, or even deviations based on the wrong string of random numbers.

3.1.4 Digital Twin Level of Detail

Building a model of any system requires a level of detail and understanding of the system mechanics. By increasing the amount of detail in the model, we assume the model provides greater accuracy of mimicking how the real physical system behaves. By understanding the logic of the real system, a model with the appropriate level of detail can help make better decisions in the real world. This idea of decomposing a model to the right level of detail or granularity is a difficult problem especially given that most simulations models often default to adding as much detail as possible.

Another component to be explored is how the update frequency effects the desired accuracy level of the DT. One of the potential benefits of the DT is to explore how updating helps correct/mitigate errors. Therefore, models with less accuracy or less details, inevitable with increased number of errors may benefit from the DT's ability to update. The balance of update frequency, model accuracy, and enabling decision makers to make the right decision is a core concept of this thesis. Understanding these components will allow and present a framework to approach the accuracy level of the DT and its effects on making decisions while providing insight on how the physical and virtual systems should communicate.

3.2 Value of Information

In order to compare and evaluate the Digital Twin framework, the common theme or variable is that all the components provide some sort of information which in turn has value. Building a more accurate and detailed model of the physical system is providing the decisions makers with better information. The update ability of the DT and communication between the physical system and its DT is the sharing of information. Choosing the right decisions is based on the information provided by the DT model where the result of the decision shows the value of the information provided.

With the basis that a model is a simplification of a real system, there will always be some information that will be lacking in the model. There will be details which can be components, connections, parts that aren't included, or sometimes false information added to the model. Managing how to handle this lack of information and being able to identify what information is missing is key to creating a model that is useful. In its bare form, a model is a function taking in information and producing output for the modeler to interpret. Based on how the model was aggregated or simplified, there may be only a specific subset of outputs that are reasonable.

3.2.1 Conceptualizing Information Loss

Marschak and Radner [56] described η as an information function (or structure): a function from X $\rightarrow$ Y. $\eta(x)$ denotes the information signal when x is the true state of the environment. The value of η, the information signal, is found by comparing the expected utility of η under certain assumptions while assuming there is a cost attached to using η and comparing it to the maximum net expected utility with no information. In other words, the value of information is the cost associated with the gain in increased utility. In the same light, we consider using this methodology, but instead, comparing different information signals and their expected utility with the real system which has complete information and the maximum expected utility for any information signal. By comparing different information signals, we can compare the effectiveness of having multiple representations of the true environment based on different information functions or in our case, different aggregated models of the real system. By having different models with varying levels of detail, or accuracy, we will better understand how to aggregate models and the level of detail needed to represent a system under the DT paradigm.

In order to better understand different information structures and different representations of the real system, we first must describe what is the real system within this experiment. Essentially, the real system is a representation of any system with any level of complexity, in it's most detailed form. The real system information signal represented as, $\eta*$, is in essence the assumed system, or an exact model of the system under question, incorporating every detail and possibility that could result in the system, as in the real world. Every result or performance measure from any replication from the "real" system model is in fact considered the true result for that given run. All other models are a representation of this real system. Theoretically, we could copy the "real" system components, but we take the assumption that the "real" system, $\eta*$, be the only model with the exact components, and every other model will at best reflect $\eta*$ with less information.

The information signal from $\eta*(x)$ is the result of the real system, meaning that its information function is 100% accurate and will give the highest expected utility based on the desire to model the system's performance measure. Here lies the method to understanding and representing information and its value. Theoretically, if there is way to represent the the system's information function $\eta*$ using a simpler model or one with less detail with a different information signal η, while maintaining accuracy, η could provide a net payoff close to the payoff using $\eta*$. However, simplification of models usually come with a cost, and this cost is the loss of information which constricts the types of questions or results that can be answered by a simpler model. Simplified models can still provide a wide range of insight and model the real system under specific bounds to make important decisions. A clear understanding and ability to represent models with varying information structures will provide the needed theory to build the foundation and framework to modeling the DT and the requirements for all of its components.

Conceptually $V(\eta)$ represents the value of the information structure. Marschak and Radner [56] compared the max expected payoff $\Omega(\eta, \alpha)$ with the expected payoff function, $\omega(x, \alpha)$ with 0 information, α being the action made by the decision maker. If the values of a model that fully represent the real system, $\eta*$ can be compared to the information structure of a simplified model η, then their difference represents the information lost in the model. Better understanding the loss of information and the implications of the model representing the real system will help define the best way to model more complicated systems. A figure of this concept can be found below, Fig. 3.1.

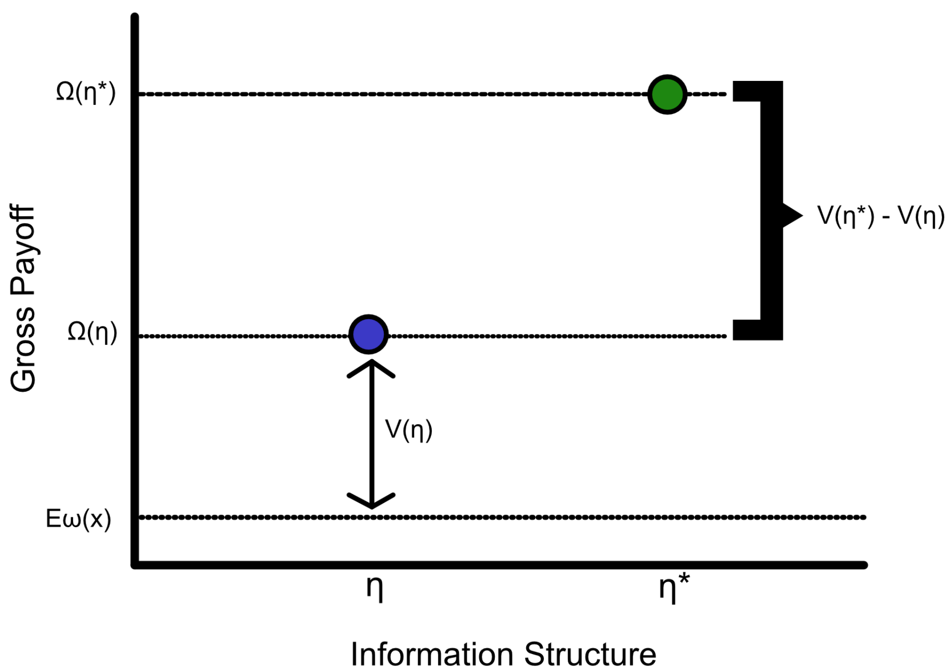


Figure 3.1. Utility Function Concept

3.2.2 Model Formulation

This section tries to understand and dive deeper into how different levels of detail effect the accuracy of models. There is a sole emphasis on the information structure element of

Marschak and Radner's [56] theory regarding information and decision functions. Although their method includes a decision making component, needed in future sections when incorporating the DT, analyzing the information structure is a crucial first step. The utility function takes into account different states of the system, and the first step is to consider when we aggregate a model with less detail or less accuracy, how this changes the landscape of understanding different information structures.

The main change in the formulation is to look at how the models of different information structures, η, are lacking in information. Compared to Marschak and Radner's [56] method of finding the cost, $\mathrm{V}(\eta)$, we are rather interested in looking to find the information needed to match the upper limit of the payoff function, the expected utility of the real system's information structure. Instead of subtracting the cost of the information signal and comparing the utility with no information, we instead find the amount of information needed to increase the expected utility to match the information signal with perfect information.

The expected payoff using the information structure η is:

$$\Omega(\eta; \rho, \boldsymbol{\pi}, \upsilon) = E\upsilon[\rho(x, \eta(x)) - \gamma(x, \eta)] \tag{3.1}$$

where x is the state of the system and ρ is the outcome function where the outcome r is a result of comparing the information signal of the model $\eta(x)$ and the real system $\eta*(x)$. $\upsilon(r)$ is a utility function for the modeler of the outcome r; a real-valued function on R. The utility function provides the method to compare the value of each model. $\boldsymbol{\pi}$ is the probability measure on X. $\gamma(x, \eta)$ is the cost of the information.

The loss of information, $L(\eta)$ from using the model η given the right conditions can be found by finding the difference between the payoffs of $\eta*$ and η:

$$L(\eta) = \Omega(\eta*; \rho, \boldsymbol{\pi}, \upsilon) - \Omega(\eta; \rho, \boldsymbol{\pi}, \upsilon) \tag{3.2}$$

3.3 Pseudo-Physical Real System

The physical systems in our examples will be a manufacturing plant managing its objectives. As we will virtualize the physical system in order to test its interactions with its DT, we will consider it a pseudo-physical ”real” system. Conceptually, this pseudo-physical ”real” system will provide to be the real system who’s dynamics are counted as final. All decisions made in the virtual pseudo-physical ”real” system will have a cost and once incurred can not be changed as time progresses. The DT will also be a virtual model and will be built based on the pseudo-physical ”real” system. The DT will have varying degrees of accuracy and information but can not know the true parametric values of the pseduo-physical ”real” system. Throughout this research we will refer to the pseudo-physical ”real” system as the PPR system.

3.4 Digital Twin all-in-one Mechanism

In order to test and understand the benefits of a Digital Twin, a model was developed encapsulating the features necessary to show the benefits and interactions of a Real System with its DT. The model also incorporated the ability to make decisions while enabling the DT to run multiple replications in a single model. This all-in-one mechanism is geared around the decision maker and believed to be applicable whenever a DT needs to be tested before real world application. Essentially, this model can be thought of as moving gears in a clock, where each layer of the model corresponds to a specific gear creating interactions between the real system and the DT. In a real world setting, a model of the system would be created, then the all-in-one mechanism could be used to show the potential benefits of the DT application.

Conceptually, the real system is a component of the simulation model and behaves in tandem next to its DT counterpart. The DT essentially runs in the model much faster allowing for updates and information exchange when needed. The real system component is allowed to behave as modeled where the only input is through the decisions made by the DT approximation or decision maker. The mechanism that allows all this to occur in a single model is through a series of signals or events where the systems within the model respond appropriately.

3.4.1 Model Signals/Events

In our study, the all-in-one mechanism has gears of the model interact through a sequence of signals/events within a discrete event simulation. Our model includes a signal for every decision period, DT update, and every DT replication that occurs by the DT. The exchange of information between the two systems occurs during each event but depending on the type of event the direction of the information exchange can be different. Every decision period resets the condition for the DT's mechanism of signals allowing for the rate of the DT replications to align with the required number of updates.

A pictorial representation of the all-in-one mechanism of how the real system and DT can be modeled simultaneously can be seen in Fig. 3.2. The decision period, is the model's largest gear and is essentially turns in real time representing the virtual real system. Within this period, costs are calculated and decisions are made for the next period. The turning of the decision period essentially effects the connected gears and allows the DT to update and replicate accordingly.

3.4.2 Information Exchange

Figure 3.2 also shows the direction in which information is exchanged between the real system and the Digital Twin. The period between decisions, the pseudo-real system continues to be simulated while updating the DT with information when needed based on the events of the updater. The DT is updated by both the updater and replicator and is represented in the discrete event simulation model as a set of arrival processes. The DT represented in the discrete event simulation model will be further explained using an example in the next section.

3.5 Digital Twin Examples

Due to the lack of quantitative research on the Digital Twin, fundamentally the study of DTs is in its infancy and at the genesis of truly understanding how to classify and approach this area of research. The DT most often should be paired with a complex system with a wide

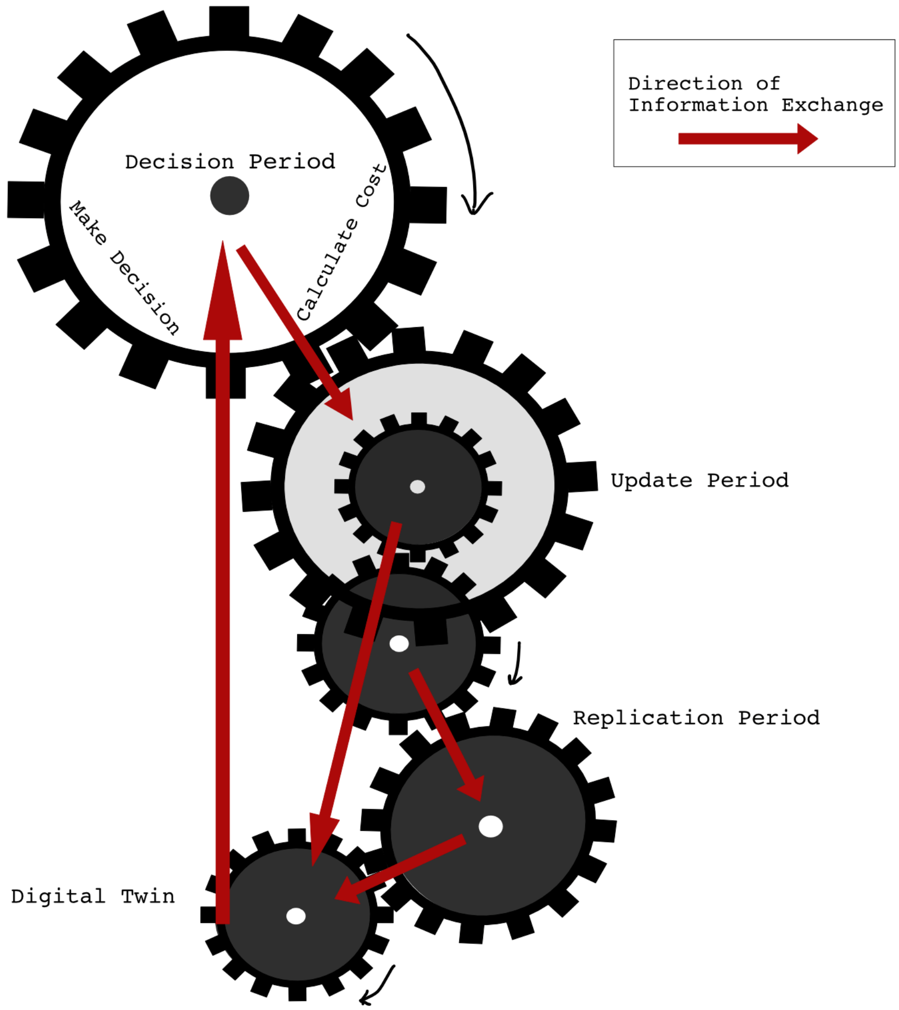


Figure 3.2. Mechanism for Digital Twin Framework

ranging list of parts and interactions with its system's components. Complex systems are difficult to understand and there really is no method to predict every outcome, however, there are ways to better understand its behavior even those that are emergent, being outcomes that weren't predicted. Emergent behavior can be considered a key component of complex systems in that its outcomes are more than a sum of its parts.

In order to fully realize the benefits of the DT, we sought to understand the DT and its effectiveness in the most simple case possible. In order to show the basic benefits of the DT we created a simple model of the DT using a well known inventory model. The inventory model provides the basic foundation of the desired needs of a system that would benefit from a DT. Essentially, a simple production plant with an inventory problem provides an example with repetitive decisions (the number of parts ordered), and a method to calculate a cost based on the decision. All the components of a regular inventory model such as lead time, reorder period, order quantity, safety stock can all be intertwined to test and see the benefits of having a DT.

We also built the DT Framework on a more complex system, based on an existing manufacturing plant. The purpose of extending the framework to a more complex system was to show and learn how the characteristics of the DT are applied with added complexity. The second model has different size parts with queue restrictions and multiple policy choices. The model also will have different performance metrics to see how the DT adapts to the different objectives.

In the following chapters we will explore this idea of the DT within both examples. Simply, the ”real” system has objectives either managing it’s inventory or choosing policies with performance objectives. Different DT models will allow the exploration of the link between the DT and it’s physical ”real” system, more specifically, help understand the connection between the DT’s update frequency, overall cost, decision making, and level of detail of the DT model. Not only will this help start create a standard of looking to provide quantitative analysis of the DT but also help realize the true benefits and its impact in the future of manufacturing.

4. DIGITAL TWIN: A SIMPLE INVENTORY MODEL

In this chapter, the ideas of the DT concepts using a simple inventory model is explored. By creating and understanding the foundation of the DT within this simple model, a goal is to not only find general conclusions but see how ideas can be expanded to more complex systems.

First, quantitative analysis of the DT and its components will be based on an inventory model that allow decision making while reacting to the changes seen by the real system. This idea of using the DT to analyze the current model's state and making a decision based on the results of the DT's simulation will create the communication desired in a Digital Twin and it's physical system. Using the simple inventory model, system behaviour and mechanics will be compared with varying accuracy levels of the DT.

4.1 Simple Inventory Model

The simple inventory model is a single machine, single item, fixed reorder period system with the PPR system making decisions minimizing its costs by meeting demand. The PPR system will incur costs when unable to meet demand through a shortage of products or through holding costs when there is a carry over of excess inventory between order periods. The decisions of the PPR system will be based on the expected demand forecast made by the PPR system's Digital Twin. In this model, the only fixed variable will be the time periods between each order. A discussion in greater detail of the components of the simple inventory model, details of the model's logic pertaining to the DT, and a cost/benefit analysis of varying the accuracy and update frequency of the DT in the subsequent sections.

4.1.1 Notation

Decision Variables

n Number of DT Updates in Decision Period

OP Order Period (Decision Period): Fixed Time Period where orders reviewed and inventory replenished

DT_Reps Number of DT replications between Updates

R_PT The PPR's Processing Time

DT_PT Digital Twin's Processing Time, an approximation of the R_PT

HC Holding Cost : Cost per unit remaining at the end of each order period

P Unit Price for each Part

T Time Period: Number of Time periods $1..T$ in the simulation run

State Variables

OQ_t Order Quantity : Number of parts ordered during period t

$I_{n,t}$ Inventory Level : Number of units on hand in the PPR system at the beginning of update period n and period t

DT_Est_t Digital Twin's estimation of PPR's Demand for period $t+1$

R_Extra_t Indicator variable determining if there are parts remaining in PPR system for period t

EI_t Ending Inventory level of the PPR system at period t

$EndTime_t$ Time at end of period t

SO_Time_t Time of stock out for period t of PPR System

$DT\_Out_{n,t}$ The average number of parts processed by the DT replications for period t and update period n

$R\_Q\_I_{n,t}$ The inventory level of the PPR system at the beginning of each update period n in period t when $n > 1$

DT_A_t The total adjustment of DT_Est_t required at the end of period t

Decision Variables set for the examples given throughout this chapter

OP 24 hours

DT_Reps 15

R_PT Normal(30,9) minutes

DT_PT Normal(x, x *.3) minutes

HC $25

P $25

T 748 hours, 31.16 periods

$ModelRunReplications$ 30 replications

4.1.2 Model Logic

DT Logic

A key component of this model is the method of building a Digital Twin that is able to communicate with a PPR system. Since both the DT and PPR system are within the same simulation there are a few ways to create a forecasting dynamic while the PPR system is also running. Currently, the logic is to create a method to predict the OQ_t in parallel by assuming the DT is predicting the PPR's demand for the coming period $t + 1$. Based on the ending inventory level of the PPR system, the order quantity for the next period can be found through Equation 4.1. If the ending inventory level exceeds the DT estimation no order would occur.

Hence:

$$OQ_{t+1} = \begin{cases} DT\_Est_t - EI_t \quad if \quad DT\_Est_t > EI_t \\ 0 \qquad otherwise \end{cases} \tag{4.1}$$

Furthermore, the trigger that allows the entire Digital Twin mechanism to function is creating a feedback loop through a dummy process every Order Period, OP. The chain of events starts with finding the Order Quantity, OQ for the new period based on the estimation of the DT. The DT estimation is based on the expected demand or the average throughput of all the replications for the order period, including the expected units when the DT goes out of stock.

$$R\_Extra_t = \begin{cases} 1 & \text{if } I > 0 \qquad \forall t \in T \\ 0 & \text{if } I = 0 \qquad \forall t \in T \end{cases} \tag{4.2}$$

Even though the predictor is based on the results of the DT, a key aspect of the DT is taking into account the current state of the PPR system, allowing for the OQ to be based not only on the DT_Est_t but also updated based on the current inventory levels of the PPR system. Once the Order Quantity is established, the cost for that period will be calculated shown in the next subsection.

In regards to the logic of the DT and the update frequency, one of the basic signaling methods used is to create dummy entities equal to n, the number of times the DT would update between each order period, OP. These dummy entities, are the gears that allow the DT mechanism to occur all-in-one. Each entity is held in a dummy process with a processing time of OP/n. Every release of these dummy entities will fire a signal to update the digital twin by resetting all the parts and variables accounted for the previous update length, OP/n. During this reset, not only do the variables and parts in the current state of the DT have to be reset, but also, must duplicate the state of the PPR system. The number of units currently in the PPR machine is duplicated and released through an alternative source which feeds into the Digital Twin.

At every OP, both the PPR system and DT are signaled to release the OQ estimated by the DT. The PPR system only adds parts based on the OQ and is otherwise untouched. However, the DT is reset every OP, copying the PPR system's state in terms of the number of entities within its system. In order to do so, the Order arrival is set to $OQ_{t+1} + EI_t$.

4.1.3 Decision Variables

The decision variables are used to better understand the effects of using a digital twin when making decisions. Every simulation run of the model is based on a specific set of parameters which are then compared. The main variables under question are n, the number of DT updates, and DT_PT, the approximation for the Real system's processing time. The variable n allows the DT to update its state to match the real system at specific time points within the order period. This transfer of information to the DT from the real system is a key component of the digital twin. Having an increased number of updates in theory reduces the error of the DT while reducing the effectiveness of the simulation's approximation. Essentially, the information gained from the simulation decreases with each update due to the approximation being based off of smaller increments of time, where the limit as $n \to \infty$ would be the real system itself.

The approximation of the Real system's processing time within this simple inventory model is being used to understand the effects of accuracy when using a DT model. R_PT is unknown to the DT side of the model and decisions are being made solely on the approximation and information gained by the DT. The only difference between the DT and the PPR system's inventory mangement is the difference between their processing times which allows for a 1:1 comparison of accuracy. Often times, simulation models bundle a set of machines or create assumptions so that the model can represent the real system but often leave out information and in most cases are a simplified version of the real system. This simplification makes it difficult to know objectively how accurate the model is but in this inventory model there are no differences in how the parts are processed, just the processing time parameter setting.

The all-in-one modeling setup of having the PPR system as well as the DT in a continuous loop of signal/events and information exchange allows for the study and testing of these decision variables. Understanding how the updates of the the DT and accuracy of the model plays a role in the exchange of information will give insights into the requirements of implementing a DT for a real physical system. As systems are complex in nature, using this simple inventory model is thr first step to understand the impacts of a DT system and the importance of each component.

4.1.4 Cost Function

The method to compare the effectiveness of the digital twin is measured through the cost function based on the ending inventory levels of the PPR system. This simple inventory model allows for the estimation of the DT to measure the effectiveness of the decision variables. Essentially, the information exchange between the PPR system and the DT can be evaluated through a cost function representing the utility function to compare the information structures of each DT representation.

This cost function, Eq.4.3 is solely dependant on the state of the PPR system's inventory. The DT's estimation is a forecast method for the PPR system to hit an inventory level of 0 units at the end of each Order Period. The cost function takes into account the holding cost for units that are left as well as missed production cost for potential orders that weren't made due to stock out. This balance of holding cost and missed production cost allows for the model to examine different levels of accuracy or in this simple model's case, the change in DT_PT and n.

$$C_t = \begin{cases} EI_t * HC & \text{if} \quad EI_t > 0 \qquad \forall t \in T \\ P * \dfrac{EndTime_t - SO\_Time_t}{R\_PT} & \text{if} \quad EI_t = 0 \qquad \forall t \in T \end{cases} \tag{4.3}$$

The comparison of the cost function for different decision variables implies the loss of information $L(\eta)$, η being the set information structure of the DT based on the set parameters. The change in decision variables and the closer the estimation of the DT shows the effectiveness of the information exchange between the DT and the PPR system. The total cost for each model $\eta(x)$, information structure of the DT, based on set decision variables is the expectation of the total cost over all periods T, Eq.4.4.

$$TC(\eta) = \sum_{t=1}^{T} C_t \tag{4.4}$$

Based on the notion of Marschak and Radner on the value of information, the idea of expected payoff is related to using different information structures η, or in this case the DT and comparing it to the real system, $\eta * (x)$. By comparing the DT with the real system, the loss of information is effectively being found, $L(\eta)$ based on the difference in payoffs between $\eta*$ and η giving us:

$$TC(\eta) = L(\eta) = \Omega(\eta*; \rho, \boldsymbol{\pi}, \upsilon) - \Omega(\eta; \rho, \boldsymbol{\pi}, \upsilon) \tag{4.5}$$

4.1.5 Assumptions

There are a number of assumptions made with this simple inventory model. One modeling assumption that is taken is that parts created for the model reset between order period updates. The time remaining of a part in the middle of being processed in the PPR system is not accounted for due to not being able to duplicate the state exactly. The part in the PPR system is created for the DT, but will enter the DT machine without having accounted for the time left in the real system. This assumption however is believed to be minor in the grand scheme of all the replications that the DT has.

Generally, the inventory model and the digital twin have been broken down into simple components. It is still unknown how such interactions will change as the complexity of the model increases. Even assuming that a simple DT model can reflect a more complicated system is an assumption. The simplifications of the DT and PPR system which are digital representations of a ”real” system are assumptions that could be questioned. The accuracy level of the DT will correlate to the level of detail in a more complex system is also assumed. The examples within this simple inventory model were arbitrarily created to show that a method to analyze the DT could be made while the generality of this method could be studied further.

4.2 Results

4.2.1 Key to Information Exchange

Through the construction and testing of the all-in-one DT model, a key concept emerged regarding the type of information to be exchanged between the PPR system and the Digital Twin. As the communication between the physical and digital world is a key component of the DT technology, there is an absolute necessity to better understand the type of information that is transmitted between the two systems. The information gained from the DT model finds value only when there is improvement shown through the cost function, the model's evaluation method of information loss, $L(\eta)$.

In order to implement a DT technology into a a physical system, this process of evaluating the type of information being exchanged will be a critical step in all DT models. A key finding even within this simple inventory model shows that information has features that can be difficult to measure and apply. The exchange of information has to be a focal point for every DT model and studied as a major process when building the DT, on par with conceptualizing the model as well as the verification/validation steps. The concern is using the DT model ineffectively due to the presumption that exchanging information between the physical and DT systems will help the decision maker. To the contrary, this study has shown how exchanging information can be misleading and how ineffective the DT model can be. There is also concern that the complexity of a system may complicate the understanding of information exchange.

In this simple inventory model, the PPR system and the DT initially exchanged the inventory state of the PPR system. Communicating the number of parts in the PPR system at each update period allows the DT to update the inventory level for that update period, n. The state of the DT matches the PPR system for every replication within the update period. As the number of updates increases between Order Periods, the error of the model decreases.

Figure 4.1 shows an example of how the DT updates the system state to match the inventory level of the PPR system. The DT is able to end the Order Period with an average

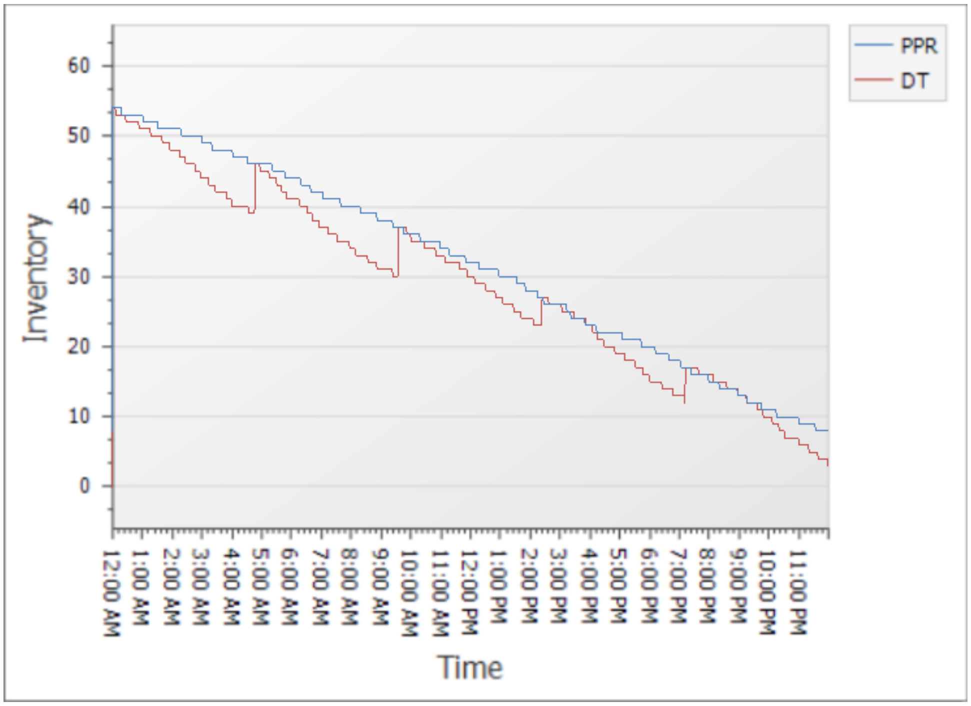


Figure 4.1. Example of the DT updating to match the PPR system's inventory level, $n = 5, DT\_Reps = 1$

inventory level closer to the PPR system's true state. Although the DT updates the inventory level every update period while also showing a more accurate average inventory, the effects of increasing the update frequency within this context does not provide value from the exchange of information based on the total cost. As seen in Fig.4.2, the effects of increasing the update frequency maintains the total cost with statistical significance regardless of n, the update frequency. Effectively, the PPR system's cost function is related to the Order Quantity predicted by the DT estimation. What this shows is that although the average inventory levels of the DT is matched with the PPR system, the estimation of the DT (the number of parts processed) is independent of its system's inventory level.

The key to the information exchange between the PPR and DT systems is the required dependence of the estimation with the information being exchanged. Essentially, the information being exchanged has to be of the same form as the predictor. In this example, as the estimator is based on the units processed by the DT, the information that needs to be

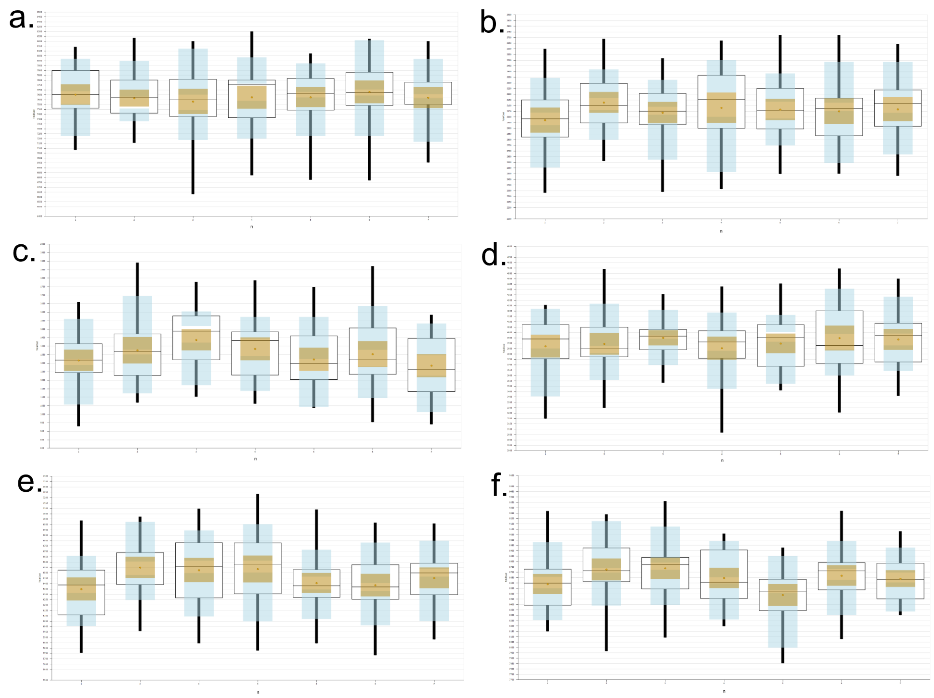


Figure 4.2. Average Total Cost with Update Frequencies for simple inventory model with change in DT_PT
a. $DT\_PT = 25$ b. $DT\_PT = 28$ c. $DT\_PT = 31$ d. $DT\_PT = 34$ e. $DT\_PT = 37$ f. $DT\_PT = 40$

exchanged is the difference in units processed between the DT and the PPR system at each update period. This subtle difference between the method to exchanging information allows the DT model to better predict the demand of the PPR system. Fig. 4.3, shows an updated graphical representation of Fig. 4.1 and highlights the information needed to have value for the DT.

For the simple inventory model, the difference in the average inventory level of the DT's estimation for each update period with the inventory level of the PPR system can be measured through Eq.4.6. Using the DT to update the difference in inventory levels allow for the approximation of the DT to be adjusted to better estimate the PPR system. By using this DT adjustment feature, incorporating the communication between the two systems results in finding value in information exchange due to the results in the cost function which can

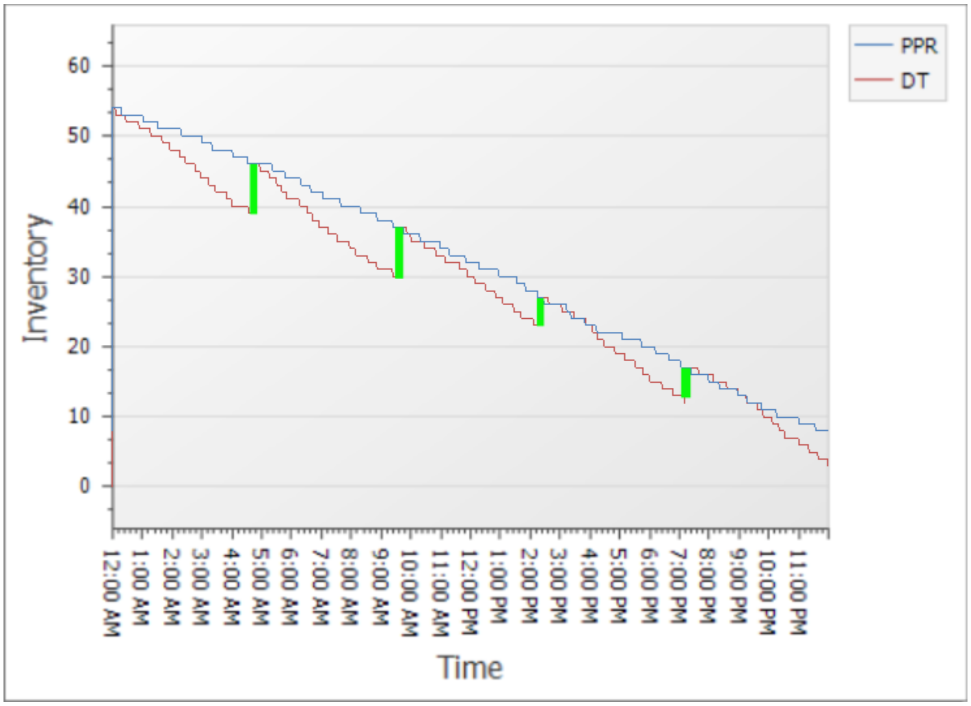


Figure 4.3. Example of the DT and the necessary information needed to improve the DT predictor highlighted in green, $n = 5, DT\_Reps = 1$

be seen in figure 4.4. Clearly, the effects of the cost function and the value of each update frequency for each estimation of the processing time, DT_PT can be seen.

$$DT\_A_t = \sum_{\mathrm{i}=1}^{n-1}((R\_Q\_I_{\mathrm{i}-1,t} - DT\_Out_{\mathrm{i},t}) - I_{\mathrm{i},t}) \tag{4.6}$$

4.2.2 Effects of Update Frequency

By updating the DT with different values of n, the update frequency, adjusting the effectiveness of the DT and its ability to forecast for the PPR system is possible. Taking a look at Fig.4.5, notice the exponentially decreasing function as the number of updates increase. As the value of n increases, there is a trade-off where the marginal value of information gained from an additional update decreases with each update within the same Order Period. This simple model shows how the effects of the DT and increasing the frequency of each update, a key component of the Digital twin is understood. There is some discussion to be had when

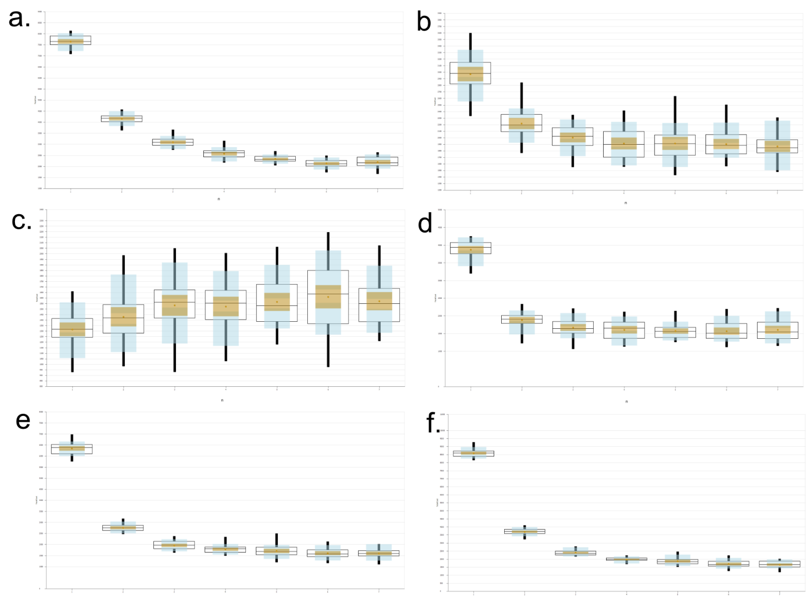


Figure 4.4. Average Total Cost with Update Frequencies for simple inventory model with change in DT_PT using DT_A_t
a. $DT\_PT = 25$ b. $DT\_PT = 28$ c. $DT\_PT = 31$ d. $DT\_PT = 34$ e. $DT\_PT = 37$ f. $DT\_PT = 40$

the DT model is accurate as adjustments made by the DT doesn't improve the cost function as seen in Graph C of Fig. 4.4.

4.2.3 Effects of Model Accuracy

In this simple inventory model, the accuracy of the DT is the comparison of the DT_PT with the PPR's R_PT. Allowing for the simple comparison of accuracy may help understand how accuracy plays a role in implementing the DT and provides insights into accuracy requirements as the system becomes more complex. Not only is there a direct relationship between the accuracy level of the DT and the total cost function, the amplitude of the information gained from each update n seems to depends on the accuracy of the DT. Increased error in the DT's estimation of the system's R_PT, in either direction, both the cost function and the value of information gained from each step n increases.

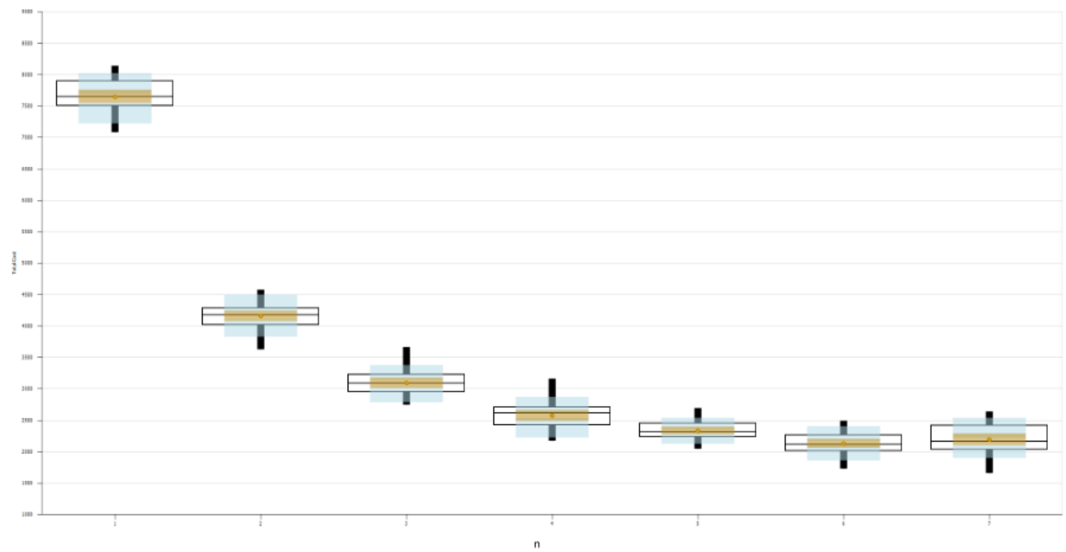


Figure 4.5. Average Total Cost with Update Frequencies for simple inventory model with change in DT_PT using DT_A_t , $DT\_PT = 25$

Observation of the cost function of both experiments show how DT_A_t effects the accuracy of the DT. In Figure 4.6 the DT's adjustment feature DT_A_t is absent and increasing the update frequency n doesn't reduce the cost at each DT_PT estimation. Finding the minimum does occur as expected when the DT_PT equals R_PT.

Figure 4.7 is a multi-view graph of having the effects of DT_A_t adjusting the DT estimation. The effects of both the accuracy of the DT_PT and number of DT updates, n can be seen together. The further the DT model's accuracy is from R_PT, the more valuable the marginal update of the DT.

4.3 Discussion

The main objective of the simple inventory model is to create a foundation implementing the DT technology while having a method to analyze the cost structure of the different components of the DT. By creating an all-in-one simulation model that has the components of the DT, the model can be expanded to incorporate more complex systems. This research

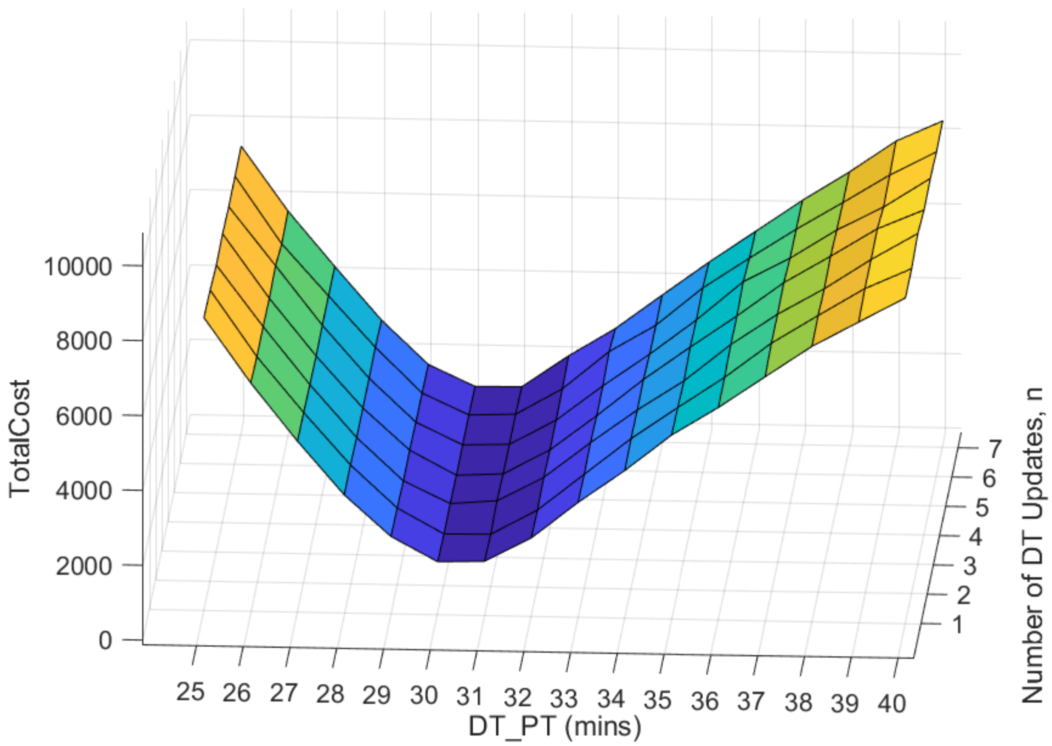


Figure 4.6. Simple inventory model represented over varying over n and DT_PT with out DT_A_t

allows for the analysis of the DT and the ability to study the cause and effects of a DT system. Consider this research a step into exploring and better understanding complex systems and the DT component requirements.

In reality, as Digital Twins become a part of complex systems, it may be difficult to measure how beneficial a DT system will be prior to its implementation. The cost structure, or the value of information gained with each update of the DT may be measured as a review process once the decision period has passed. However, the true cost structure may be unknown and difficult to calculate and so an approximation of the cost structure can be used. The cost structure for this simple inventory model was measured through the lens of the real system or the PPR system where the missed production costs due to stock out were calculated using the PPR's R_PT. The true system's values such as R_PT may not be known and so the cost structure would instead be formulated around the estimation DT_PT. One point to emphasize is the importance of how information is communicated

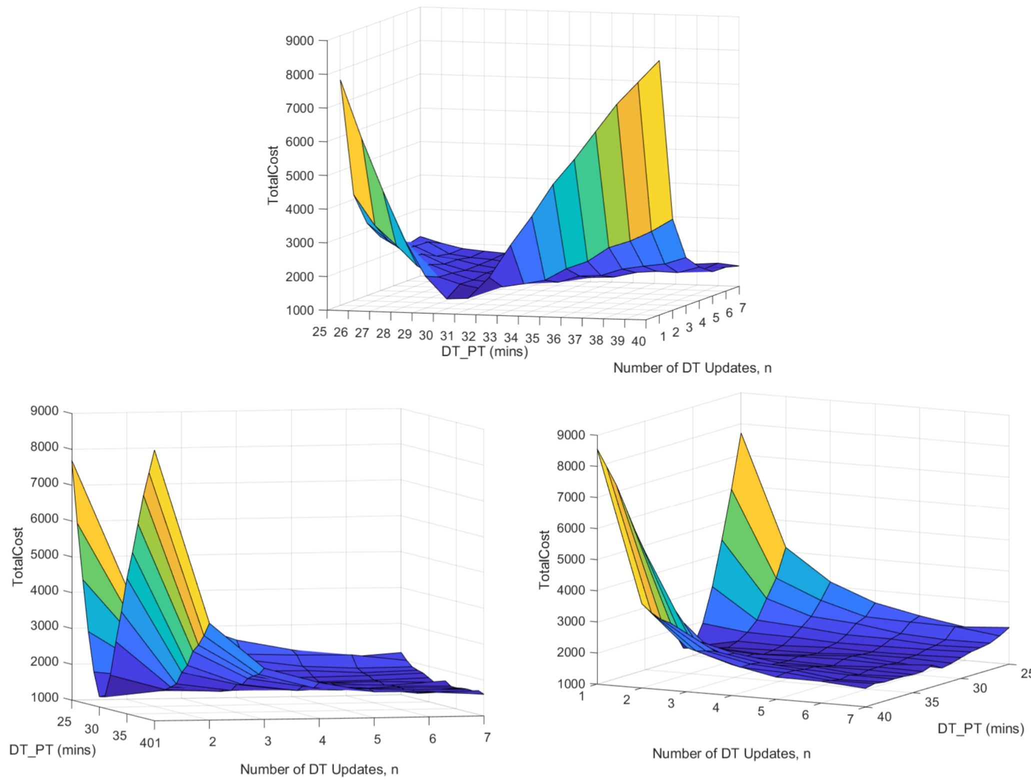


Figure 4.7. Simple inventory model represented over varying over n and DT_PT with DT_A_t adjustments with three views

and the type of information that is relayed between the real physical system and its Digital Twin. A careful study should be conducted prior to the implementation of the DT so that there is added value. Although most systems with a DT will be enabled to collect all kinds of data, it is up to the managers to understand the importance of measuring the right data that the DT needs.

Another point to discuss is the trade-off between the the number of updates and the accuracy of the model. As the model becomes more complex in nature, it may be possible to find an optimal level of updates based on a cost structure for the update frequency n. Quantifying the cost of increasing the number of updates will allow the comparison of the Total Cost with the cost to increase n as seen in Fig. 4.8. The linear plane in Fig. 4.8 can be thought of as the cost for increasing the number of updates. Essentially, the intersection of the plane and the cost function will be the optimal update frequency for a each specific accuracy level of the DT. As the DT's DT_PT approaches the PPR system's R_PT, the effects of update frequency is noticeable. By increasing n, there is less new information gained from the DT's simulation and instead the weight of information used would mainly be from updating the model. The goal of a DT should be to minimize the number of updates as long as the accuracy of the model fits within an acceptable margin. Less frequent updates signifies that more of the decisions are impacted by the estimation of the model, implying that as long as the most favorable decisions are made the information gained through the model is accurate.

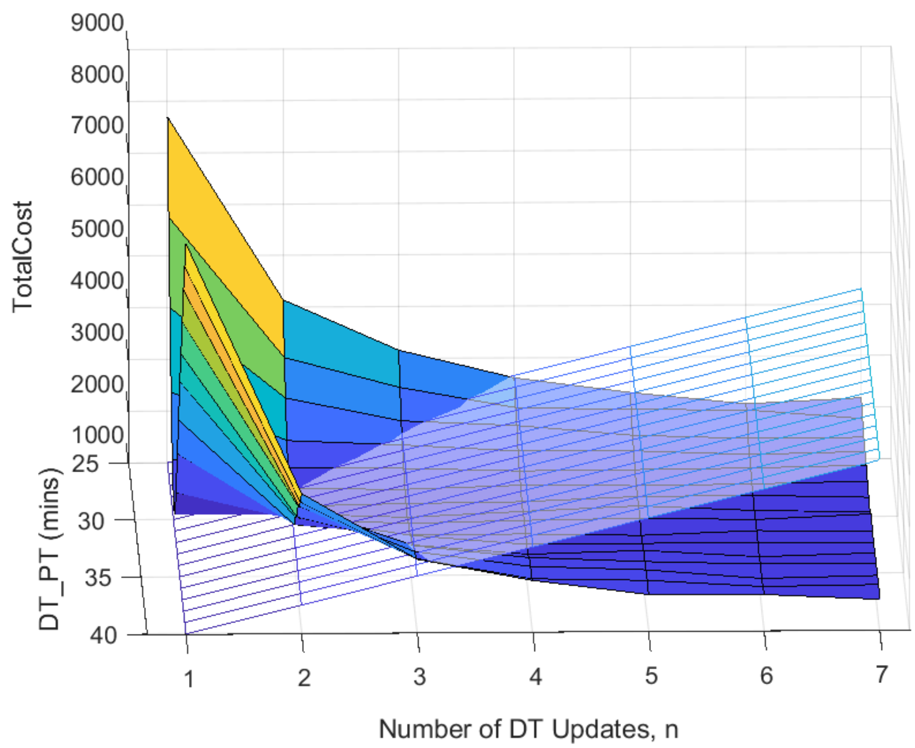


Figure 4.8. Cost of n, the the number of updates and its impact on the Total Cost of the DT

Understanding the compromises of the DT and finding ways to effectively implement this process paves a way to analyze more complex systems. The accuracy of the model will change based on the amount of detail needed to represent a complex system. The level of detail needed to approximate a system will be further explored in the later chapters of this thesis.

5. DIGITAL TWIN FRAMEWORK: MODELING DETAILS

This chapter specifies the model building process of this thesis. In order to develop a digital twin framework, a model was developed based off of a real manufacturing firm in Indiana. By taking the plant's layout design, logic, and processing parameters, we are able to better understand the effects of the digital twin as well as its potential concerns. Although a simulation model existed from a previous consulting job, a new model was built in order to incorporate the digital twin framework. The skeleton of the model was used and the digital twin aspects were imposed above. In this chapter we explore the design, covering the logic as well as variables used in this experiment.

5.1 Simulation software and PC hardware

Like the previous experiments, Simio was used to build this Digital Twin Framework. Specifically, through Purdue University, Simio 12 32 bit Academic RPS edition. The software was run on a Windows 10 PC using an AMD Ryzen 5 3600 6-Core 3.59 GHz processor with 32.0 GB of memory.

In order to help understand the framework and this thesis, a short introduction of Simio will be presented. Simio is considered an object oriented simulation software and was created to design, emulate, and provide scheduling solutions of complex systems. Based in Pittsburgh PA, the software has been used by hundreds of universities and companies around the world. Some of the industries using Simio include healthcare, manufacturing, mining, supply chain, transportation and others. (Simio.com)

5.1.1 Objects, Tokens, Process Window

Simio is based on using intelligent objects which supports both discrete and continuous systems, while also being able to mix different modeling paradigms like discrete event and agent-based modeling. Each object has their own set of attributes such as processes, elements, properties, states and events. Although there is a hierarchy of objects within Simio, some common objects include entities, links, nodes, transporters, and even fixed stationary objects such as machines. As each object has their own set of attributes, the behavior of the objects in the model can be customized through what are called processes. There are standard processes such as $OnNewSiezeRequest$, $OnRunInitialized$, $OnWarmUpEnding$, but more importantly, processes can be user-defined through Add-On Processes which enable customized steps with the use of elements and tokens that flow through the process window. Many of the digital twin logic will utilize the process window.

In Simio, there is a difference between tokens and entities and how they interact. Tokens execute the steps in a process and carry information throughout each step. Tokens can be associated with objects such as entities. Entities in fact can have their own behavior by making decisions such as moving across networks, or even being created/destroyed. Movement of entities in and out of objects may trigger steps in processes which are then carried out by created tokens which flow through the process steps, not the entity itself.

Many objects come with built in process flows enabling behaviors common to such predetermined objects such as servers ie. $sieze, delay, release$. But also, process flows can be created to cater to the specific modeling requirements or logic through the steps feature in the process window. Some common steps are $decide, assign, fire, and search$. For example, an assign step can be used to change the value of state variables. The utilized steps used in this Digital Twin model are labeled and defined in table 5.1.

5.1.2 Definitions Window

Simio also provides a method to define elements, properties, states, events and other user-defined parameters in the definitions window.

Elements

Elements are simio defined components with built-in properties, states, and behaviors. The digital twin framework uses routing groups, stations and tally statistic elements. The routing group element allows entities to be routed to different locations with ranking rules. A routing group element requires a list for destination nodes, a route request ranking rule, and a route request ranking expression. Within the context of a digital twin, routing group

Table 5.1. Utilized steps and definitions in Simio process window (Simio)

Assign	Assign/change value to a state variable
Decide	Control flow of a token through process logic based on condition or probability
Create	Create new objects, duplicate an existing entity, or create new tokens
Destroy	Destroy Entity objects
Fire	Execute an event
Search	Look through collection of objects or table rows, found entries exit as new token through found exit
Set Node	Sets destination node for an entity object
Transfer	Moves entity object to a new location
End Transfer	Indicates completed transfer of an entity to new location
Tally	Records an observed value for a specified tally statistic element
Release	Releases Capacity of a resource that is seized currently by specified object
Remove	Takes an object off of a specified queue
Clear Statistics	Resets model defined statistics

elements are used as a queue to the machines where the job is chosen based on a specified rank within the queue such as earliest due date or shortest processing time. As the routing element rank expression dynamically changes based on the policy chosen for the PPR system, the route request ranking expression for the digital twins remain static. Table 5.2 shows the route request rank expressions for each of the six digital twins, to accommodate the different policy rules for choosing which queue to enter.

Station elements can be seen in Table. 5.3 and are place holders for created entities to reside. Stations are used to hold entities and can be transferred in and out and often represents a capacity constrained location. In the model, stations allow to represent the state of the PPR system at the time of replication. As both the PPR system and digital twins progress in time, and as their state changes, the entities in the stations can be called and duplicated to mirror the original state of the PPR system at a specified point. Stations

Table 5.2. Routing Elements used in Digital Twin Framework

Routing Group Name	Destination Node List	Route Request Rank Expression
$Routing_A$	$Main\_Routing_A$	$JobSelectRule[JobSelectNum].PPR$
$Routing_B$	$Main\_Routing_B$	$JobSelectRule[JobSelectNum].PPR$
$Routing_C$	$Main\_Routing_C$	$JobSelectRule[JobSelectNum].PPR$
$Routing_D$	$Main\_Routing_D$	$JobSelectRule[JobSelectNum].PPR$
$Routing_j\_DTx_0$	$DTx_0\_Routing_j$	$ModelEntity.tmp$
$Routing_j\_DTx_1$	$DTx_1\_Routing_j$	$ModelEntity.tmp$
$Routing_j\_DTx_2$	$DTx_2\_Routing_j$	$ModelEntity.FBProcTime$
$Routing_j\_DTx_3$	$DTx_3\_Routing_j$	$ModelEntity.FBProcTime$
$Routing_j\_DTx_4$	$DTx_4\_Routing_j$	$ModelEntity.duedate$
$Routing_j\_DTx_5$	$DTx_5\_Routing_j$	$ModelEntity.duedate$

allow the model to hold entities without time having an effect on its parts. There is a station which represents each key machine and queue in the PPR system as seen in Table 5.3.

Table 5.3. Station Elements used in Digital Twin Framework

$M_i Station$	Stations for parts that are being processed in M_i machine in the PPR system, $i = 1, 2, ..m$
$Routing_A$Station	Station to hold replicated parts from PPR System's Queue Area 1, for Machine Zone 1 (M_1, M_2, M_3 machines) of the PPR system
$Routing_B$Station	Station to hold replicated parts from PPR System's Queue Area 2, for Machine Zone 2 (M_4, M_5, M_6, M_7 machines) of the PPR system
$Routing_C$Station	Station to hold replicated parts from PPR System's Queue Area 3, for Machine Zone 3 (M_7, M_8, M_9, M_{10} machines) of the PPR system
$Routing_D$Station	Station to hold replicated parts from PPR System's Queue Area 4, for Machine Zone 4 (M_{11}, M_{12}, M_{13}, M_{14} machines) of the PPR system

Tally statistic elements are used to record observational statistics throughout the model and are recorded using the tally step. A list of the tally statistics used in the model are found in table 5.4. The model's performance measure to compare the results of the six different digital twins as well as the effect of the chosen policy between decision periods are recorded using the tally statistic element. Once a policy is chosen, tally statistics can be reset for each digital twin's recorded performance measure using the *clearstatistics* step. There are separate tally statistics for each digital twin and its performance measure as seen in Table 5.4.

Table 5.4. Tally Statistic Elements used in Digital Twin Framework

PPR_LateTime	Performance measure for PPR system recording lateness compared to due date
PPR_WaitingTime	Performance measure for PPR system recording waiting time of parts in queue before being processed
DT_PerformanceMeasure	Tally statistic keeping track of the performance measure based on chosen policy used by the digital twin, can be specified before start of simulation run (Waiting time or late time)
$DTX_i\_LateTime$	Observed late time for digital twin i, performance measure tallied between decisions periods, i $= 0, 1, ..N$
$DTX_i\_WaitingTime$	Observed waiting time for parts in queue before being processed for digital twin i, performance measure tallied between decisions periods, i, $= 0, 1, ..N$

Properties

Properties are static input parameters that can be adjusted between simulation runs but does not change during the simulation. Properties are useful in having global parameters that the model can use or change and adjust as needed between simulation runs. Table. 5.5 shows the parameters that were included and used throughout this thesis. As the different parameters will be discussed in later chapters of this thesis, a brief discussion of some of the parameters will help introduce the idea of properties and its use in Simio. For this explanation, we will be focusing on small parts but the same logic can be applied to medium and large parts. *S_Part_Arrival* is used by the source object representing the inter arrival time of entities, or time between part arrivals in the PPR system. The $S\_duedate\_orders$ represents the time remaining until the part is due once the part arrives. Each entity is assigned a due date based on a random number generated by the expression $S\_duedate\_order$. The $S\_DT\_Duedate$ is similar to $S\_duedate\_orders$ but used for the digital twin systems, however, the initial default values have the same expressions, but the parameters are available to adjust if needed. $WTPerfMeasure$ is an indicator variable used to decide the performance measure the PPR system uses seen in Eq. 5.1. This property can be adjusted prior to running the model which performance measure to use, and is fixed during the simulation run.

$$WTPerfMeasure = \begin{cases} 1 & \text{if performance measure is average waiting time in queue} \\ 0 & \text{if performance measure is average time over due date} \end{cases} \tag{5.1}$$

Table 5.5. Properties and default values used in Digital Twin Framework

Property	Definition	Default Value
$DecisionPeriod$	The time between decisions in hours and Update Period	120 hours
DT_Reps	How many replications between the number of updates	15
$S\_Part\_Arrival$	Small part's arrival rate	Random.Exponential(4)
$M\_Part\_Arrival$	Medium part's arrival rate	Random.Exponential(.85)
$L\_Part\_Arrival$	Large part's arrival rate	Random.Exponential(.95)
$S\_duedate\_order$	Time until Small Part's due date for PPR system	Random.Triangular(2.679, 5.358, 10.716)
$M\_duedate\_order$	Time until Medium Part's due date for PPR system	Random.Triangular(8.4631, 16.9262, 33.8524)
$L\_duedate\_order$	Time until Large Part's due date for PPR system	Random.Triangular(18.6549, 37.3097, 74.6194)
$S\_DT\_Duedate$	Time until Small Part's due date for DT systems	Random.Triangular(2.679, 5.358, 10.716)
$M\_DT\_Duedate$	Time until Medium Part's due date for DT systems	Random.Triangular(8.4631, 16.9262, 33.8524)
$L\_DT\_Duedate$	Time until Large Part's due date for DT systems	Random.Triangular(18.6549, 37.3097, 74.6194)
$S\_DT\_FB\_PT$	Fabrication bay processing time for small parts in DT	Random.Uniform(.5,2.5)
$M\_DT\_FB\_PT$	Fabrication bay processing time for medium parts in DT	Random.Uniform(1.5,6)
$L\_DT\_FB\_PT$	Fabrication bay processing time for large parts in DT	Random.Uniform(4,9)
$WTPerfMeasure$	Indicator function for which performance measure model uses	0

States

In the Definitions page, simio also has a section to define variables, termed states, where its values can change during the simulation run. Simio supports both discrete and continuous values. Many of the states can be changed using the assign step in the processes window, or by using the state assignment functions from the pre-made objects. States allow the simulation model to adjust its function based on the value of the state by changing how tokens behave using a conditional decide step. In table 5.6 we see a list of states that are used in the model.

Table 5.6. States defined in Digital Twin Framework

MachineSelectNum	Variable that the PPR system uses to determine the policy for which queue to place incoming parts
JobSelectNum	Variable that the PPR system uses to determine the policy for which job is chosen when a machine is open
PPR_TPT_{j}	PPR system's total processing time for queue area j
DT_TPT_{ij}	Total processing time for queue area j for digital twin number i

5.1.3 Events

Events are also a part of the definitions page and is used as a method to call a function or can be used as a signal to fire other events. Events can be used to signal actions such as creating entities or also be used to start processes. Events are widely used throughout this model to connect the model's different systems. Table 5.7 shows the definition of each event that can be fired.

5.2 Tables Window

Simio also allows for the compilation of data tables with values that can be referenced throughout the simulation. The standard method to locate a particular cell of a table is through $TableName[RowNumber].Column$ format. Tables can contain various forms of data including user-defined states, constants, simulation reference properties, even values in different tables.

Table 5.7. Events defined in Digital Twin Framework

DT_GO	This event is the main signal start the DT mechanism and starts the DT_GO process which takes the PPR system's state and replicates it for its corresponding station and digital twins.
DT_Reset	This even signals the DT_Reset Process which clears the states of the digital twin
DT_DecisionPeriod	Is a signal fired every time a *DecisionPeriod* ends and is the arrival mode for *NumberUpdatesTrigger* Source object.
DT_Replicate	An event which is fired to trigger the replication process of the Digital Twins. Replication of the state of the PPR system is used to find an average of the performance measure. Replications of the PPR system is made by using the stations that hold a copy of the state of the PPR system.

5.2.1 Routing

Tables 5.8, 5.9, 5.10 show how small, medium, and large parts are routed to the correct destination node. Arriving parts are sorted by size and then find a destination based on the minimum value found for the corresponding routing table. Digital Twin systems when i = $0, 2, 4$ use the number of parts in queue to decide its destination while DT systems when i = $1, 3, 5$ are based on the total processing time of parts in the queue. Table 5.8 shows how the PPR system has both routing policies enabled. An entity token is used to decide first the size, then, based on the chosen policy, finds the minimum value for the specified part and policy type to find the queue destination.

Table 5.8. Routing Table for PPR

Destination	S_NINQ	S_LINQ	M_NINQ	M_LINQ	L_NINQ	L_LINQ
Q_A	$Routing_A.RouteRequestQueue$	PPR_TPT_A	1000000	1000000	1000000	1000000
Q_B	$Routing_B.RouteRequestQueue$	PPR_TPT_B	$Routing_B.RouteRequestQueue$	PPR_TPT_B	1000000	1000000
Q_C	$Routing_C.RouteRequestQueue$	PPR_TPT_C	$Routing_C.RouteRequestQueue$	PPR_TPT_C	$Routing_C.RouteRequestQueue$	PPR_TPT_C
Q_D	$Routing_D.RouteRequestQueue$	PPR_TPT_D	$Routing_D.RouteRequestQueue$	PPR_TPT_D	$Routing_D.RouteRequestQueue$	PPR_TPT_D

Table 5.9. Routing Table for Digital Twin for i $= 0, 2, 4$

$Destination\_DT_i$	S_NINQ_i	M_NINQ_i	L_NINQ_i
$Q_A\_DT_i$	$Routing_A\_DT_i.RouteRequestQueue$	1000000	1000000
$Q_B\_DT_i$	$Routing_B\_DT_i.RouteRequestQueue$	1000000	1000000
$Q_C\_DT_i$	$Routing_C\_DT_i.RouteRequestQueue$	$Routing_C\_DT_i.RouteRequestQueue$	$Routing_C\_DT_i.RouteRequestQueue$
$Q_D\_DT_i$	$Routing_D\_DT_i.RouteRequestQueue$	$Routing_D\_DT_i.RouteRequestQueue$	$Routing_D\_DT_i.RouteRequestQueue$

Table 5.10. Routing Table for Digital Twin for i $= 1, 3, 5$

$Destination\_DT_i$	S_LINQ_i	M_LINQ_i	L_LINQ_i
$Q_A\_DT_i$	$DT_i\_TPT_A$	1000000	1000000
$Q_B\_DT_i$	$DT_i\_TPT_B$	$DT_i\_TPT_B$	1000000
$Q_C\_DT_i$	$DT_i\_TPT_C$	$DT_i\_TPT_C$	1000000
$Q_D\_DT_i$	$DT_i\_TPT_D$	$DT_i\_TPT_D$	$DT_i\_TPT_D$

When the PPR system's state is being replicated, the method to direct copied entities to the proper nodes and routing group uses table 5.11 and 5.12. For the queue in the PPR system, also known to be a routing group area, each digital twin uses the location of column Q and routes the contents of the routing group to each of the corresponding routing nodes and station element as seen in Table. 5.11. However, when digital twins are being replicated between decision periods, the model will use the contents of the corresponding station column. Similarly, Table. **??** is used to replicate and direct contents of the PPR system's machines.

Table 5.11. Routing destination for PPR system's machine queues when replicated for all DT_i $\forall$i $\in D$

Q	Station	Destination Node
$Routing_A$	$Routing_A Station$	$Q_A DT_i$
$Routing_B$	$Routing_B Station$	$Q_B DT_i$
$Routing_C$	$Routing_C Station$	$Q_C DT_i$
$Routing_D$	$Routing_D Station$	$Q_D DT_i$

Table 5.12. Routing destination for PPR system's 14 machines when replicated

PPR Processing	Station Copy	DT_0	DT_1	DT_2	DT_3	DT_4	DT_5
$M_1.Processing$	$M_1Station$	$Input@DTM1x$	$Input@DTM1x1$	$Input@DTM1x2$	$Input@DTM1x3$	$Input@DTM1x4$	$Input@DTM1x5$
$M_2.Processing$	$M_2Station$	$Input@DTM2x$	$Input@DTM2x1$	$Input@DTM2x2$	$Input@DTM2x3$	$Input@DTM2x4$	$Input@DTM2x5$
$M_3.Processing$	$M_3Station$	$Input@DTM3x$	$Input@DTM3x1$	$Input@DTM3x2$	$Input@DTM3x3$	$Input@DTM3x4$	$Input@DTM3x5$
$M_4.Processing$	$M_4Station$	$Input@DTM4x$	$Input@DTM4x1$	$Input@DTM4x2$	$Input@DTM4x3$	$Input@DTM4x4$	$Input@DTM4x5$
$M_5.Processing$	$M_5Station$	$Input@DTM5x$	$Input@DTM5x1$	$Input@DTM5x2$	$Input@DTM5x3$	$Input@DTM5x4$	$Input@DTM5x5$
$M_6.Processing$	$M_6Station$	$Input@DTM6x$	$Input@DTM6x1$	$Input@DTM6x2$	$Input@DTM6x3$	$Input@DTM6x4$	$Input@DTM6x5$
$M_7.Processing$	$M_7Station$	$Input@DTM7x$	$Input@DTM7x1$	$Input@DTM7x2$	$Input@DTM7x3$	$Input@DTM7x4$	$Input@DTM7x5$
$M_8.Processing$	$M_8Station$	$Input@DTM8x$	$Input@DTM8x1$	$Input@DTM8x2$	$Input@DTM8x3$	$Input@DTM8x4$	$Input@DTM8x5$
$M_9.Processing$	$M_9Station$	$Input@DTM9x$	$Input@DTM9x1$	$Input@DTM9x2$	$Input@DTM9x3$	$Input@DTM9x4$	$Input@DTM9x5$
$M_10.Processing$	$M_10Station$	$Input@DTM10x$	$Input@DTM10x1$	$Input@DTM10x2$	$Input@DTM10x3$	$Input@DTM10x4$	$Input@DTM10x5$
$M_11.Processing$	$M_11Station$	$Input@DTM11x$	$Input@DTM11x1$	$Input@DTM11x2$	$Input@DTM11x3$	$Input@DTM11x4$	$Input@DTM11x5$
$M_12.Processing$	$M_12Station$	$Input@DTM12x$	$Input@DTM12x1$	$Input@DTM12x2$	$Input@DTM12x3$	$Input@DTM12x4$	$Input@DTM12x5$
$M_13.Processing$	$M_13Station$	$Input@DTM13x$	$Input@DTM13x1$	$Input@DTM13x2$	$Input@DTM13x3$	$Input@DTM13x4$	$Input@DTM13x5$
$M_14.Processing$	$M_14Station$	$Input@DTM14x$	$Input@DTM14x1$	$Input@DTM14x2$	$Input@DTM14x3$	$Input@DTM14x4$	$Input@DTM14x5$

5.2.2 Selection Tables

The Digital Twin Framework model also uses a series of tables mainly used to determine how the DT and the PPR system makes decisions. Explained further in the Logic section later in this chapter describing the processes window, there will always be a reference to the different combination of choices available for the PPR and DT systems referencing Tables 5.13. The three choices refer to which policy number the PPR system chooses to utilize during the current decision period, which alter the way parts choose which queue to enter and how jobs are pulled into fabrication machines. The policy table seen in Table.5.13 shows the different combinations of choices that will be chosen based on the row with the smallest performance measure. For example, if DT_2 had the smallest average waiting time, the policy would then choose the values of that row for the next decision period, where, $machineselectnum = 1$ and j$obseledctnum = 2$.

Table 5.13. PPR system's policy selection

WaitingTime	LateTime	MachineSelectNum	JobSelectNum	Policy Number
$DT_0WaitingTime.Average$	$DT_0LateTime.Average$	1	1	P_1
$DT_1WaitingTime.Average$	$DT_1LateTime.Average$	2	1	P_2
$DT_2WaitingTime.Average$	$DT_2LateTime.Average$	1	2	P_3
$DT_3WaitingTime.Average$	$DT_3LateTime.Average$	2	2	P_4
$DT_4WaitingTime.Average$	$DT_4LateTime.Average$	1	3	P_5
$DT_5WaitingTime.Average$	$DT_5LateTime.Average$	2	3	P_6

The chosen policy now alters the process window when machines become available and chooses parts using the row of Table. 5.14 which is referenced by the route request rank expression in the routing group element from Table 5.2. The value of $JobSelectRule[JobSelectNum].PPR$ uses the value chosen from the policy table $jobselectnum$ to represent the row of Table 5.14, which finds the job waiting in queue with the minimum corresponding entity attribute. In our example if $jobselectnum = 2$, the job with the smallest processing time would be chosen based on the value in the second row, $ModelEntity.FBProcTime$.

Table 5.14. PPR system's Job Select Rule

PPR
ModelEntity.tmp
ModelEntity.FBProcTime
ModelEntity.duedate

Similarly, when parts arrive to the system and go through the Drill/Punch/Saw processes they are placed in a queue for each zone of machines based on the chosen policy, $MachineSelectNum$. Table. 5.15 is used to determine which zone the item should queue for based on the size of the part. The columns represent the size of the part and the row represents the policy, $MachineSelectNum$ directs the part to use the $Routing\_PPR$ table, Table. 5.8 which will choose the smallest value row as the queue to join. In our example, if $machineselectnum = 1$, for a small part, the queue destination would be the minimum number of parts in each of the routing areas, $Routing\_PPR.S\_NINQ$ based on the first row of Table. 5.15.

Table 5.15. PPR system's Machine Select Rule

S	M	L
$Routing\_PPR.S\_NINQ$	$Routing\_PPR.M\_NINQ$	$Routing\_PPR.L\_NINQ$
$Routing\_PPR.S\_LINQ$	$Routing\_PPR.M\_LINQ$	$Routing\_PPR.L\_LINQ$
$Routing\_PPR.S\_Random$	$Routing\_PPR.M\_Random$	$Routing\_PPR.L\_Random$

5.2.3 Reset Tables

There are also tables in the Digital Twin Framework that are used for the reset process explained by the process *DT_Reset*. In order to reset the digital twin, tables were used to list the different stations (Table 5.16). Work-in-progress contents in machines (Table 5.17), routing groups (Table 5.18) and other machine queues (Table 5.19) along with their resources. A digital twin reset requires a system to clear all of the components in the DT systems and the following tables are the components that potentially can hold an object.

Table 5.16. List of Stations used for the Digital Twin Framework

Station List
$M_1 Station$
$M_2 Station$
$M_3 Station$
$M_4 Station$
$M_5 Station$
$M_6 Station$
$M_7 Station$
$M_8 Station$
$M_9 Station$
$M_{10} Station$
$M_{11} Station$
$M_{12} Station$
$M_{13} Station$
$M_{14} Station$
$DrillPunchStation$
$SawDrillStation$
$PaintHoldAreaStation$
$PaintStation$
$Routing_A Station$
$Routing_B Station$
$Routing_C Station$
$Routing_D Station$

Table 5.17. List of Digital Twin Processes and their resource $\forall \mathrm{i} \in D$

DT_WIP	Resource
$DTM1X_{\mathrm{i}}.Processing$	$DTM1X_{\mathrm{i}}$
$DTM2X_{\mathrm{i}}.Processing$	$DTM2X_{\mathrm{i}}$
$DTM3X_{\mathrm{i}}.Processing$	$DTM3X_{\mathrm{i}}$
$DTM4X_{\mathrm{i}}.Processing$	$DTM4X_{\mathrm{i}}$
$DTM5X_{\mathrm{i}}.Processing$	$DTM5X_{\mathrm{i}}$
$DTM6X_{\mathrm{i}}.Processing$	$DTM6X_{\mathrm{i}}$
$DTM7X_{\mathrm{i}}.Processing$	$DTM7X_{\mathrm{i}}$
$DTM8X_{\mathrm{i}}.Processing$	$DTM8X_{\mathrm{i}}$
$DTM9X_{\mathrm{i}}.Processing$	$DTM9X_{\mathrm{i}}$
$DTM10X_{\mathrm{i}}.Processing$	$DTM10_{\mathrm{i}}$
$DTM11X_{\mathrm{i}}.Processing$	$DTM11X_{\mathrm{i}}$
$DTM12X_{\mathrm{i}}.Processing$	$DTM12X_{\mathrm{i}}$
$DTM13X_{\mathrm{i}}.Processing$	$DTM13X_{\mathrm{i}}$
$DTM14X_{\mathrm{i}}.Processing$	$DTM14X_{\mathrm{i}}$
$DTSawDrillX_{\mathrm{i}}.Processing$	$DTSawDrillX_{\mathrm{i}}$
$DTDrillPunchX_{\mathrm{i}}.Processing$	$DTDrillPunchX_{\mathrm{i}}$
$DTPaintHoldAreaX_{\mathrm{i}}.Processing$	$DTPaintHoldAreaX_{\mathrm{i}}$
$DTPaintX_{\mathrm{i}}.Processing$	$DTPaintX_{\mathrm{i}}$

Table 5.18. List of Digital Twin Routing Groups $\forall \mathrm{i} \in D$

DT Routing Group
$Routing_A\_DT_{\mathrm{i}}$
$Routing_B\_DT_{\mathrm{i}}$
$Routing_C\_DT_{\mathrm{i}}$
$Routing_D\_DT_{\mathrm{i}}$

5.3 DT Logic

The developed DT framework is a method to test and understand the benefits of using the Digital Twin within a real physical plant, by creating a system that has both the Pseudo physical real (PPR) system and the Digital Twin. In order for the Digital Twin to be used in a manner that would replicate reality, the use of real time was essential in that the PPR system continues to run regardless of the replication effects of the DT. In order for the model to propagate the communication of both the PPR and DT systems, dummy entities were

Table 5.19. List of Digital Twin Process Queues and their resource $\forall \mathrm{i} \in D$

Queue	Object
$DTDrillPunch_{\mathrm{i}}.InputBuffer$	$DTDrillPunch_{\mathrm{i}}$
$DTSawDrill_{\mathrm{i}}.InputBuffer$	$DTSawDrill_{\mathrm{i}}$
$DTPaintHoldArea_{\mathrm{i}}.InputBuffer$	$DTPaintHoldArea_{\mathrm{i}}$
$DTPaint_{\mathrm{i}}$	$DTPaint_{\mathrm{i}}$

created to signal events that would initiate the mechanics of the DT's interaction with the PPR system.

5.3.1 Decision Period Timer

The decision period timer source object creates an entity every decision period with its interarrival time set to the variable **DecisionPeriod**. With each created entity, a *DecisionPeriod_Timer_Exited* add-on process is triggered as each entity exits the *DecisionPeriodTimer* source. In the *DecisionPeriod_Timer_Exited* add-on process, a series of decisions will take place for each token that passes through starting with a decide step to find which performance measure is being used. Depending on the performance measure, **WaitingTime/LateTime**, the minimum value is chosen from the search of each digital twin's performance within the decision period. An assign step is used to update the PPR system's policy based on the chosen row seen in the *Policy* table, Table 5.13. Each token will then continue in the add-on process and clear the performance measure of each DT. The values of each queues estimated processing times will also be set to 0. Lastly, the add-on process will fire events **DT_Reset, DT_DecisionPeriod, DT_GO, DT_Replicate**. These events reset all six Digital Twins and initializes the model for the next decision period. The decision period also serves as the DT's update frequency based on the time between decisions.

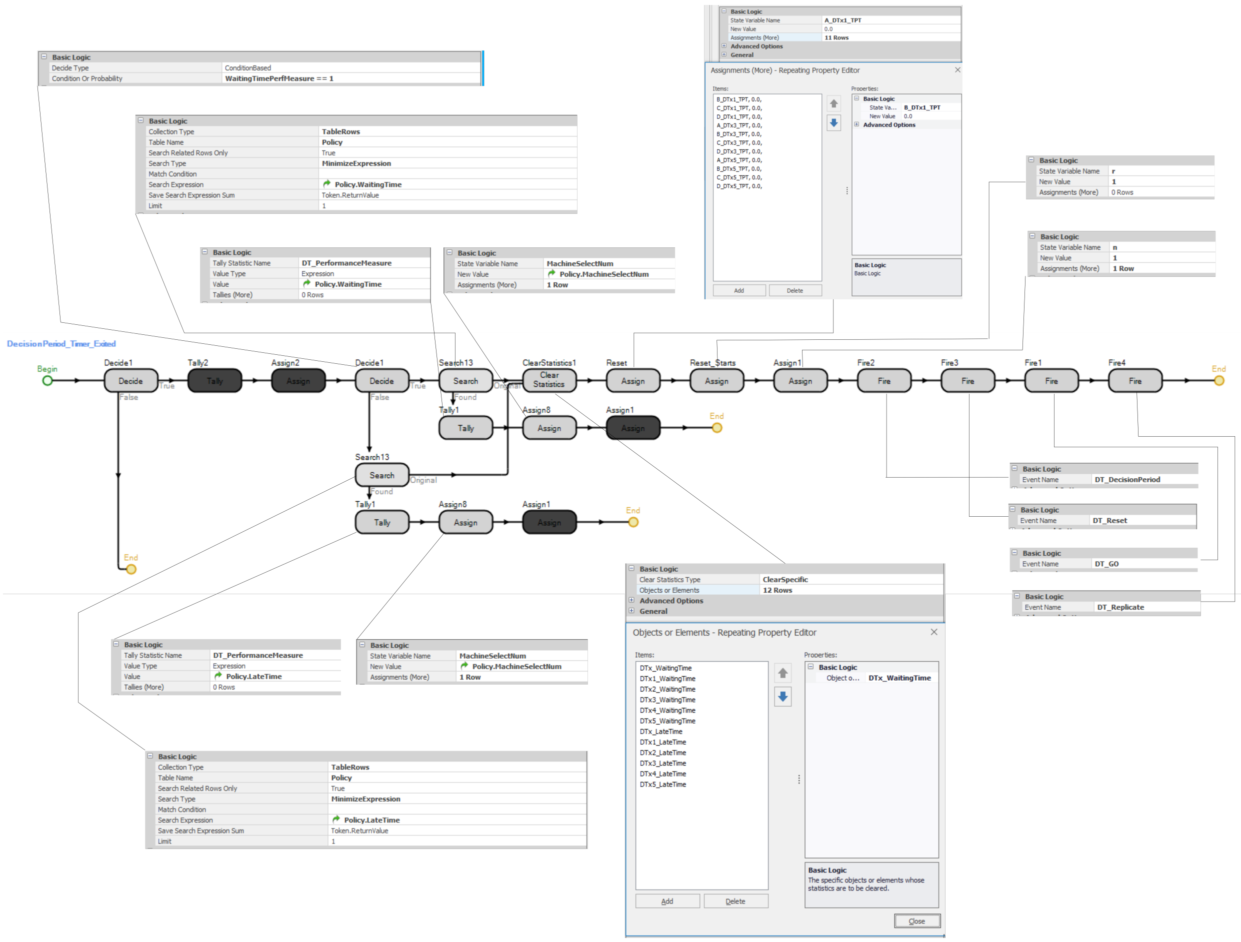


Figure 5.1. Decision Period Timer Add-on Process

5.3.2 DT_Reset

Before any function is called or replication process occurs, the digital twin has to be cleared of its current state. The *DT_Reset* process acts as a function whenever the *DT_Reset* event is triggered or called in the model. Once called, a token moves through the steps seen in Fig. 5.2. finding entries in tables *DT_Stations_Table* (Table 5.16), *DT_WIP_Table* (Table 5.17), *DT_RoutingGrp_Table* (Table 5.18), *DT_Queue_Table* (Table 5.19). The first search is initially a global scan of all the stations, queues, parts in process in each of the six digital twin models. Secondly, each entry of the first search representing found results, ie. stations, will then be searched for entities and then deleted with a destroy step. If entities are in the middle of a process such as those entities within the fabrication bays of the digital twin, the parts must first release its resource then be destroyed seen by the second search trail in Fig. 5.2. Any call of the *DT_Reset* function fully clears all six digital twins and can freely occur without tampering the original PPR system.

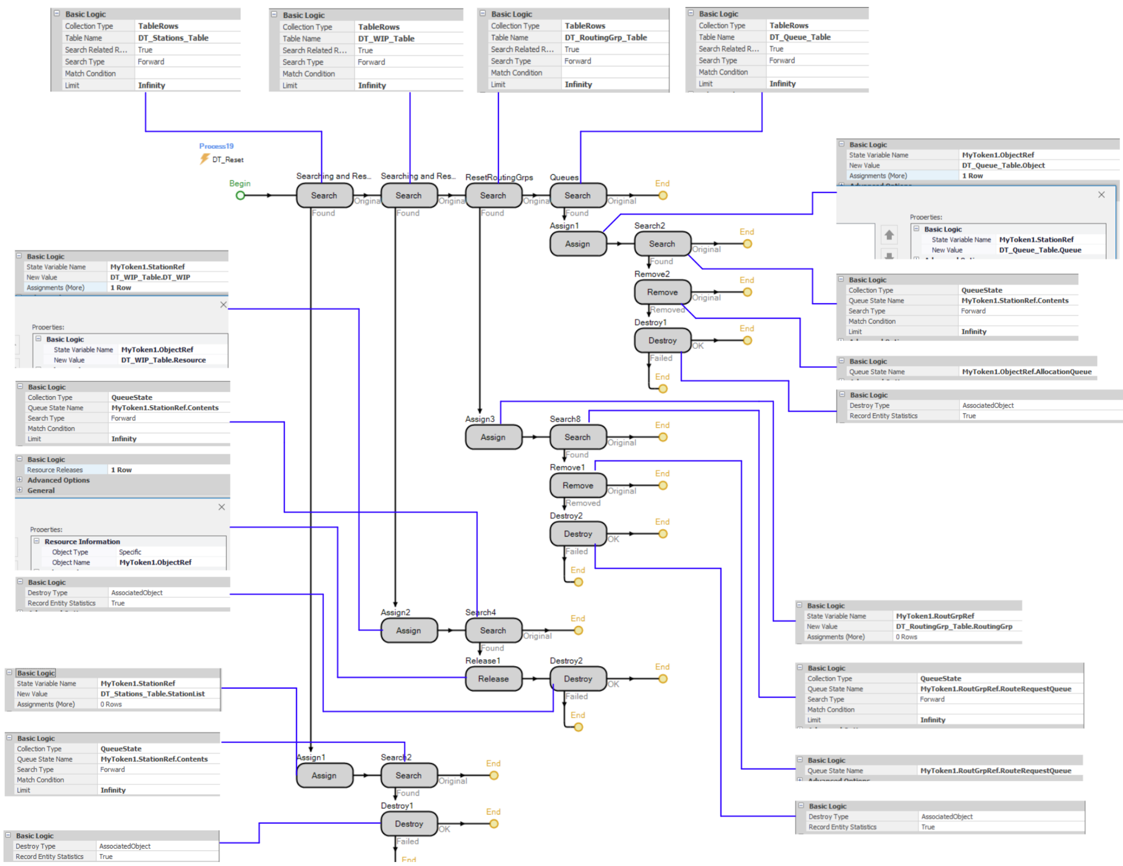


Figure 5.2. DT_Reset Process

5.3.3 DT_GO

The *DT_GO* function is the main method of starting and using the digital twin mechanism. There are multiple points in time where the *DT_GO* is used by the digital twin and will be discussed heavily throughout this chapter. This process is called every time the event *DT_GO* is fired from any of the other processes. A token runs through the steps seen in Fig.5.3 which shows the the *DT_GO* process in its full split between its main to sections, A and B. Section A of the *DT_GO* process seen in detail in Fig. 5.4 is a process which searches the *RoutingGrpArea* table to replicate the state of the PPR system's queues to not only each of the digital twins but also creating a copied state at a Simio's station element. The station is used by the digital twin as a replica of the routing group area queue's state at the time the *DT_GO* process was called and can be used to recall the state even as the digital twin's state changes as the clock continues to run.

Under this Digital Twin framework, one of the major concepts in regards to time and the application of replicating the PPR system requires changing each unit's attributes to reflect the altered time frame of the digital twin. Copying each part's attributes such as due date, or time waiting in queue has to be altered to fit the digital twin's time frame. What we mean by time frame is depending on the run, the digital twin's control properties such as $DecisionPeriod, NumberUpdatePeriods, DT\_Reps$ alters the speed at which the digital twins runs compared to the PPR system. In Fig. 5.4 we see an assign step which changes the $ModelEntity.tmp$ variable to $TimeNow - ((TimeNow - ModelEntity.tmp)/DT_Reps)$. $TimeNow - ModelEntity.tmp$ represents the time that the copied part has been in queue in the PPR system, and is assigned a new entry time as it is transferred into one of the digital twin queues. Similarly, each job's due date is updated based on $TimeNow + ((ModelEntity.duedate - TimeNow)/DT_Reps)$. Fig. 5.4 shows how every part is found though the search steps of the four PPR routing groups and then is copied seven times to be transferred to the six digital twins and each corresponding station element.

The steps in the lower half, section B of the *DT_GO* process is similar to section A but is searching parts within the fabrication bay area where parts are already in process. Since such found parts are already though the queue portion of the PPR system, only the part's due dates are updated with an assign step, $ModelEntity.duedate = (TimeNow + ((ModelEntity.duedate - TimeNow)/DT_Reps))$. Once copied, each of the copied parts are transferred each digital twin's machine based on its corresponding PPR system's machine.

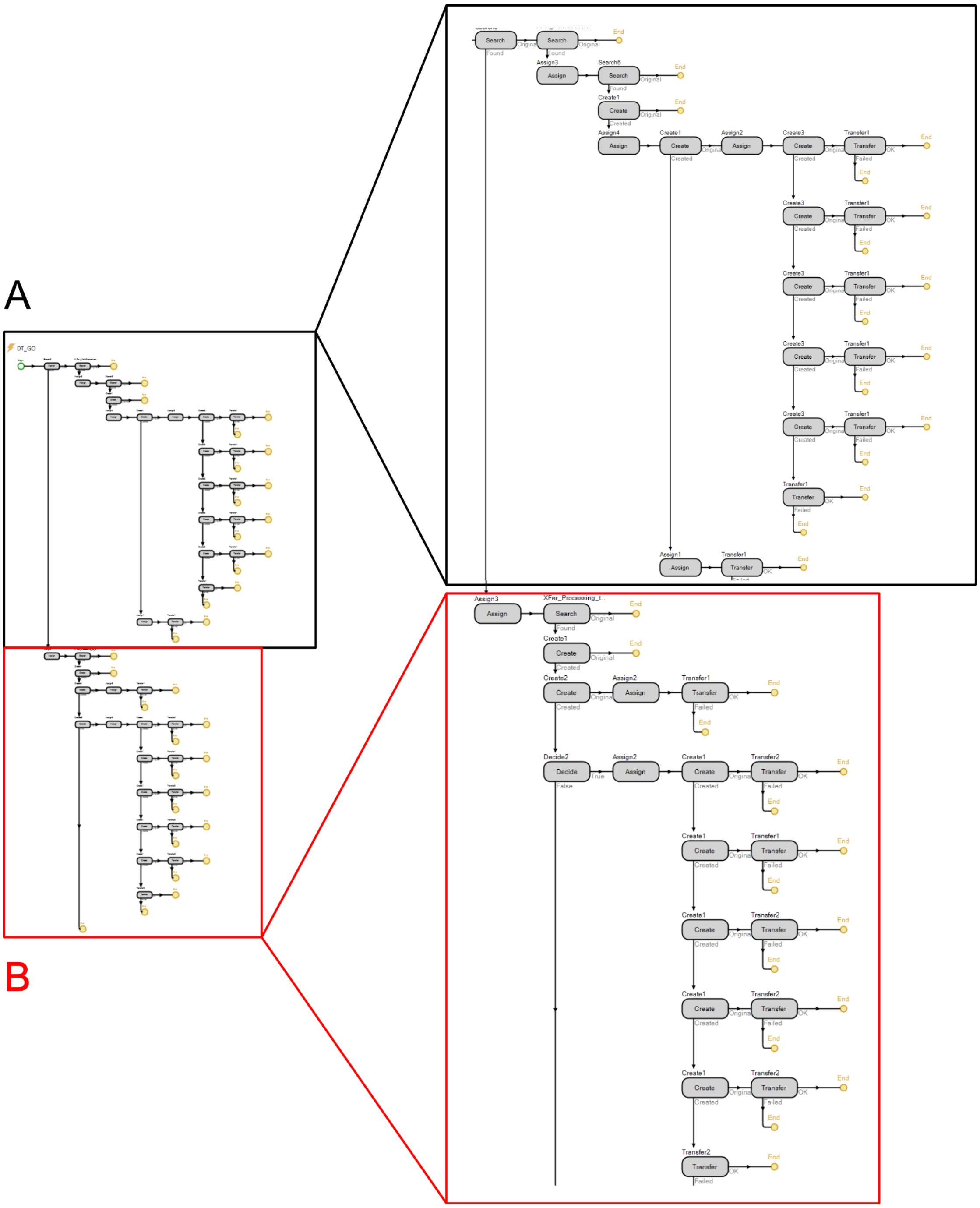


Figure 5.3. The Full DT_GO process with zoom in A. Upper Half B. Lower Half

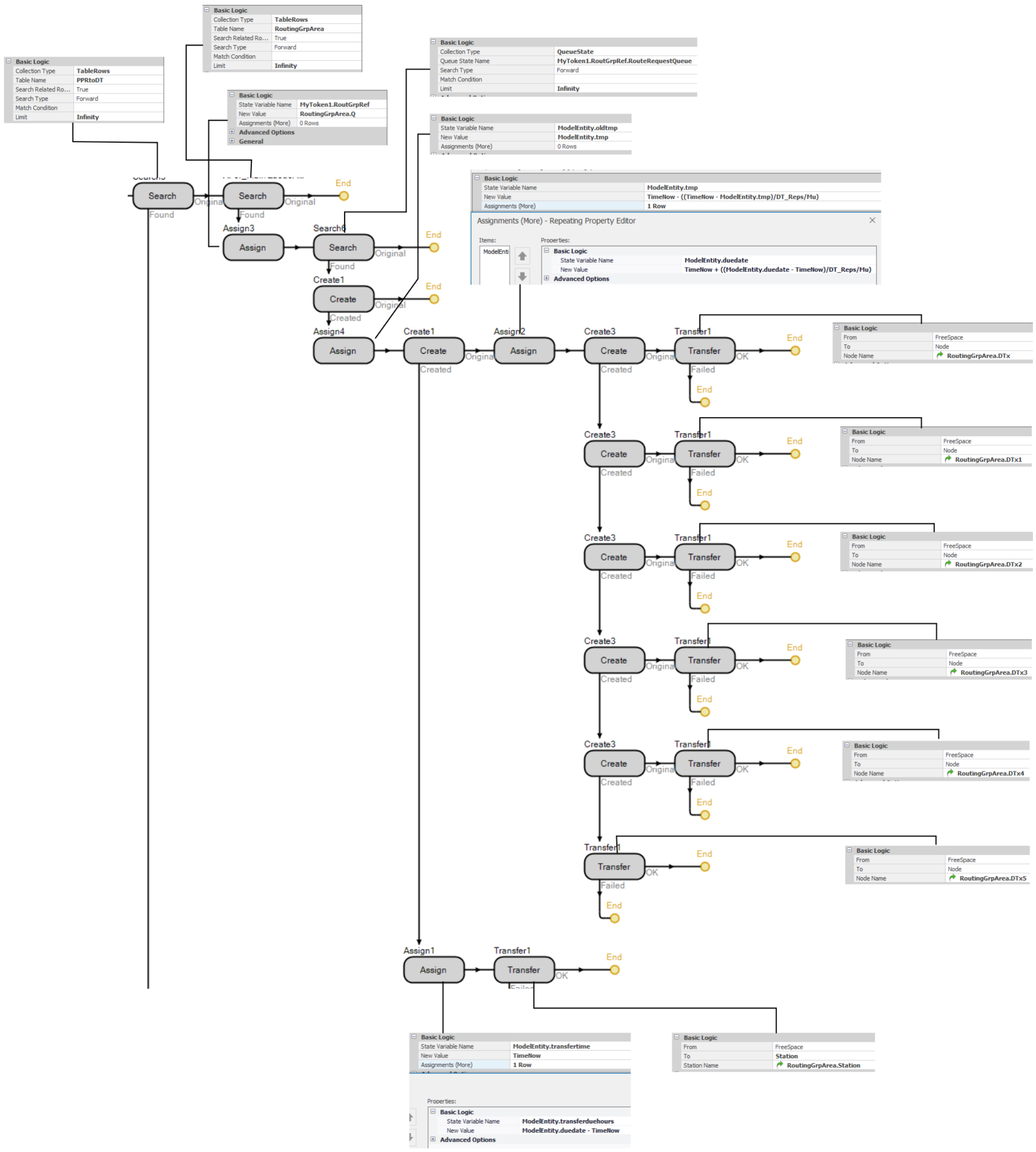


Figure 5.4. Section A of DT_GO process

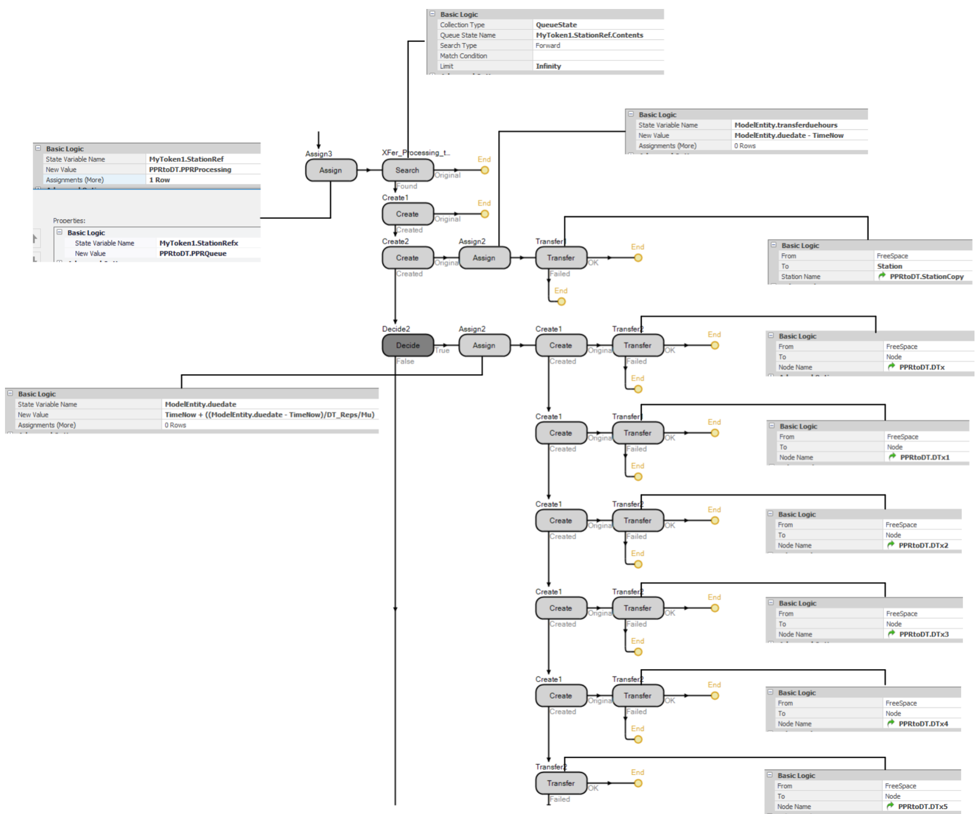


Figure 5.5. Section B of DT_GO process

6. ANALYSIS OF COMPLEX SYSTEM USING DIGITAL TWIN FRAMEWORK

A method to empirically test the digital twin and its components was developed for a more complex system and the results will be discussed in this chapter. This experimental investigation of the characteristics and elements of the digital twin is an important stepping stone to developing and using the digital twin effectively in real life scenarios. The impact of accuracy on the system's performance is also studied. Developing this Digital Twin Framework gives modelers, managers, in both industry and academia see the subtleties of the DT and gives insights into improving the future of manufacturing.

6.1 Effectiveness of the Digital Twin Framework

First, the effectiveness of the digital twin and its aid in the decision making process is based on the available policies. The goal is to show how the DT can be used to make decisions though simulation. This initial study is treated as the foundation of setting up and designing an effective method to study how the DT communicates with the PPR system.

6.1.1 Research Question and Hypothesis

Can the digital twin framework help the PPR system use the DTs to choose dominant policies? Understanding how the DT Framework will help the PPR system make decisions is important. Also, understanding how different performance measures changes the way the PPR system responds to using the DT framework is of concern.

6.1.2 Experiment

In order to show that the digital twin is able to make the right decision with different scenarios, testing the performance of the PPR with updates versus without updates was incorporated into the experiment. The default values mentioned in the previous chapter will be used with the added part arrival variability of Table 6.1. Changing how parts arrive into the system will allow the model to use the DT under different stress levels.

Each part type has their own set of inter-arrival times using an exponential distribution. The *Random.Exponential*(*mean*) is the expression used to specify an exponential distribution with its mean. Each part type will also have two modes, fast and slow rate of arrivals. The arrival rates of the PPR and DT systems will both be adjusted together using the S/F (Slow/Fast) rates for small, medium, and large parts (small/medium/large). S/S/S Part arrivals represents slow rates for all parts while, S/F/F part arrivals represents an exponentially distributed inter-arrival rate with mean .45 hours for the small parts (slow) and the faster rates for both the medium and large parts, both exponentially distributed inter-arrival rates with means .8 and .9 hours respectively.

Table 6.1. Inter-Arrival Rate Expression by Part Type in Hours

PartType	Slow (S)	Fast (F)
Small Parts	Random.Exponential(.45)	Random.Exponential(.4)
Medium Parts	Random.Exponential(.85)	Random.Exponential(.8)
Large Parts	Random.Exponential(.95)	Random.Exponential(.9)

6.1.3 Results

Table 6.2 and 6.3 are the results of the PPR system using each of the policies without updates compared to the DT. Notice that for both late time and waiting time performance measures there are different dominating policies. Policy 1 and Policy 5 work well for Average late time (ALT) which uses the number of parts for its queue selection rule, and FIFO and EDD for its job selection rule respectively. For average waiting time (AWT) performance measure, policies 3 and 4 outperform the rest, both sharing SPT job selection rule.

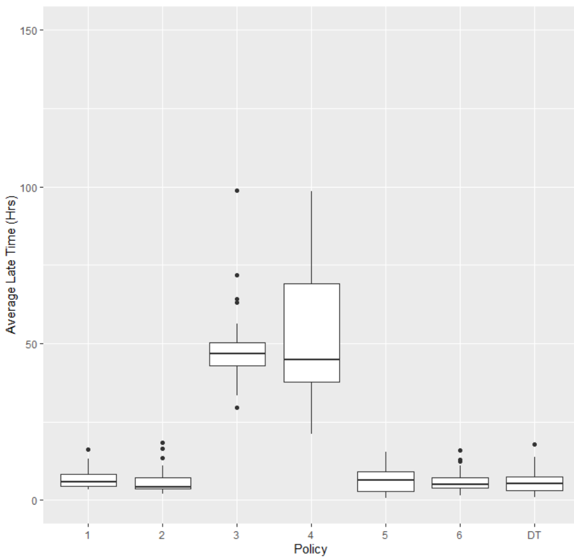
Figure 6.1, 6.2 and figures 6.3, 6.4 are the box plots for Table 6.2 and 6.3 receptively. The Bonferroni pairwise comparison results can be found in Figure 6.5 for average late time and Figure 6.6 for average waiting time.

Table 6.2. Average Late Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange (Fast (F) / Slow (S) - rates)

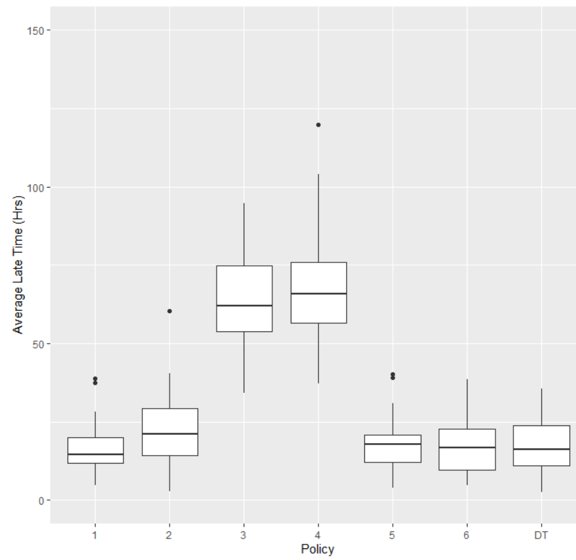
S/M/L Part Arrivals	P_1	P_2	P_3	P_4	P_5	P_6	DT
S/S/S	6.87735	5.86001	48.795	50.9472	6.70193	5.99577	6.1841
S/S/F	16.7605	22.4313	63.9074	67.347	18.0177	17.3781	17.6803
S/F/S	13.8088	14.7843	61.5709	63.2733	12.3037	14.8086	12.5062
S/F/F	29.9989	32.3212	68.9776	77.2789	30.8731	29.4986	30.07
F/S/S	15.331	27.8363	62.5238	66.1535	13.3993	26.169	14.622
F/S/F	34.7712	54.4541	67.9679	79.4381	33.3717	53.3128	40.0559
F/F/S	26.8342	42.3262	61.7979	88.6639	26.0844	46.6895	29.1415
F/F/F	46.4866	72.3044	64.6121	77.6292	50.2265	68.387	63.4887

Table 6.3. Average Waiting Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange (Fast (F) / Slow (S) - rates)

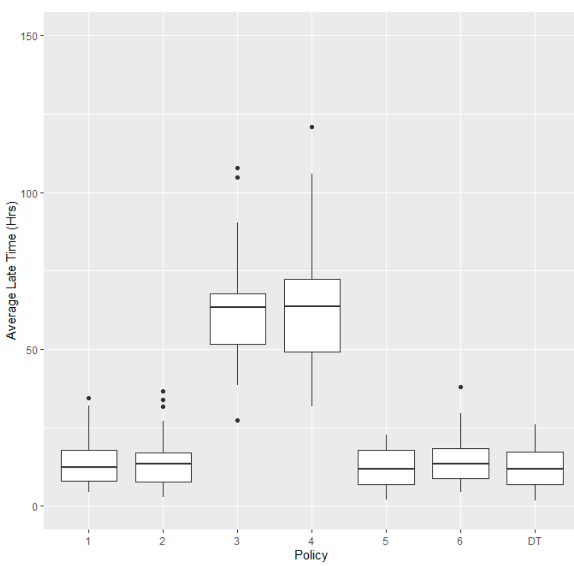
S/M/L Part Arrivals	P_1	P_2	P_3	P_4	P_5	P_6	DT
S/S/S	11.8579	10.7214	6.33241	7.39755	13.8706	11.8504	7.379
S/S/F	25.2664	32.0202	9.30463	10.2361	27.3339	27.2768	9.2631
S/F/S	22.3734	23.3391	8.82424	9.43944	21.5758	23.2524	8.6414
S/F/F	40.2685	42.5153	10.1536	11.5646	41.7317	40.5889	10.1724
F/S/S	25.2788	36.6175	8.55553	9.55101	23.1697	34.6008	9.2631
F/S/F	47.7449	67.0146	9.57719	11.3882	47.0194	65.116	9.5216
F/F/S	38.4073	53.1649	8.79844	12.0629	38.7554	58.1549	9.1842
F/F/F	59.9563	85.506	9.11681	11.1801	64.0104	82.6364	10.1954



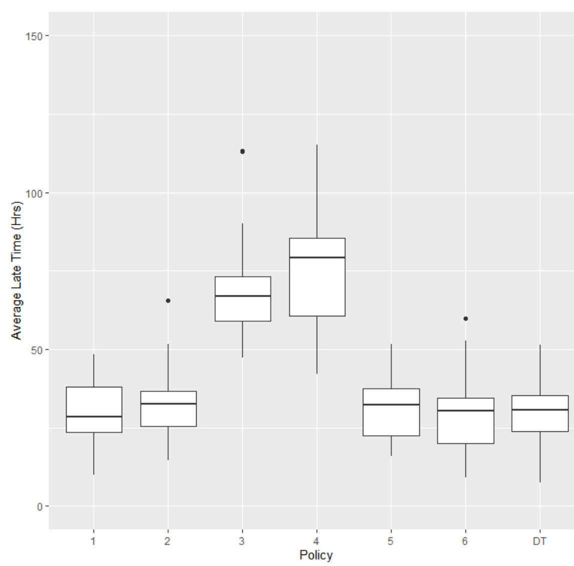
(a) SSS Part Arrivals



(b) SSF Part Arrivals

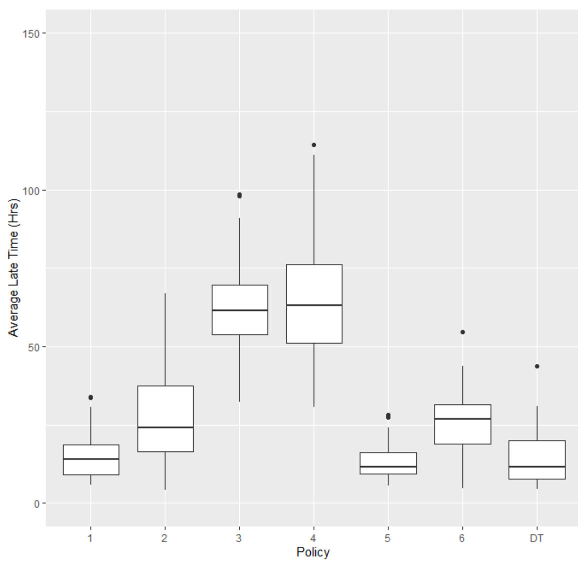


(c) SFS Part Arrivals

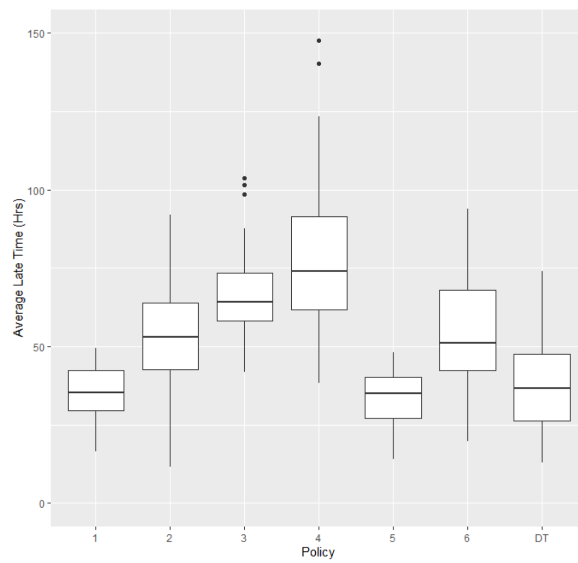


(d) SFF Part Arrivals

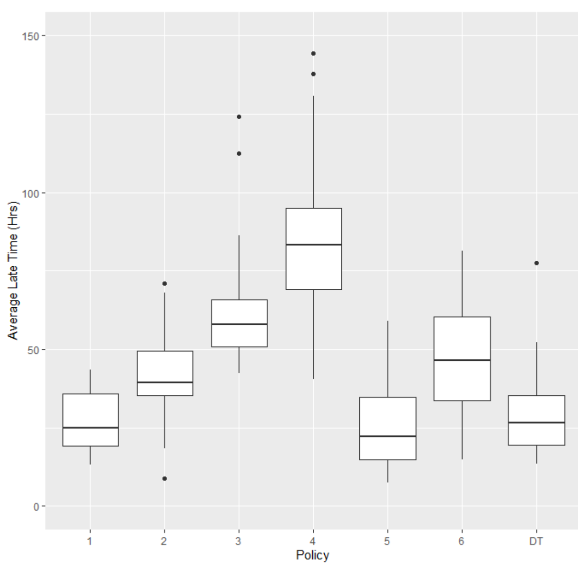
Figure 6.1. Average Late Time Performance Measure of PPR system policies with and without DT Part 1



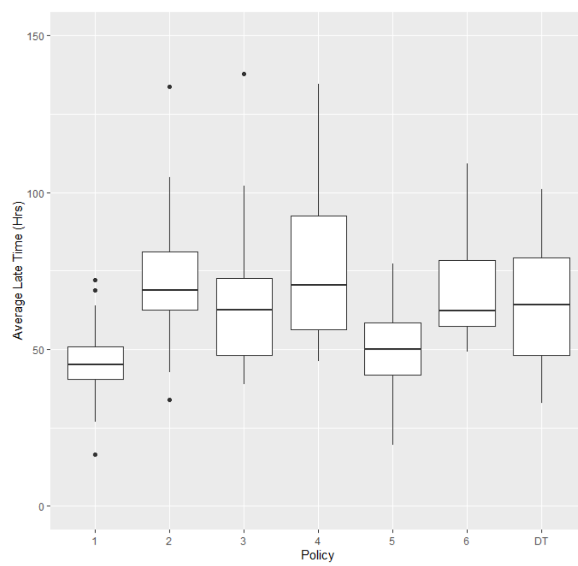
(a) FSS Part Arrivals



(b) FSF Part Arrivals

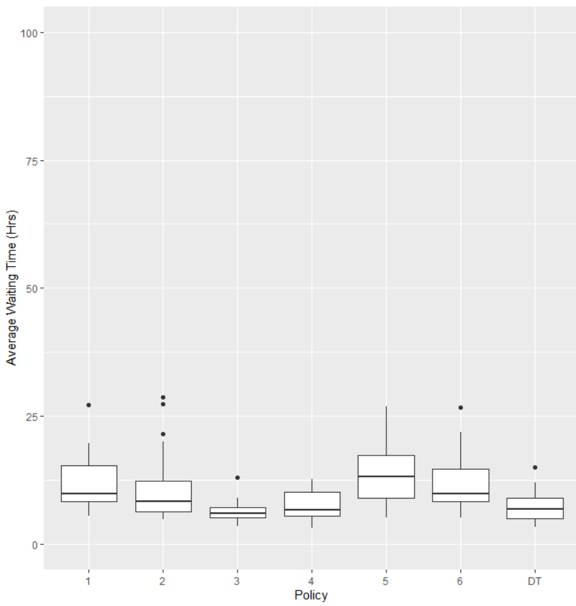


(c) FFS Part Arrivals

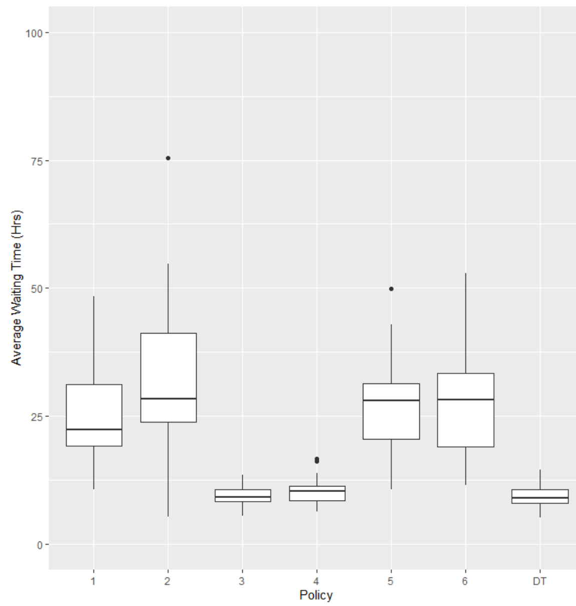


(d) FFF Part Arrivals

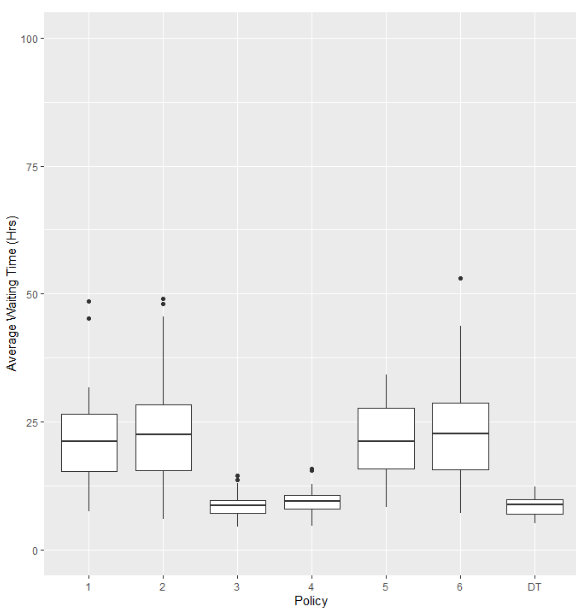
Figure 6.2. Average Late Time Performance Measure of PPR system policies with and without DT Part 2



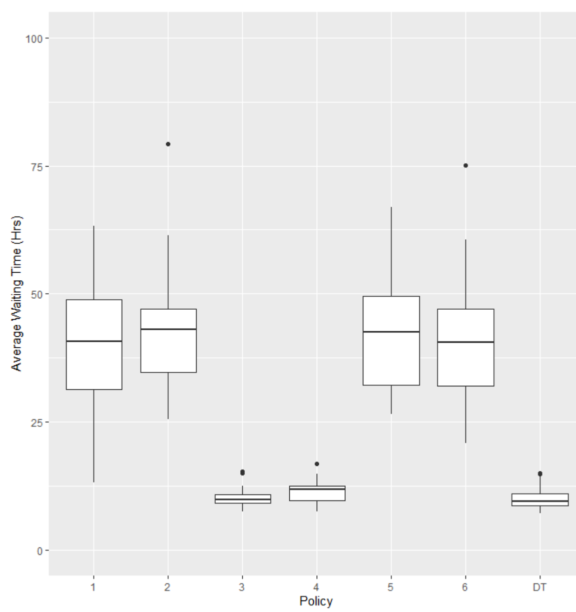
(a) SSS Part Arrivals



(b) SSF Part Arrivals

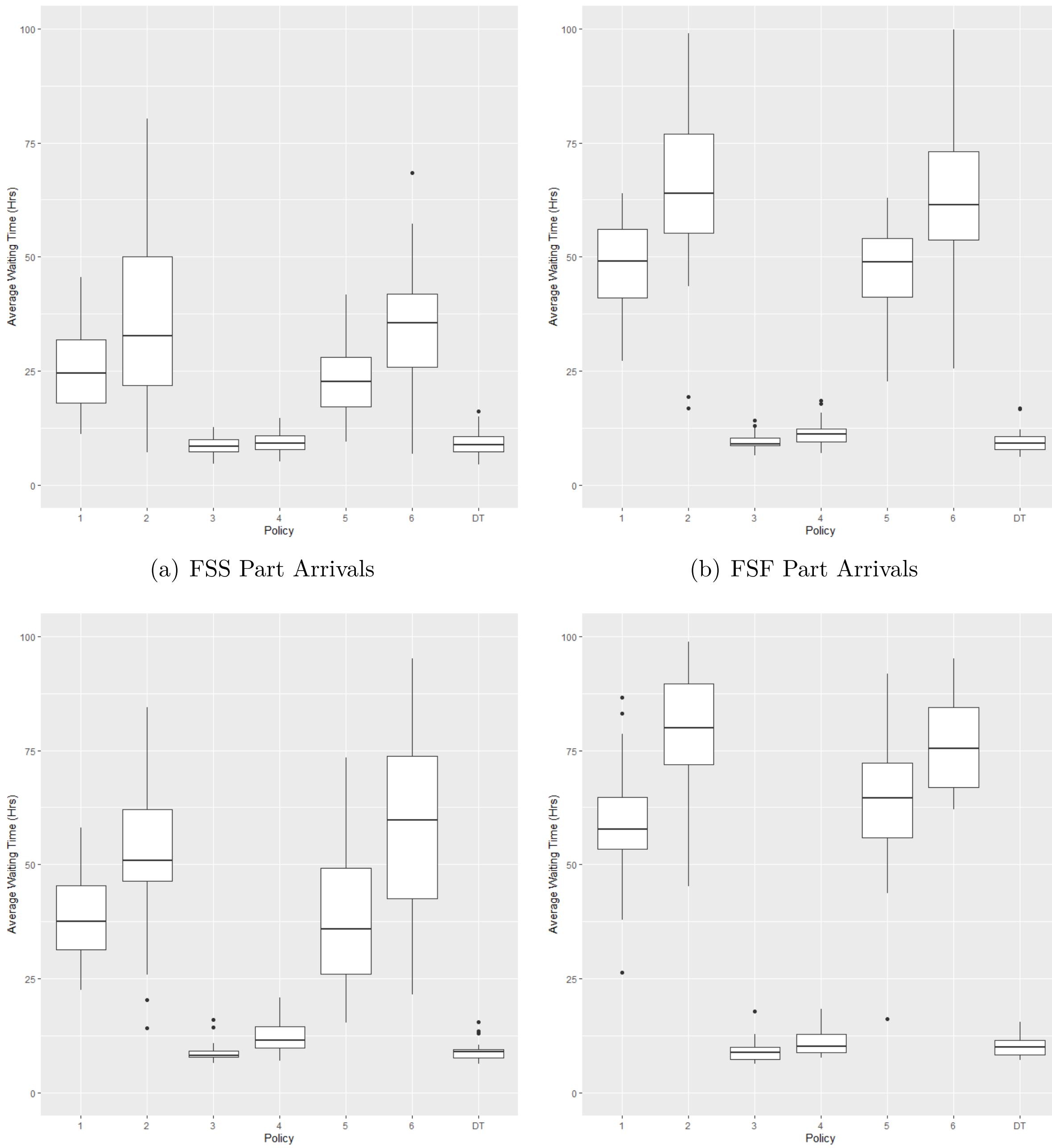


(c) SFS Part Arrivals



(d) SFF Part Arrivals

Figure 6.3. Average waiting time performance measure of PPR system policies with and without DT Part 1



(a) FSS Part Arrivals

(b) FSF Part Arrivals

(c) FFS Part Arrivals

(d) FFF Part Arrivals

Figure 6.4. Average waiting time performance measure of PPR system policies with and without DT Part 2

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	1.000000e+00	Not reject
2	1	3	1.589087e-16	Reject
3	1	4	5.279514e-11	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	1.000000e+00	Not reject
6	1	DT	1.000000e+00	Not reject
7	2	3	2.708966e-17	Reject
8	2	4	2.467691e-11	Reject
9	2	5	1.000000e+00	Not reject
10	2	6	1.000000e+00	Not reject
11	2	DT	1.000000e+00	Not reject
12	3	4	1.000000e+00	Not reject
13	3	5	4.378235e-17	Reject
14	3	6	7.212798e-17	Reject
15	3	DT	3.083060e-17	Reject
16	4	5	3.869487e-11	Reject
17	4	6	3.134794e-11	Reject
18	4	DT	2.901930e-11	Reject
19	5	6	1.000000e+00	Not reject
20	5	DT	1.000000e+00	Not reject
21	6	DT	1.000000e+00	Not reject

(a) SSS Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	8.548933e-01	Not reject
2	1	3	4.028972e-17	Reject
3	1	4	4.276292e-15	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	1.000000e+00	Not reject
6	1	DT	1.000000e+00	Not reject
7	2	3	8.720078e-15	Reject
8	2	4	1.477400e-13	Reject
9	2	5	1.000000e+00	Not reject
10	2	6	1.000000e+00	Not reject
11	2	DT	1.000000e+00	Not reject
12	3	4	1.000000e+00	Not reject
13	3	5	9.810893e-17	Reject
14	3	6	4.466743e-17	Reject
15	3	DT	7.337323e-17	Reject
16	4	5	8.910062e-15	Reject
17	4	6	4.294100e-15	Reject
18	4	DT	6.972188e-15	Reject
19	5	6	1.000000e+00	Not reject
20	5	DT	1.000000e+00	Not reject
21	6	DT	1.000000e+00	Not reject

(b) SSF Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	1.000000e+00	Not reject
2	1	3	7.774144e-15	Reject
3	1	4	9.815870e-14	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	1.000000e+00	Not reject
6	1	DT	1.000000e+00	Not reject
7	2	3	7.648869e-15	Reject
8	2	4	1.010871e-13	Reject
9	2	5	1.000000e+00	Not reject
10	2	6	1.000000e+00	Not reject
11	2	DT	1.000000e+00	Not reject
12	3	4	1.000000e+00	Not reject
13	3	5	5.008315e-15	Reject
14	3	6	1.004492e-14	Reject
15	3	DT	3.712023e-15	Reject
16	4	5	6.111614e-14	Reject
17	4	6	1.286292e-13	Reject
18	4	DT	4.927855e-14	Reject
19	5	6	1.000000e+00	Not reject
20	5	DT	1.000000e+00	Not reject
21	6	DT	1.000000e+00	Not reject

(c) SFS Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	1.000000e+00	Not reject
2	1	3	6.577137e-14	Reject
3	1	4	8.627003e-14	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	1.000000e+00	Not reject
6	1	DT	1.000000e+00	Not reject
7	2	3	7.107002e-13	Reject
8	2	4	4.206753e-13	Reject
9	2	5	1.000000e+00	Not reject
10	2	6	1.000000e+00	Not reject
11	2	DT	1.000000e+00	Not reject
12	3	4	1.000000e+00	Not reject
13	3	5	1.377035e-13	Reject
14	3	6	1.136408e-13	Reject
15	3	DT	8.109559e-14	Reject
16	4	5	1.895997e-13	Reject
17	4	6	5.686237e-14	Reject
18	4	DT	8.259784e-14	Reject
19	5	6	1.000000e+00	Not reject
20	5	DT	1.000000e+00	Not reject
21	6	DT	1.000000e+00	Not reject

(d) SFF Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	7.508303e-03	Reject
2	1	3	9.684793e-16	Reject
3	1	4	3.311215e-13	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	8.936065e-04	Reject
6	1	DT	1.000000e+00	Not reject
7	2	3	5.957761e-10	Reject
8	2	4	3.157288e-09	Reject
9	2	5	7.659278e-04	Reject
10	2	6	1.000000e+00	Not reject
11	2	DT	5.501007e-03	Reject
12	3	4	1.000000e+00	Not reject
13	3	5	1.039186e-15	Reject
14	3	6	4.988216e-12	Reject
15	3	DT	3.114356e-16	Reject
16	4	5	2.503370e-13	Reject
17	4	6	2.450117e-10	Reject
18	4	DT	1.366043e-13	Reject
19	5	6	1.680417e-05	Reject
20	5	DT	1.000000e+00	Not reject
21	6	DT	8.286185e-04	Reject

(e) FSS Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	1.508720e-04	Reject
2	1	3	4.327582e-12	Reject
3	1	4	9.897152e-09	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	5.955074e-04	Reject
6	1	DT	1.000000e+00	Not reject
7	2	3	8.140073e-02	Not reject
8	2	4	2.987012e-03	Reject
9	2	5	4.940873e-05	Reject
10	2	6	1.000000e+00	Not reject
11	2	DT	7.817786e-02	Not reject
12	3	4	1.000000e+00	Not reject
13	3	5	1.161550e-12	Reject
14	3	6	4.682524e-02	Reject
15	3	DT	4.881862e-07	Reject
16	4	5	4.597973e-09	Reject
17	4	6	1.827061e-03	Reject
18	4	DT	5.079236e-07	Reject
19	5	6	2.043236e-04	Reject
20	5	DT	1.000000e+00	Not reject
21	6	DT	1.724979e-01	Not reject

(f) FSF Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	6.083014e-04	Reject
2	1	3	1.629446e-10	Reject
3	1	4	6.805857e-11	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	4.931017e-05	Reject
6	1	DT	1.000000e+00	Not reject
7	2	3	9.408523e-04	Reject
8	2	4	9.912394e-08	Reject
9	2	5	2.340735e-03	Reject
10	2	6	1.000000e+00	Not reject
11	2	DT	2.833836e-02	Reject
12	3	4	3.600941e-03	Reject
13	3	5	5.439515e-10	Reject
14	3	6	4.039807e-02	Reject
15	3	DT	7.845190e-09	Reject
16	4	5	2.875414e-11	Reject
17	4	6	1.311429e-06	Reject
18	4	DT	1.235845e-10	Reject
19	5	6	1.683462e-04	Reject
20	5	DT	1.000000e+00	Not reject
21	6	DT	2.096588e-03	Reject

(g) FFS Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	3.191374e-06	Reject
2	1	3	5.741501e-03	Reject
3	1	4	3.444860e-06	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	5.076560e-06	Reject
6	1	DT	5.188915e-03	Reject
7	2	3	1.000000e+00	Not reject
8	2	4	1.000000e+00	Not reject
9	2	5	1.319212e-04	Reject
10	2	6	1.000000e+00	Not reject
11	2	DT	1.000000e+00	Not reject
12	3	4	7.274766e-01	Not reject
13	3	5	8.431172e-02	Not reject
14	3	6	1.000000e+00	Not reject
15	3	DT	1.000000e+00	Not reject
16	4	5	5.963035e-05	Reject
17	4	6	1.000000e+00	Not reject
18	4	DT	3.731422e-01	Not reject
19	5	6	4.489693e-04	Reject
20	5	DT	9.655467e-02	Not reject
21	6	DT	1.000000e+00	Not reject

(h) FFF Part Arrivals

Figure 6.5. Bonferroni Pairwise Comparison for Average Late Time Performance Measure of PPR system Policies with DT

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	1.000000e+00	Not reject
2	1	3	2.804974e-05	Reject
3	1	4	1.584638e-03	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	1.000000e+00	Not reject
6	1	DT	1.819866e-03	Reject
7	2	3	1.885369e-02	Reject
8	2	4	2.459589e-01	Not reject
9	2	5	9.972085e-01	Not reject
10	2	6	1.000000e+00	Not reject
11	2	DT	2.540038e-01	Not reject
12	3	4	1.000000e+00	Not reject
13	3	5	1.060341e-06	Reject
14	3	6	8.098049e-05	Reject
15	3	DT	1.000000e+00	Not reject
16	4	5	2.915260e-05	Reject
17	4	6	3.279316e-03	Reject
18	4	DT	1.000000e+00	Not reject
19	5	6	1.000000e+00	Not reject
20	5	DT	3.206596e-05	Reject
21	6	DT	3.660518e-03	Reject

(a) SSS Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	8.057040e-01	Not reject
2	1	3	4.292935e-09	Reject
3	1	4	1.577734e-08	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	1.000000e+00	Not reject
6	1	DT	3.750433e-09	Reject
7	2	3	4.453916e-08	Reject
8	2	4	1.046822e-07	Reject
9	2	5	1.000000e+00	Not reject
10	2	6	1.000000e+00	Not reject
11	2	DT	4.170946e-08	Reject
12	3	4	1.000000e+00	Not reject
13	3	5	5.905072e-11	Reject
14	3	6	4.650342e-09	Reject
15	3	DT	1.000000e+00	Not reject
16	4	5	1.869463e-10	Reject
17	4	6	1.447815e-08	Reject
18	4	DT	1.000000e+00	Not reject
19	5	6	1.000000e+00	Not reject
20	5	DT	4.794719e-11	Reject
21	6	DT	4.131507e-09	Reject

(b) SSF Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	1.000000e+00	Not reject
2	1	3	1.750034e-07	Reject
3	1	4	4.577578e-07	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	1.000000e+00	Not reject
6	1	DT	1.359249e-07	Reject
7	2	3	2.600570e-06	Reject
8	2	4	5.878901e-06	Reject
9	2	5	1.000000e+00	Not reject
10	2	6	1.000000e+00	Not reject
11	2	DT	2.060518e-06	Reject
12	3	4	1.000000e+00	Not reject
13	3	5	3.548075e-09	Reject
14	3	6	5.565802e-07	Reject
15	3	DT	1.000000e+00	Not reject
16	4	5	1.098372e-08	Reject
17	4	6	1.321701e-06	Reject
18	4	DT	1.000000e+00	Not reject
19	5	6	1.000000e+00	Not reject
20	5	DT	2.781415e-09	Reject
21	6	DT	4.393325e-07	Reject

(c) SFS Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	1.000000e+00	Not reject
2	1	3	2.419010e-13	Reject
3	1	4	6.625278e-13	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	1.000000e+00	Not reject
6	1	DT	1.906454e-13	Reject
7	2	3	2.708751e-14	Reject
8	2	4	6.616566e-14	Reject
9	2	5	1.000000e+00	Not reject
10	2	6	1.000000e+00	Not reject
11	2	DT	2.033781e-14	Reject
12	3	4	2.269318e-01	Not reject
13	3	5	7.824888e-16	Reject
14	3	6	1.746180e-12	Reject
15	3	DT	1.000000e+00	Not reject
16	4	5	1.728200e-15	Reject
17	4	6	4.876968e-12	Reject
18	4	DT	4.428893e-01	Not reject
19	5	6	1.000000e+00	Not reject
20	5	DT	4.923124e-16	Reject
21	6	DT	1.469202e-12	Reject

(d) SFF Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	1.236951e-01	Not reject
2	1	3	3.536720e-09	Reject
3	1	4	1.325170e-08	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	7.504640e-02	Not reject
6	1	DT	8.061523e-09	Reject
7	2	3	1.438010e-07	Reject
8	2	4	2.946390e-07	Reject
9	2	5	2.189319e-02	Reject
10	2	6	1.000000e+00	Not reject
11	2	DT	2.337162e-07	Reject
12	3	4	1.000000e+00	Not reject
13	3	5	1.493720e-09	Reject
14	3	6	3.830167e-10	Reject
15	3	DT	1.000000e+00	Not reject
16	4	5	7.158128e-09	Reject
17	4	6	8.758830e-10	Reject
18	4	DT	1.000000e+00	Not reject
19	5	6	5.700033e-03	Reject
20	5	DT	3.981793e-09	Reject
21	6	DT	6.091644e-10	Reject

(e) FSS Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	9.961374e-04	Reject
2	1	3	6.990950e-19	Reject
3	1	4	3.257507e-19	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	6.520558e-03	Reject
6	1	DT	1.559671e-19	Reject
7	2	3	7.153615e-14	Reject
8	2	4	1.233244e-13	Reject
9	2	5	5.881559e-04	Reject
10	2	6	1.000000e+00	Not reject
11	2	DT	5.787976e-14	Reject
12	3	4	1.127475e-01	Not reject
13	3	5	1.593735e-18	Reject
14	3	6	5.569090e-13	Reject
15	3	DT	1.000000e+00	Not reject
16	4	5	8.495775e-19	Reject
17	4	6	1.032243e-12	Reject
18	4	DT	2.237960e-01	Not reject
19	5	6	4.013556e-03	Reject
20	5	DT	3.817131e-19	Reject
21	6	DT	4.682406e-13	Reject

(f) FSF Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	6.792128e-03	Reject
2	1	3	7.287055e-15	Reject
3	1	4	5.363306e-14	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	2.934615e-04	Reject
6	1	DT	8.859928e-15	Reject
7	2	3	8.786379e-13	Reject
8	2	4	4.199674e-12	Reject
9	2	5	3.816269e-02	Reject
10	2	6	1.000000e+00	Not reject
11	2	DT	1.050190e-12	Reject
12	3	4	9.396918e-04	Reject
13	3	5	6.480685e-10	Reject
14	3	6	4.684046e-13	Reject
15	3	DT	1.000000e+00	Not reject
16	4	5	7.534848e-09	Reject
17	4	6	1.894154e-12	Reject
18	4	DT	6.606942e-03	Reject
19	5	6	2.018200e-03	Reject
20	5	DT	8.525667e-10	Reject
21	6	DT	5.501361e-13	Reject

(g) FFS Part Arrivals

Bonferroni Correction (alpha = 0.05)

	Level (a)	Level (b)	p.value	No difference
1	1	2	1.406954e-05	Reject
2	1	3	1.145610e-18	Reject
3	1	4	2.466487e-18	Reject
4	1	5	1.000000e+00	Not reject
5	1	6	5.909761e-06	Reject
6	1	DT	2.788053e-18	Reject
7	2	3	1.717275e-17	Reject
8	2	4	3.099847e-17	Reject
9	2	5	7.148050e-04	Reject
10	2	6	1.000000e+00	Not reject
11	2	DT	2.818950e-17	Reject
12	3	4	8.653972e-02	Not reject
13	3	5	4.338933e-17	Reject
14	3	6	8.615030e-20	Reject
15	3	DT	1.000000e+00	Not reject
16	4	5	9.735654e-17	Reject
17	4	6	1.421867e-19	Reject
18	4	DT	1.000000e+00	Not reject
19	5	6	8.551139e-04	Reject
20	5	DT	8.901555e-17	Reject
21	6	DT	1.589997e-19	Reject

(h) FFF Part Arrivals

Figure 6.6. Bonferroni Pairwise Comparison for Average Waiting Time Performance Measure of Policies against DT

6.1.4 Discussion

Both performance measures, average waiting time and average late time were studied using the Digital Twin Framework. These initial experiments are able to show how the DT is able to take policies and perform at least not worse than any of the individual policies for average waiting time and all but one condition for average late time. Due to the static environment of parameters within each experiment, as in the conditions of arrivals and processing times have the same distribution throughout, its expected that a dominant policy will exist. This framework is able to use the DTs to compare policies and see the impact of different system strains.

Average Late Time

Each of the different scenarios in Figure 6.1 shows the effect of policy and the ability of the DT to perform as well as any of the individual policies. As long as the job selection rule is either FIFO or EDD, the PPR system performs well, and the Bonferroni pairwise comparison shows no difference. Between the available policies, and the scenarios SSS, SSF, SFS, and SFF, the queue selection rule has little effect on the performance.

The scenarios in Figure 6.2 show cases of the DT's ability to respond to different arrival rates but also sheds light into how the DT can be compromised. Notice the different policies and their impact on performance compared to the scenarios in Fig. 6.1 as the combination of queue selection and job selection rules make a difference. As long as the job selection rule is not based on SPT, using the NINQ queue selection rule is optimal. Using the TPT queue selection rule with either FIFO or EDD performs better than either combination of SPT job selection rule.

The DT in 7 of the 8 scenarios perform as good as the best policies. However, a key characteristic when taking a look at Figure 6.2(d). Policy 1 and 5 and results using DT and policy 5 have similar average late time performance metrics, and yet there exists a difference between using the DT and policy 1. With FFF part arrivals, the DT fails to perform as good as the best policy nor does it outperform any of the other policies seen through the Bonferroni pairwise comparison in Figure 6.5(h). Scenario FFF shows that in special cases where the system becomes overloaded with parts and when performance results of different policies are statistically similar, the DT effectively is more likely to make the wrong choice. Due to the update characteristic of the DT, the state of a congested system creates issues when the dominant policy's impact on the system is prior to the copied state. To explain further, with this performance metric, the NINQ queue selection rule is optimal as long as its in combination with either FIFO or EDD, however, the queue states are being copied after the point where the optimal policy has its impact. Longer queue lengths may result in the DT using parts that were copied from the PPR system with part arrivals having less impact on performance. Another factor may be due to the performance metric, where lateness is tallied as the parts exit the system further along the system.

There is clear indication on the importance of using the DT and keeping track of the system's decisions and what part of the process they impact. When designing the DT model for systems, being aware of how decisions interact with each other and its effect on copied states will result in better performance and better decisions.

Average Waiting Time

The dominating policy for average waiting time depends on the job selection rule shortest processing time. From Figure 6.6 only in one case (FFS) does choosing the queue selection rule have an impact on performance when SPT is used. Otherwise, NINQ dominates TPT for queue selection rules although there are cases where the difference is negligible. Using the DT performs as good as the best policy in every scenario.

The Digital Twin Framework is able to show the flexibility of the DT to adjust its decisions based on the performance measure. Instances of different objectives could arise due to the season of the year, or even from major supply chain disruptions and the DT is able to change and help make policy decisions.

6.2 Impact of Accuracy on Performance Measure

The benefits of a digital twin framework may be realized most when you have situations where the approximation of the model is facing instances of error when the accuracy of the model is compromised. There can be a number of reasons that cause a model to be inaccurate such as unforeseen changes to the real system, random error, mistake in the model building process, or even mistakes in the verification and validation techniques. The DT allows for real time updates of the system to make corrections and make decisions that are better aligned with the real system. In this section, examples of how accuracy of the DT impacts the performance measure are shown and how DTs are connected and communicate with the physical system. The developed DT Framework helps to visualize the real time transfer of information as the PPR system updates, moves forward in time and ultimately make defining decisions. This modified framework will help show the system requirements of implementing a DT and the importance understanding its components.

6.2.1 Research Question and Hypothesis

In order to test the Digital Twin Framework and the impact of accuracy on performance there are two tested components, accuracy of the model and update frequency. The accuracy of the model having no effect on performance measure is tested first to see the impact of model error. Using models with error, the decision period variable was used to show whether there is any effect of update frequency on performance measure. In order to test these hypothesis a statistical analysis was performed to show the impacts of accuracy and update frequency.

6.2.2 Experiment

This experiment changes the processing times of fabrication bays of each of the DTs and compares the impact of different decision periods. This experiment is inline with not knowing the true distribution of a task where approximations are used based on time studies. Not capturing the true distribution of values is an error that can come up when modeling any system. The wrong distributions for processing times is arbitrarily set for each of the different part sizes with varying arrival rates to show the use of the DT and the performance impact of real time information.

Table 6.4. Digital Twin Fabrication Processing Time Changes for Each Part Type in Hours

PartType	PPR System	Digital Twin System
Small Parts	Random.Triangular(.5,1.25,2.333)	Random.Uniform(.5,3.5)
Medium Parts	Random.Triangular(1.6667,3,6)	Random.Uniform(1.5,8)
Large Parts	Random.Triangular(4,6,9)	Random.Uniform(4,12)

Error

Table 6.4 shows the changes made to the digital twins in the Digital Twin Framework. The new fabrication processing times are assigned for new parts when arriving from the digital twin source objects.

6.2.3 Results

Table 6.5 and 6.6 shows a range of different arrival rates and the expected performance measure of each individual policy without updates. Given that these results are a reflection to the changes in the adjusted fabrication processing times, the best policy for Average Late Time is *Policy* 3, where the queue for each zone is chosen based on number in queue and parts are chosen based on shortest processing time. This change is a direct result of the change in the fabrication processing times meaning without updates the policy chosen will result in a far worse performance in the real system by comparing policy results from Table 6.2. The best policy for average waiting time even with the adjusted processing times however is still *policy* 3 which is more aligned with the best policy for addressing the AWT performance measure as seen in Table 6.3.

Table 6.7 shows the results for average late time using the adjusted DT where the fabrication processing times are changed. The results show the effects of different decision periods, and changing how often you update the system does have an impact on your performance

Table 6.5. Average Late Time Performance Measure For Adjusted Fabrication Processing Times Without Information Exchange (Fast (F) / Slow (S) - rates)

S/M/L Part Arrivals	P_1	P_2	P_3	P_4	P_5	P_6
S/S/S	264.245	340.547	61.6019	76.2248	262.55	337.867
S/S/F	284.418	359.554	63.6673	81.51	280.045	364.547
S/F/S	279.699	351.412	64.6951	75.9444	275.823	358.469
S/F/F	300.361	377.681	63.4645	78.3287	299.162	379.319
F/S/S	295.253	372.92	58.1583	73.8104	291.175	372.493
F/S/F	311.069	394.934	60.0783	72.5394	309.46	393.942
F/F/S	313.6	384.946	58.941	77.1453	308.911	388.39
F/F/F	331.767	414.146	60.7264	70.0869	328.59	409.048

Table 6.6. Average Waiting Time Performance Measure For Adjusted Fabrication Processing Times Without Information Exchange (Fast (F) / Slow (S) - rates)

S/M/L Part Arrivals	P_1	P_2	P_3	P_4	P_5	P_6
S/S/S	278.287	356.053	11.3858	13.7836	276.611	353.395
S/S/F	298.761	375.456	11.6768	14.6285	294.336	380.485
S/F/S	293.806	366.978	11.8004	13.6434	289.878	374.083
S/F/F	314.709	393.612	11.6032	13.8862	313.509	395.245
F/S/S	308.842	387.899	10.7051	13.2065	304.772	387.431
F/S/F	324.843	410.223	10.9398	13.0737	323.193	409.229
F/F/S	327.24	399.935	10.7133	13.5969	322.42	403.454
F/F/F	345.557	429.584	11.0498	12.5158	342.424	424.403

measure in the PPR system. One thing to notice is that the minimum average late time for the PPR system eventually gets worse after initial improvements as the number of updates become more frequent. Moreover, a reason for this trend may be due to the trade-off of using the benefits of the DT and update frequency.

The results of the simulation runs of both the average late time and average waiting time performance measures were analyzed. The statistical analysis of the results help make better judgements on the effects of the decision periods and its impact on performance measure. Although the trends can be analyzed, in order to make such conclusions a series of statistical

Table 6.7. Average Late Time Performance Measure For PPR System using DT Framework with Adjusted Fabrication Processing Times for the DT

	Decision Period									
S/M/L Part Arrivals	30	60	90	120	180	240	300	360	420	480
S/S/S	12.253	6.691	6.566	5.775	14.044	25.470	28.672	28.626	36.008	38.203
S/S/F	33.709	24.362	23.771	14.887	20.709	30.651	42.422	31.133	34.954	39.226
S/F/S	29.428	18.688	16.560	14.297	17.425	26.658	34.853	30.826	33.566	38.830
S/F/F	63.384	45.251	35.451	40.728	37.442	44.010	67.391	47.327	50.743	56.065
F/S/S	25.781	25.666	20.605	15.639	25.424	33.941	32.745	29.531	32.550	34.337
F/S/F	55.304	52.439	57.518	42.520	50.183	62.766	76.427	50.142	60.319	67.687
F/F/S	42.077	46.147	41.428	46.449	56.065	53.475	62.041	43.922	48.486	52.926
F/F/F	53.488	60.864	72.147	77.769	90.677	81.483	101.090	65.528	89.067	99.592

tests were run. We considered using ANOVA [57] and Tukey Honest Significant Differences test [58], however, the variances in the groups were found to be statistically different using a Bartlett test of homogeneity of variances test [59] and instead decided to use Welch's t-test assuming the variances may not be equal. Likewise, instead of the Tukey test, we preferred the Bonferroni method [60] to check the difference in performance measure group by group. The results are as follows.

An example of the results from one of the simulation runs, specifically the F/S/S part arrival setting will be used to help explain the results. The Average Late Time performance measure is used in this example. By using the Bartlett's K-Squared test, we are dealing with the null hypothesis that there is no differences in variances between the decision variable, decision periods. Give the P-value < 0.05, it leads us to reject the null hypothesis and that there likely is a difference between the variances of the performance measure.

Bartlett's K-squared = 39.723, df = 9, p-value = 8.529e-06

Due to rejecting the null hypothesis of the variances from the Bartlett's K-Squared test, we chose to use Welch's F Test, a better alternative for realistic scenarios and unequal variances [57]. Welch's F Test, can be used to reject that decision periods have no effect on performance measure with models that are inaccurate. As seen in the results using RStudio, with an alpha $= 0.05$, due to the p-value < 0.05, we can reject the null hypothesis for this model and conclude that there is an association between the decision period and performance measure mean due to at least one group being different with another at $\alpha = 0.05$ level of significance. From this test alone, the performance measure for average late time is associated with which decision period is chosen and is an important factor to consider.

Table 6.8. Average Late Time Comparison using Welch's Heteroscedastic F Test (alpha = 0.05) for F/S/S Part Arrival for Adjusted Fabrication Processing Times

	Values
statistic	8.624287
num df	9
denom df	117.9044
p.value	7.461361e-10
Result	Defference is statistically significant

A deeper look into the results of this experiment is taken by conducting a pairwise comparison. This can show which of the performance measure means are statistically different from each other and show insights into the effects of decision periods in this framework. The F/S/S part arrival example will continued to be explained in detail before presenting results from each run. Figure 6.7 shows the results of the F/S/S part arrival as a box plot with 5 visual summary statistics, median, two hinges and two whiskers as well as individual outliers. The lower and upper hinge are the first and third quartiles, while the upper and lower whiskers represent the largest or lowest value no further than 1.5 * inter-quartile range from the hinge.

A pairwise comparison of the decision variables is conducted using the Bonferonni method and the results can be seen in Table 6.9. Through this method, a closer look at the decision variable and the impact of changing decision periods is seen. In the example shown using the F/S/S part arrivals the average late time performance measure for when the decision period is 120 hours is significantly different compared to when the decision period is 240, 300, 360, 420, and 480 hours. However, this doesn't hold true for when the decision period is 30 hours as the hypothesis test can not be rejected when compared to any of the other decision periods. The pairs (90,240), (90,420), and (90, 480) also show significant difference in performance measure means.

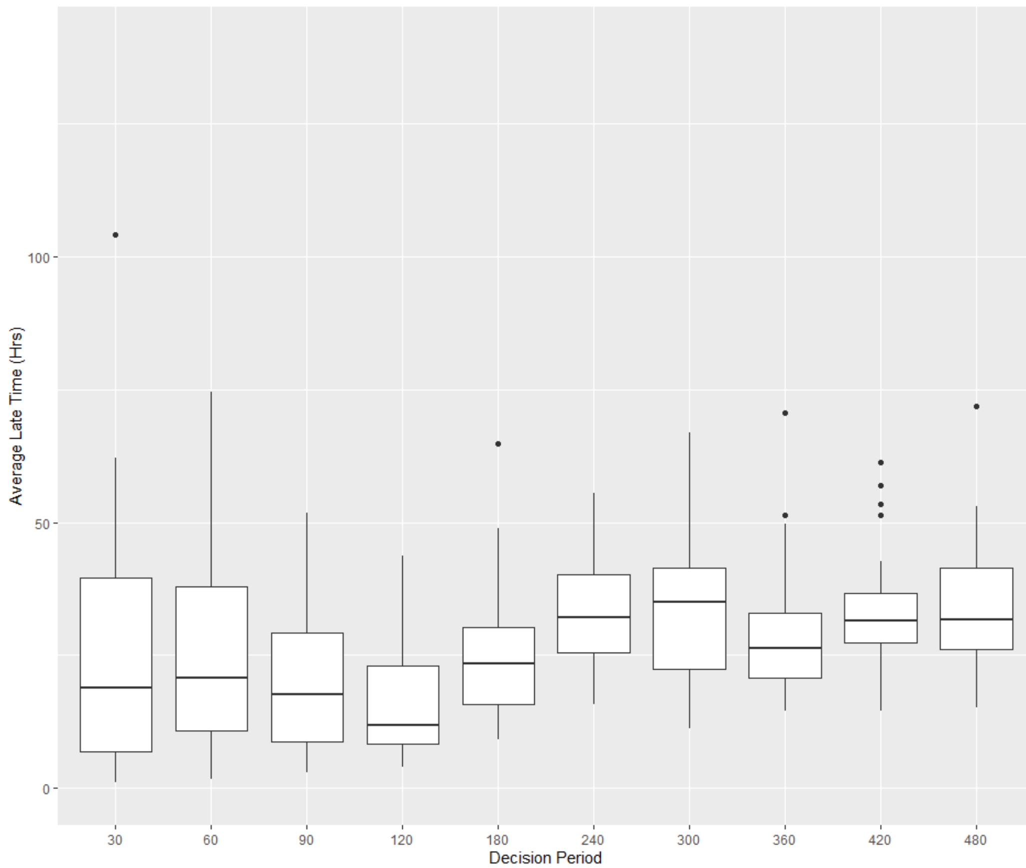


Figure 6.7. F/S/S Part arrival showing impact of update frequency on Average Late Time Performance Measure using Digital Twin Framework with Adjusted Fabrication Processing Times

Table 6.9. Pairwise Comparison of Decision Periods on Average Late Time Performance Measure Using Bonferroni Method for F/S/S Part Arrivals

Level (a)	Level (b)	p.value	No difference
30	60	1.00000	Not reject
30	90	1.00000	Not reject
30	120	1.00000	Not reject
30	180	1.00000	Not reject
30	240	1.00000	Not reject
30	300	1.00000	Not reject
30	360	1.00000	Not reject
30	420	1.00000	Not reject
30	480	1.00000	Not reject
60	90	1.00000	Not reject
60	120	0.65041	Not reject
60	180	1.00000	Not reject
60	240	1.00000	Not reject
60	300	1.00000	Not reject
60	360	1.00000	Not reject
60	420	1.00000	Not reject
60	480	1.00000	Not reject
90	120	1.00000	Not reject
90	180	1.00000	Not reject
90	240	0.00621	Reject
90	300	0.07835	Not reject
90	360	0.56760	Not reject
90	420	0.03102	Reject
90	480	0.00927	Reject
120	180	0.08229	Not reject
120	240	0.00000	Reject
120	300	0.00011	Reject
120	360	0.00081	Reject
120	420	0.00001	Reject
120	480	0.00000	Reject
180	240	0.38776	Not reject
180	300	1.00000	Not reject
180	360	1.00000	Not reject
180	420	1.00000	Not reject
180	480	0.45043	Not reject
240	300	1.00000	Not reject
240	360	1.00000	Not reject
240	420	1.00000	Not reject
240	480	1.00000	Not reject
300	360	1.00000	Not reject
300	420	1.00000	Not reject
300	480	1.00000	Not reject
360	420	1.00000	Not reject
360	480	1.00000	Not reject
420	480	1.00000	Not reject

The data for testing each of the different arrival rates are as follows. Table 6.10 is the results for Welch's t-test for the different arrival rates using the DT framework with adjusted fabrication processing times for the DT. This test allows to determine if there are any differences in the means of the performance measure, average late time. Each of the different arrival rates can reject the null hypothesis at 0.05 significance level. Figures 6.8 and 6.9 provide an overview of each of the different arrival rates and box plots for each of the different decision variables. Tables 6.13, 6.15, 6.16, 6.14, 6.19, 6.18, 6.17 are the rest of the pairwise comparison of decision periods on average late time performance measure Using the Bonferroni method for different part arrivals.

Table 6.10. Welch's t-test for Different Arrival Rates using Digital Twin Framework with Adjusted Fabrication Processing Times for Average Late Time

	statistic	num df	denom df	p.value	difference
sss	61.06052	9	117.313	4.21E-40	Reject Null
ssf	18.17207	9	117.505	1.34E-18	Reject Null
sfs	16.26125	9	117.703	4.55E-17	Reject Null
sff	10.03457	9	117.816	2.48E-11	Reject Null
fss	8.624287	9	117.9044	7.46E-10	Reject Null
fsf	7.3853	9	118.022	1.72E-08	Reject Null
ffs	3.0167	9	118.0495	0.002816	Reject Null
fff	16.502	9	117.9167	2.81E-17	Reject Null

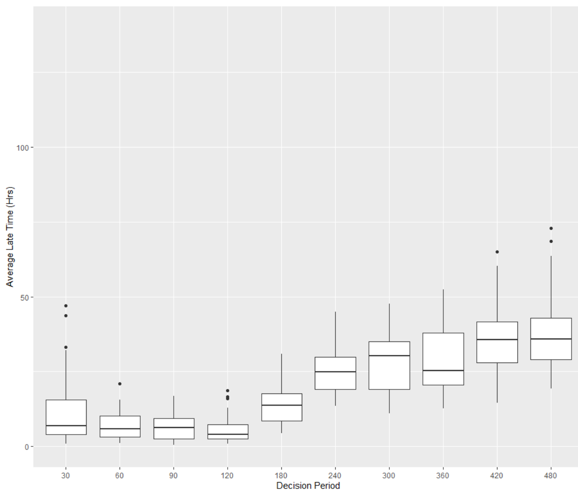
Table 6.11, 6.12 and Figures 6.10 , 6.11 show the impact of the DT even with adjusted fabrication processing times. We fail to reject the null hypothesis that there is a difference in the performance measure means when changing the decision period using the average waiting time performance measure.

Table 6.11. Welch's t-test for Different Arrival Rates using Digital Twin Framework with Adjusted Fabrication Processing Times for Average Waiting Time

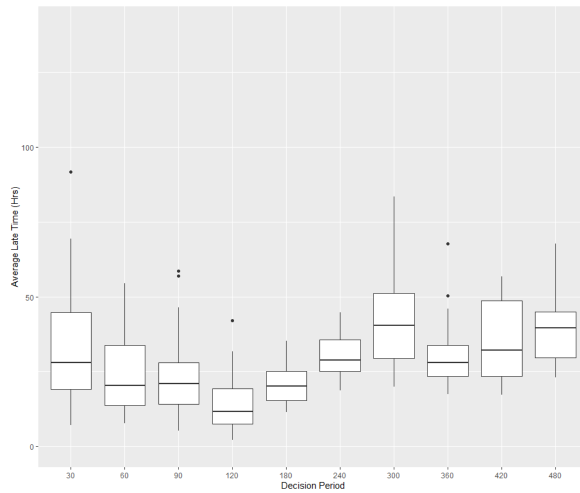
	statistic	num df	denom df	p.value	difference
sss	1.3112	9	118.0534	0.23796	Fail to Reject Null
ssf	1.3474	9	117.9402	0.22015	Fail to Reject Null
sfs	.9321	9	117.9295	0.5001	Fail to Reject Null
sff	1.3619	9	118.012	0.2132	Fail to Reject Null
fss	0.9655	9	117.9952	0.4721	Fail to Reject Null
fsf	1.8928	9	117.8341	.0595	Fail to Reject Null
ffs	3.0336	9	117.7347	0.0027	Fail to Reject Null
fff	1.9534	9	118.0627	0.0509	Fail to Reject Null

Table 6.12. Average Waiting Time Performance Measure For PPR System using DT Framework with Adjusted Fabrication Processing Times for the DT

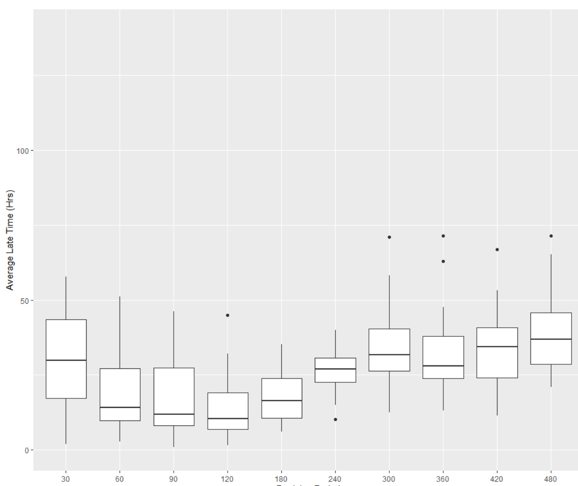
	Decision Period									
S/M/L Part Arrivals	30	60	90	120	180	240	300	360	420	480
S/S/S	6.837	6.498	6.732	7.539	7.168	7.117	5.973	6.798	6.740	6.608
S/S/F	9.630	9.523	9.042	8.964	8.962	8.624	8.359	8.671	8.440	8.660
S/F/S	8.828	8.590	8.313	8.800	9.227	8.948	8.296	8.127	8.530	8.067
S/F/F	10.426	9.517	10.230	10.078	10.664	9.512	9.513	9.946	9.596	9.432
F/S/S	8.590	7.803	8.669	8.310	8.747	8.173	7.816	8.117	7.858	8.459
F/S/F	9.785	9.784	9.994	9.142	9.010	9.084	9.042	9.305	8.671	8.507
F/F/S	9.294	9.099	8.102	8.810	9.335	8.614	8.344	8.113	8.027	7.957
F/F/F	10.409	9.855	9.283	9.369	9.327	9.216	8.826	9.597	8.996	8.880



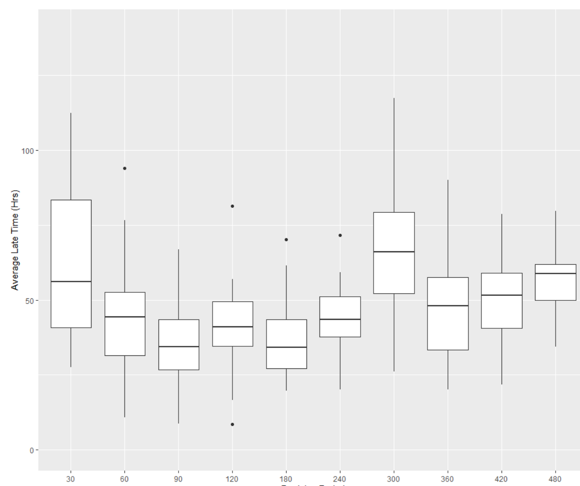
(a) SSS



(b) SSF

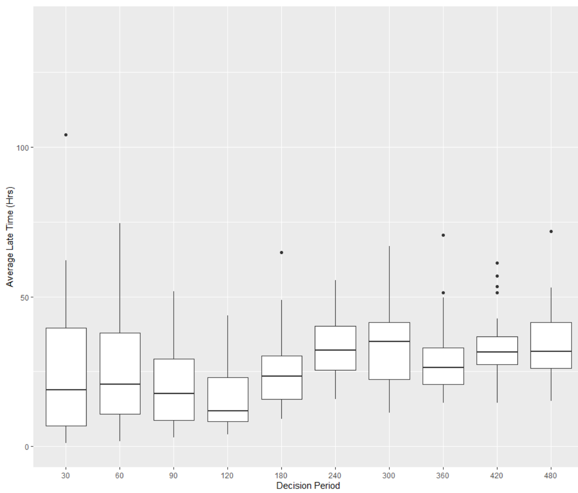


(c) SFS

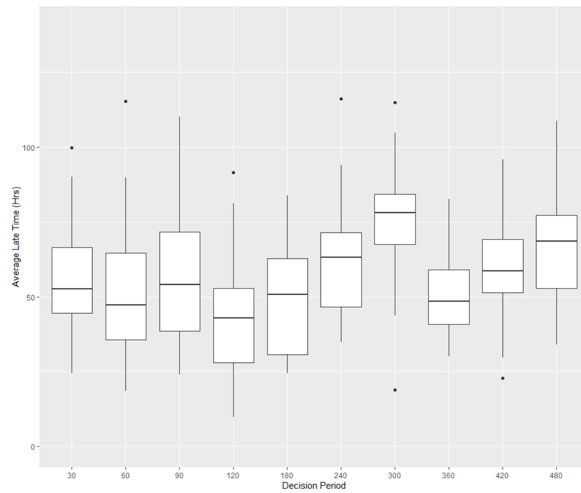


(d) SFF

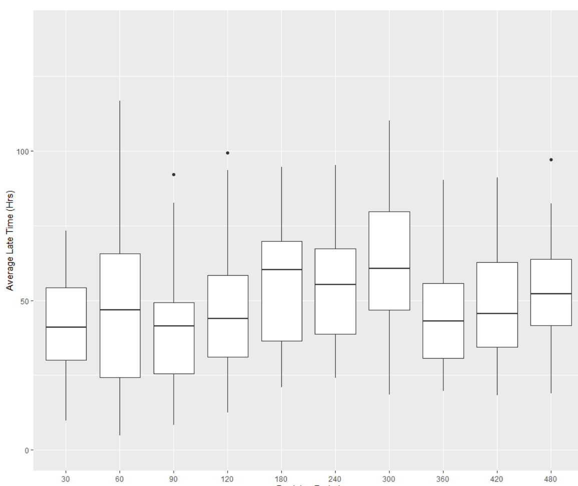
Figure 6.8. Average Late Time Performance and Impact of Update frequency using DT Framework with Adjusted Fabrication Processing Times, part 1



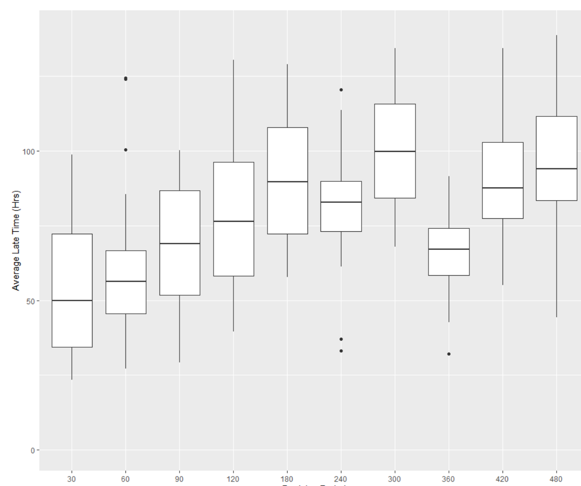
(a) FSS



(b) FSF

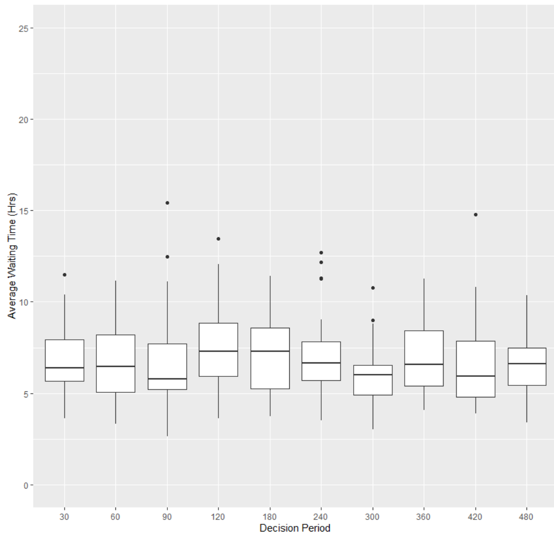


(c) FFS

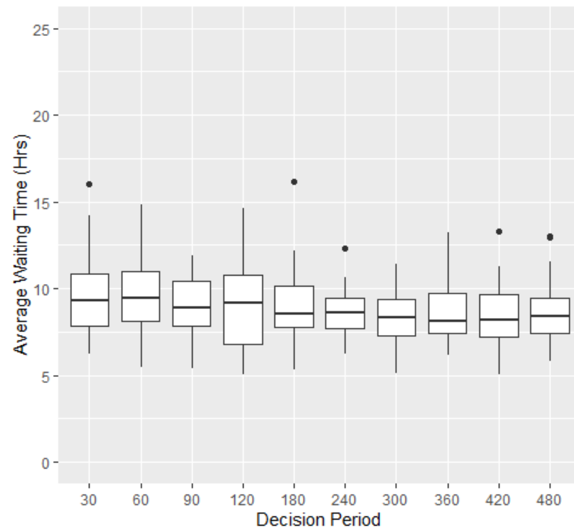


(d) FFF

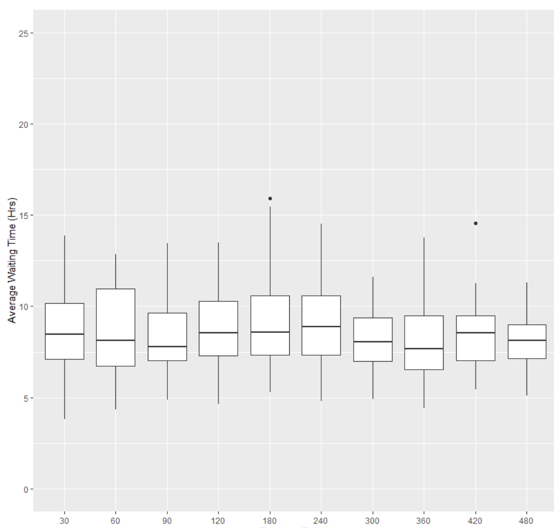
Figure 6.9. Average Late Time Performance and Impact of Update frequency using DT Framework with Adjusted Fabrication Processing Times, part 2



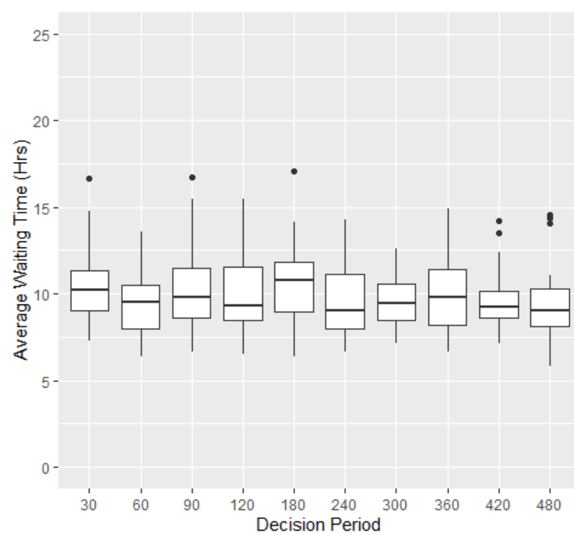
(a) SSS



(b) SSF

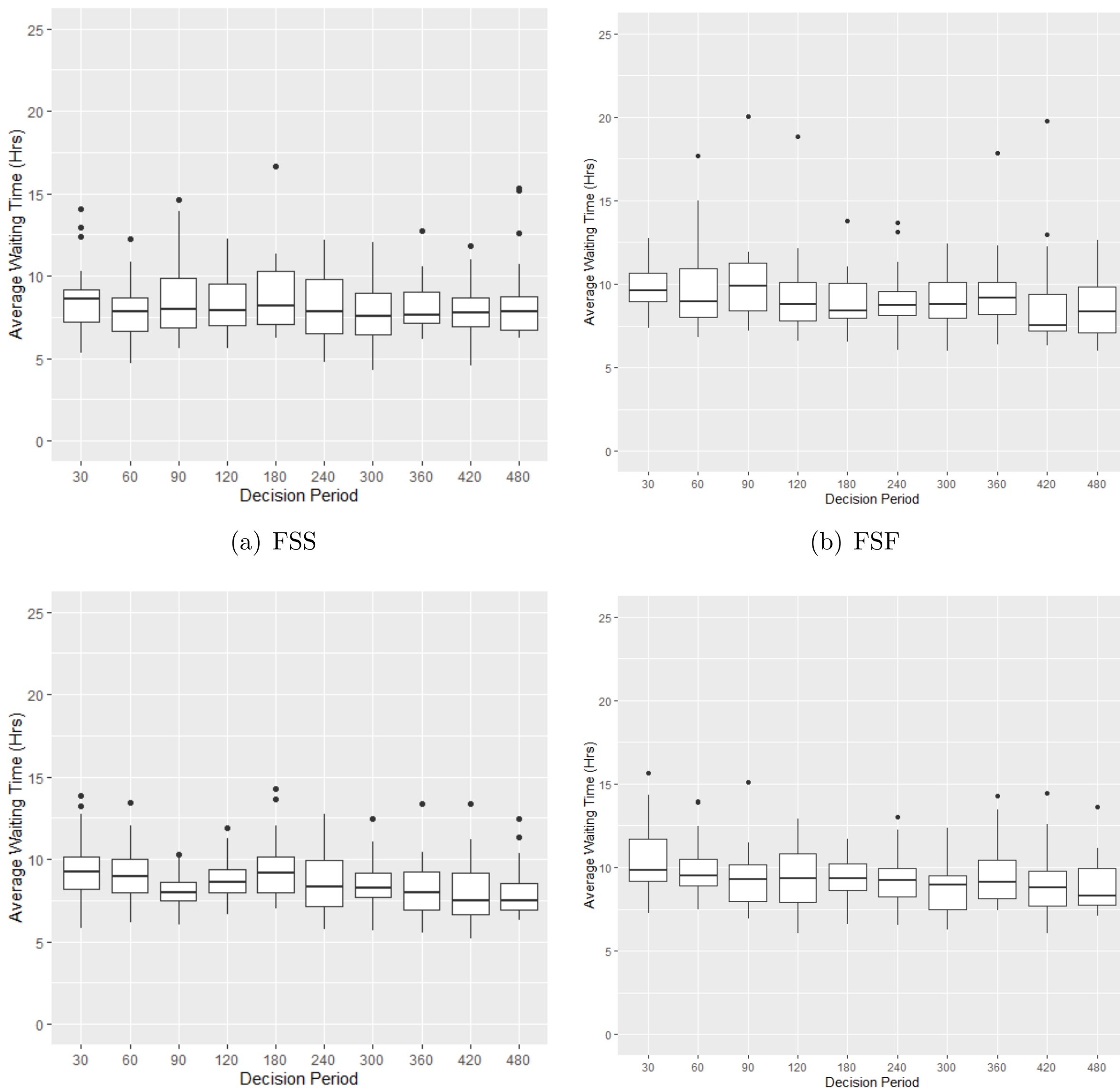


(c) SFS



(d) SFF

Figure 6.10. Average Waiting Time Performance and Impact of Update frequency using DT Framework with Adjusted Fabrication Processing Times, part 1



(a) FSS (b) FSF

(c) FFS (d) FFF

Figure 6.11. Average Waiting Time Performance and Impact of Update frequency using DT Framework with Adjusted Fabrication Processing Times, part 2

Table 6.13. Pairwise Comparison of Decision Periods on Average Late Time Performance Measure Using Bonferroni Method for S/S/S Part Arrivals

Level (a)	Level (b)	p.value	No difference
30	60	1	Not reject
30	90	1	Not reject
30	120	0.570055	Not reject
30	180	1	Not reject
30	240	0.000561	Reject
30	300	3.31E-05	Reject
30	360	8.62E-05	Reject
30	420	3.16E-08	Reject
30	480	3.05E-08	Reject
60	90	1	Not reject
60	120	1	Not reject
60	180	0.000366	Reject
60	240	2.43E-13	Reject
60	300	3.69E-12	Reject
60	360	1.64E-10	Reject
60	420	5.70E-13	Reject
60	480	1.07E-11	Reject
90	120	1	Not reject
90	180	0.000226	Reject
90	240	1.83E-13	Reject
90	300	3.22E-12	Reject
90	360	1.44E-10	Reject
90	420	5.49E-13	Reject
90	480	1.03E-11	Reject
120	180	3.59E-05	Reject
120	240	4.31E-14	Reject
120	300	1.04E-12	Reject
120	360	5.19E-11	Reject
120	420	2.35E-13	Reject
120	480	4.97E-12	Reject
180	240	3.82E-06	Reject
180	300	6.84E-07	Reject
180	360	7.29E-06	Reject
180	420	2.24E-09	Reject
180	480	1.13E-08	Reject
240	300	1	Not reject
240	360	1	Not reject
240	420	0.011009	Reject
240	480	0.004899	Reject
300	360	1	Not reject
300	420	0.629091	Not reject
300	480	0.199761	Not reject
360	420	0.82845	Not reject
360	480	0.264274	Not reject
420	480	1	Not reject

Table 6.14. Pairwise Comparison of Decision Periods on Average Late Time Performance Measure Using Bonferroni Method for S/S/F Part Arrivals

Level (a)	Level (b)	p.value	No difference
30	60	1	Not reject
30	90	1	Not reject
30	120	0.001674	Reject
30	180	0.085659	Not reject
30	240	1	Not reject
30	300	1	Not reject
30	360	1	Not reject
30	420	1	Not reject
30	480	1	Not reject
60	90	1	Not reject
60	120	0.081743	Not reject
60	180	1	Not reject
60	240	0.952178	Not reject
60	300	0.000406	Reject
60	360	1	Not reject
60	420	0.093884	Not reject
60	480	0.000308	Reject
90	120	0.267186	Not reject
90	180	1	Not reject
90	240	0.92106	Not reject
90	300	0.000464	Reject
90	360	1	Not reject
90	420	0.09388	Not reject
90	480	0.000514	Reject
120	180	0.408325	Not reject
120	240	1.02E-07	Reject
120	300	6.65E-09	Reject
120	360	4.93E-06	Reject
120	420	3.89E-07	Reject
120	480	2.20E-11	Reject
180	240	3.34E-05	Reject
180	300	1.29E-06	Reject
180	360	0.002455	Reject
180	420	0.000135	Reject
180	480	6.47E-09	Reject
240	300	0.028647	Reject
240	360	1	Not reject
240	420	1	Not reject
240	480	0.026357	Reject
300	360	0.105172	Not reject
300	420	1	Not reject
300	480	1	Not reject
360	420	1	Not reject
360	480	0.23791	Not reject
420	480	1	Not reject

Table 6.15. Pairwise Comparison of Decision Periods on Average Late Time Performance Measure Using Bonferroni Method for S/F/S Part Arrivals

Level (a)	Level (b)	p.value	No difference
30	60	0.193373	Not reject
30	90	0.047315	Reject
30	120	0.002148	Reject
30	180	0.023175	Reject
30	240	1	Not reject
30	300	1	Not reject
30	360	1	Not reject
30	420	1	Not reject
30	480	0.728466	Not reject
60	90	1	Not reject
60	120	1	Not reject
60	180	1	Not reject
60	240	0.149558	Not reject
60	300	0.000305	Reject
60	360	0.022508	Reject
60	420	0.000488	Reject
60	480	5.90E-06	Reject
90	120	1	Not reject
90	180	1	Not reject
90	240	0.027739	Reject
90	300	6.15E-05	Reject
90	360	0.004626	Reject
90	420	9.71E-05	Reject
90	480	1.28E-06	Reject
120	180	1	Not reject
120	240	6.80E-05	Reject
120	300	4.14E-07	Reject
120	360	6.87E-05	Reject
120	420	3.48E-07	Reject
120	480	7.93E-09	Reject
180	240	0.000775	Reject
180	300	5.57E-06	Reject
180	360	0.000948	Reject
180	420	4.46E-06	Reject
180	480	1.04E-07	Reject
240	300	0.203666	Not reject
240	360	1	Not reject
240	420	0.396885	Not reject
240	480	0.004324	Reject
300	360	1	Not reject
300	420	1	Not reject
300	480	1	Not reject
360	420	1	Not reject
360	480	1	Not reject
420	480	1	Not reject

Table 6.16. Pairwise Comparison of Decision Periods on Average Late Time Performance Measure Using Bonferroni Method for S/F/F Part Arrivals

Level (a)	Level (b)	p.value	No difference
30	60	0.137027	Not reject
30	90	0.000265	Reject
30	120	0.005556	Reject
30	180	0.000653	Reject
30	240	0.022236	Reject
30	300	1	Not reject
30	360	0.298512	Not reject
30	420	1	Not reject
30	480	1	Not reject
60	90	1	Not reject
60	120	1	Not reject
60	180	1	Not reject
60	240	1	Not reject
60	300	0.006576	Reject
60	360	1	Not reject
60	420	1	Not reject
60	480	0.502814	Not reject
90	120	1	Not reject
90	180	1	Not reject
90	240	0.706686	Not reject
90	300	2.77E-06	Reject
90	360	0.310817	Not reject
90	420	0.011539	Reject
90	480	1.63E-05	Reject
120	180	1	Not reject
120	240	1	Not reject
120	300	9.30E-05	Reject
120	360	1	Not reject
120	420	0.500629	Not reject
120	480	0.001848	Reject
180	240	1	Not reject
180	300	7.06E-06	Reject
180	360	0.789457	Not reject
180	420	0.031098	Reject
180	480	2.83E-05	Reject
240	300	0.000414	Reject
240	360	1	Not reject
240	420	1	Not reject
240	480	0.006057	Reject
300	360	0.015557	Reject
300	420	0.074261	Not reject
300	480	0.938348	Not reject
360	420	1	Not reject
360	480	1	Not reject
420	480	1	Not reject

Table 6.17. Pairwise Comparison of Decision Periods on Average Late Time Performance Measure Using Bonferroni Method for F/S/F Part Arrivals

Level (a)	Level (b)	p.value	No difference
30	60	1	Not reject
30	90	1	Not reject
30	120	0.50618	Not reject
30	180	1	Not reject
30	240	1	Not reject
30	300	0.003789	Reject
30	360	1	Not reject
30	420	1	Not reject
30	480	0.761643	Not reject
60	90	1	Not reject
60	120	1	Not reject
60	180	1	Not reject
60	240	1	Not reject
60	300	0.001623	Reject
60	360	1	Not reject
60	420	1	Not reject
60	480	0.291167	Not reject
90	120	0.322547	Not reject
90	180	1	Not reject
90	240	1	Not reject
90	300	0.047132	Reject
90	360	1	Not reject
90	420	1	Not reject
90	480	1	Not reject
120	180	1	Not reject
120	240	0.00498	Reject
120	300	5.33E-07	Reject
120	360	1	Not reject
120	420	0.026979	Reject
120	480	0.00038	Reject
180	240	0.511964	Not reject
180	300	0.000121	Reject
180	360	1	Not reject
180	420	1	Not reject
180	480	0.048667	Reject
240	300	0.369097	Not reject
240	360	0.183987	Not reject
240	420	1	Not reject
240	480	1	Not reject
300	360	1.39E-05	Reject
300	420	0.096443	Not reject
300	480	1	Not reject
360	420	0.888786	Not reject
360	480	0.013386	Reject
420	480	1	Not reject

Table 6.18. Pairwise Comparison of Decision Periods on Average Late Time Performance Measure Using Bonferroni Method for F/F/S Part Arrivals

Level (a)	Level (b)	p.value	No difference
30	60	1	Not reject
30	90	1	Not reject
30	120	1	Not reject
30	180	0.235401	Not reject
30	240	0.67535	Not reject
30	300	0.014394	Reject
30	360	1	Not reject
30	420	1	Not reject
30	480	0.960904	Not reject
60	90	1	Not reject
60	120	1	Not reject
60	180	1	Not reject
60	240	1	Not reject
60	300	0.820984	Not reject
60	360	1	Not reject
60	420	1	Not reject
60	480	1	Not reject
90	120	1	Not reject
90	180	0.359281	Not reject
90	240	0.958057	Not reject
90	300	0.026439	Reject
90	360	1	Not reject
90	420	1	Not reject
90	480	1	Not reject
120	180	1	Not reject
120	240	1	Not reject
120	300	0.535343	Not reject
120	360	1	Not reject
120	420	1	Not reject
120	480	1	Not reject
180	240	1	Not reject
180	300	1	Not reject
180	360	0.876814	Not reject
180	420	1	Not reject
180	480	1	Not reject
240	300	1	Not reject
240	360	1	Not reject
240	420	1	Not reject
240	480	1	Not reject
300	360	0.065348	Not reject
300	420	0.81188	Not reject
300	480	1	Not reject
360	420	1	Not reject
360	480	1	Not reject
420	480	1	Not reject

Table 6.19. Pairwise Comparison of Decision Periods on Average Late Time Performance Measure Using Bonferroni Method for F/F/F Part Arrivals

Level (a)	Level (b)	p.value	No difference
30	60	1	Not reject
30	90	0.100621	Not reject
30	120	0.005418	Reject
30	180	2.38E-07	Reject
30	240	7.34E-05	Reject
30	300	3.82E-10	Reject
30	360	0.602778	Not reject
30	420	4.28E-07	Reject
30	480	4.79E-08	Reject
60	90	1	Not reject
60	120	0.32632	Not reject
60	180	8.98E-05	Reject
60	240	0.016999	Reject
60	300	1.64E-07	Reject
60	360	1	Not reject
60	420	0.000177	Reject
60	480	6.94E-06	Reject
90	120	1	Not reject
90	180	0.091344	Not reject
90	240	1	Not reject
90	300	0.00034	Reject
90	360	1	Not reject
90	420	0.17381	Not reject
90	480	0.004403	Reject
120	180	1	Not reject
120	240	1	Not reject
120	300	0.010376	Reject
120	360	0.918387	Not reject
120	420	1	Not reject
120	480	0.073215	Not reject
180	240	1	Not reject
180	300	1	Not reject
180	360	5.35E-05	Reject
180	420	1	Not reject
180	480	1	Not reject
240	300	0.021674	Reject
240	360	0.024615	Reject
240	420	1	Not reject
240	480	0.18359	Not reject
300	360	5.10E-08	Reject
300	420	1	Not reject
300	480	1	Not reject
360	420	9.67E-05	Reject
360	480	1.01E-05	Reject
420	480	1	Not reject

6.2.4 Discussion

From the experiments conducted in this chapter, the developed Digital Twin Framework empirically shows how the DT impacts performance and in some cases accounts for modeling error.

Average Late Time

Update frequency adjusted by the decision period has an impact on the average late time performance measure. Further research is needed to understand how the update frequency impacts performance when updating too frequently. In majority of the average late time cases, excluding the scenarios where the system may have been overloaded, there is an improvement in performance as decision period increases to around 120 hours, and then performance dropping as decision period continues to increase. A key characteristic for developing and applying a DT is to monitor the update frequency. This implies that there may be necessary research to find optimal update periods when utilizing a DT. Frequent updates may not allow enough time for the DT to utilize the updated information, while, infrequent updates may negatively impact performance depending on model accuracy.

Figure 6.9(c) and 6.8(d) show how the DT can run into issues as the arrival rates increase with adjusted fabrication processing times. Not only does this occur due to the DT being less accurate, with the combination of decision policies, there can be cases where the DT fails make the best decisions. Some solutions could be to run the DT for longer periods but also might imply the limitations of the DT in that there may exist a limit to how much error the DT can compensate for.

Average Waiting Time

Using the DT on average waiting time due to the discrete decision policies had less of an impact on performance. Even though the adjusted fabrication processing times resulted in average waiting times that were extremely inaccurate, the better performing policy was still chosen resulting in a PPR system that performed well. Discrete policies may affect the decision making process for the DT but also highlights that for some performance measures, even with less accuracy, the optimal policies can still be chosen.

6.3 Conclusion

From the experiments conducted in this chapter, the Digital Twin Framework provides an experimental test bed to investigate the characteristics of the the DT. Error in the DT compared to the PPR system impacts performance however, the DT works well under certain combinations of update frequency, error, performance measure, and system load. There are limits to how well the DT responds and is an area that needs further investigation.

Compared to the study of different dominant rules in the work done by Kemppainen [61] we find similarly how there are more drastic differences in policies as the system load increases. Although the problem specifics is different, in the study we find that EDD policy performs better than SPT or FCFS for weighted mean tardiness while SPT performs better than EDD or FCFS for work-in-process holding cost. Although a direct comparison can not be made, the general trends of the policies seen in this thesis match the results seen in Kemppainen's study [61]. The effectiveness of using Digital Twin with these policies regardless of which performance measure is chosen provides insights into the effectiveness and potential impact on real manufacturing systems. Integrating DT is still a real challenge and using real manufacturing plant logic helps bridging the gap that exists due to studies having too simple objectives and unrealistic assumptions

7. CONCLUSION

The 4th Industrial Revolution and the world of modern manufacturing is well under way as the digital and physical worlds begin to integrate. The Digital Twin will have tremendous impact and be an integral part of this transition and the future of manufacturing. There are immense opportunities and challenges that still await and understanding how these new technologies can be used will provide research topics for many years to come. As most real systems are complex in nature, implementing digital twin technologies may have a black box effect where the process of converting inputs to outputs become untraceable. There is a need to simplify and take a deep dive into how the DT is used and the impact it has on real systems. Many publications lack the empirical experiments of using the DT. Incorporating a DT mechanism with real time feedback and decision making can be very expensive which may be a reason for the lack of empirical data. This dissertation investigates creating a framework which allows the investigation of the characteristics of the DT and their impact on performance.

7.1 Summary of Contributions

The main contribution of this dissertation is the idea of creating a framework that allows for the study of the DT and empirically show how its components impact performance. This framework is a methodology that allows academics and practitioners to study the relationship of the real system and its DT. We termed the real system, Pseudo-Physical Real System (PPR) as a way to differentiate the real system compared to its DTs. This framework allows for the separation of the PPR and DT systems based on using different time scales. The Digital Twin Framework provides a means to see the impacts of the DT components along with some of its shortcomings to help design the DT in real manufacturing settings.

First, a simple inventory model was presented using the Digital Twin Framework, taking a classic problem enabled with communication between PPR and DT systems. Although updating the state of the PPR system reduced error in the DT's state approximation, there was less of an effect on the decision variable, order quantity. This is an important finding in that knowing just the state of the system alone may not help make better decisions.

For the simple inventory model, making decisions that impact the cost function require the information exchange to include a factor that measures the difference in states of the DT prediction and PPR system's current state. Results from the simple inventory model highlights the value of exchanging the right information and the necessity of understanding how information impacts your performance. Model accuracy was also explored using the simple inventory model by experimenting how it impacts total cost and update frequency. The main objective of the simple inventory model was to create a foundation to implement the DT Framework and introduce analyzing DT components.

The need to analyze this DT Framework in a more realistic and complex system was highlighted by the committee and was developed to better understand the DT. Based off a fabrication manufacturing plant serving the United State's Midwest, a model was built having drill/punch/paint machines along with 14 fabrication bays. Each of the fabrication bays have their own set of part size fulfillment rules in line with the manufacturing plant. Common scheduling rules were implemented for both queue selection and job selection rules. The DT Framework was developed and included 6 different DTs for the six available policies used by the PPR system. Accuracy of the model was adjusted through the approximation error of the DT's fabrication processing times and showed that the decision period and update frequency statistically has an impact on the performance measure in specific cases. Due to the distinct policies and the information exchanged from DT to PPR, the magnitude of the DT's performance prediction had less impact on the PPR system. More importantly, finding that when the error in the DT leads to choosing less optimal policies, the update frequency can impact the PPR system's performance measure. The results also showed that choosing the right update frequency is an important factor as there exists a trade-off between update frequency, performance measure and information exchange.

The developed Digital Twin Framework provides a means to study the exchange of real time information and the DT concept. This methodology showed the importance of the value of information and its impact on performance measure through a simple inventory model and a more complex manufacturing system. Accuracy of the model can impact the performance measure but also greatly depends on the decision variable. Update frequency in the model does impact the DT and help make better decisions, however, there is a trade-off and finding the right update period plays a critical role in the overall impact of the DT.

7.2 Future Research

This dissertation highlights a method to research the Digital Twin and opens the door to understand the impacts of different decision types in a manufacturing setting. Decisions can have discrete and continuous values which can alter how the DT responds and ultimately its impact on a performance measure. There is a need to build upon this framework to study different scenarios and different types of systems with different decisions and constraints.

Exploring the trade-offs of model accuracy can help further the foundation needed to developing DT models. Modeling complex systems require time to build and even through verification and validation techniques, all models fall short of reality, there is a need to research this gap. Finding how the DT impacts performance based on different types of model errors whether due to accuracy in information or even aggregation techniques will help further solidify best practices.

In both the simple inventory model and the more complex manufacturing system, the Digital Twins time horizon for its prediction is a single period. Although using a single period has shown to provide the ability for the DT to help make cost saving predictions, a potential research area is to study the effects of changing the DT's time horizon. Questions involving how long you run your Digital Twin prior to making a decision is an important factor and research could lead to show further improvements to how the DT is utilized. Cost implications for running a longer simulation is a factor that has to be considered as well.

The manufacturing process may also impact the effectiveness of the DT based on the specific requirements of each system. Research on how different processes benefit differently from using the DT may be an important factor to identifying which systems should pursue implementing DT technologies. Although this thesis showed two different systems and the impact of using the DT, calculating cost savings or return on investment is another area of research that needs to be followed up. Finding systems that respond differently to DT can help show how application can favor those systems with specific types of decisions or processes that react well to the DT. Furthering this research area will ensure DT implementation finds success.

Model fidelity is also an area of research that needs studied further when dealing with Digital Twins. In both the simple inventory model and more complex manufacturing system we approached the problem with the assumption that modeling error could be accounted for through adjustment of parameter distribution errors. However, model fidelity could impact the effectiveness of the DT pertaining to how information is used and the value gained from information exchange between the DT and real system. A DT model that is sparse in detail with less fidelity may use information differently due to the gap in details between the real system and the DT. Research regarding model fidelity and the impact it has on DTs and information exchange will be a critical area to study due to the nature of model fidelity and the gap that exists when modeling complex systems.

This research area also is primed to apply different algorithm and optimization techniques with machine learning to automate how a DT updates and improves its decisions through time. DT concept is one that has many benefits to help systems understand its current state and react to changes in real time. Some of the mentioned areas of research regarding the DT shows how much more is needed and required to truly develop DT models that are able to effect and impact real systems.

7.3 Closing Remarks

Developing this Digital Twin Framework helps better understand the potential impacts and benefits of using DTs in a manufacturing setting. The industrial revolution and the future of manufacturing will be a blend of the physical and digital worlds that can communicate, learn, and make smart decisions. Creating an effective system using these technologies will result in a competitive advantage and be an invaluable asset to any industry. The advancement of cyber-physical systems will allow for smoother integration of DT models resulting in adaptive and more intelligent systems. It is necessary to further this research through empirical studies like this thesis and continue to study the interactions of DT components. Update frequency, value of information, types of decisions and model accuracy are some of the topics in this thesis that provides insights into the characteristics of Digital Twins and their impact on performance. The future of manufacturing is bright and the work in this document plays a role in advancing the technology to make impactful changes that are to come.

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A. APPENDIX

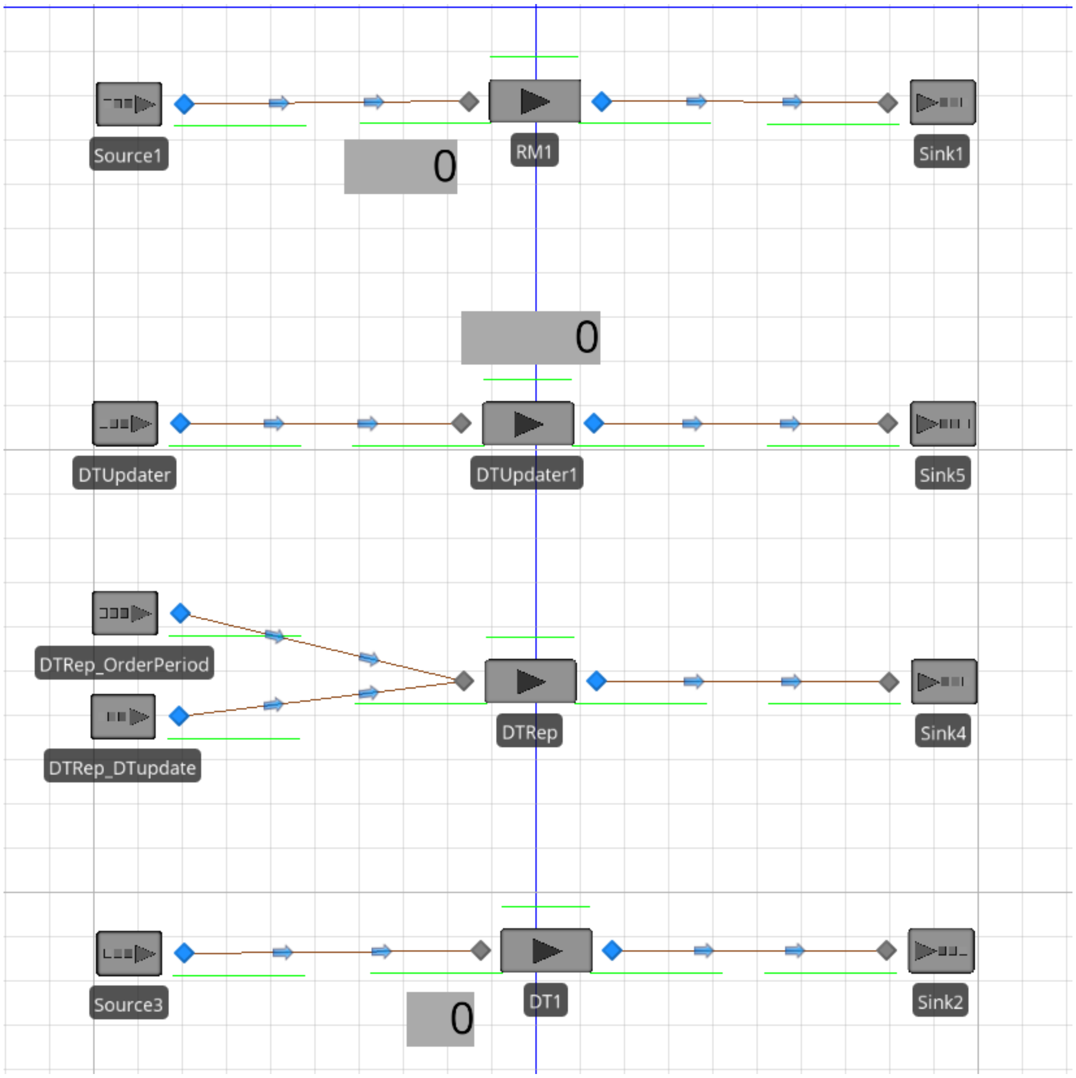

Figure A.1. Digital Twin Framework example using Simio

Table A.1. Simple Inventory Model Total Cost with DT_AvgProcessingTime = 25 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	325	100	100	50	75	25	50
2	300	100	125	75	50	100	25
3	275	100	50	75	75	19.52298	50
4	275	125	125	125	50	25	75
5	275	100	100	25.66262	50	20.24202	25
6	325	125	75	150	125	50	17.64871
7	275	75	50	50	75	50	100
8	250	125	25	50	14.98613	75	100
9	225	150	100	150	25	25	50
10	250	100	75	50	44.57299	10.49855	50
11	275	125	75	50	13.64659	1.748961	25
12	225	125	100	50	7.041852	25	50
13	275	125	75	25	25	75	50
14	300	150	75	50	25	75	25
15	250	125	75	75	75	50	3.288676
16	300	100	100	50	75	25	25
17	225	50	100	25	100	75	25
18	250	125	100	75	125	25	25
19	250	125	75	100	50	50	11.82015
20	225	150	100	25	100	17.17097	25
21	250	125	125	75	25	125	9.304795
22	225	50	100	50	5.12184	50	8.78456
23	250	125	25	75	50	25	25
24	275	150	100	75	75	11.90565	50
25	250	150	100	50	75	50	11.11572
26	250	75	125	25	75	50	100
27	250	150	125	25	75	25	50
28	250	150	25	50	50	50	50.99459
29	250	50	125	25	75	12.91173	50
30	250	100	75	75	2.19047	4.353788	10.11548

Table A.2. Simple Inventory Model Total Cost with DT_AvgProcessingTime = 26 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	200	75	25	75	50	25	75
2	200	75	25	75	50	1.345145	25
3	225	100	100	75	50	25	20.52755
4	200	150	100	75	75	5.054185	50
5	200	75	50	25	100	25	50
6	200	100	50	100	23.10149	50	12.39393
7	250	75	100	25	5.958315	13.55286	75
8	225	100	50	75	9.260481	50	25
9	200	150	75	25.11464	50	50	50
10	200	75	100	25	25	25	100
11	200	125	25	19.29942	19.62558	16.63107	50
12	175	150	25	25	25	25	12.48104
13	225	100	75	100	50	50	50
14	200	75	100	75	75	2.388745	7.626575
15	150	100	50	25	25	25	50
16	200	100	50	25	5.158867	25	34.76592
17	200	100	75	25	25	1.909443	25
18	200	125	75	50	25	100	25
19	225	100	75	25	100	25	100
20	175	125	50	25	50	50	50
21	225	75	75	75	0.887305	0.019736	4.12835
22	125	50	25	1.245952	5.282425	50	25
23	225	100	100	75	25	25	50
24	275	50	25	50	50	100	25
25	200	150	50	25	100	0.222609	25
26	200	100	50	50	100	50	50
27	200	100	25	25	25	25	17.69726
28	200	50	50	25	4.324756	75	50
29	225	125	100	50	25	50	50
30	175	25	125	75	30.47685	75	25

Table A.3. Simple Inventory Model Total Cost with DT_AvgProcessingTime = 27 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	125	50	50	13.55703	40.98642	17.9002	16.32763
2	175	50	50	75	25	25	22.34162
3	150	75	75	50	50	75	75
4	150	50	50	50	12.69511	14.07783	50
5	175	100	50	75	25	32.54954	11.46741
6	175	50	75	22.49389	18.38981	25	25
7	200	50	75	36.52757	100	20.15192	50
8	75	75	25	25	75	75	25
9	125	50	25	25	50	25	14.46361
10	150	100	25	25	75	6.222331	19.74196
11	125	75	20.57022	12.44525	50	25	50
12	175	25	25	17.47762	50	25	0.593169
13	175	75	25	75	18.93238	100	25
14	125	12.24571	50	17.90703	50	25	50
15	125	75	25	9.835362	25.49473	27.36367	50
16	150	100	50	100	25	75	75
17	175	50	12.40083	0.369178	100	50	21.71732
18	150	75	100	25	25	59.4411	50
19	150	25	75	12.05362	75	25	52.2627
20	175	100	25	100	25	1.534065	75
21	150	50	25	100	50	17.6756	0.153838
22	150	75	75	75	25	25	75
23	150	100	100	25	25	50	14.1128
24	150	75	75	100	75	25	25
25	150	75	25	4.321792	24.32815	50	50
26	175	100	75	75	75	25	100
27	125	50	8.517619	75	19.48041	25	1.075061
28	150	75	50	11.56249	14.79954	5.596247	50
29	225	9.155654	22.46822	25	9.175954	19.58777	25
30	150	75	19.38874	25	75	25	50

Table A.4. Simple Inventory Model Total Cost with DT_AvgProcessingTime = 28 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	100	50	75	25	9.839243	15.41609	25
2	125	75	75	25	20.15131	25	25
3	100	23.50153	50	10.1568	15.2417	15.61169	25
4	125	16.21427	25	100	27.63891	50	36.73334
5	100	50	14.43143	50	2.270211	50	50
6	75	18.50697	20.70821	26.24764	10.27825	22.54441	43.85121
7	75	25	25	50	5.784888	17.25326	25.89563
8	100	25	100	25	2.42433	25	1.35268
9	50	25	3.047552	50	18.65301	25	1.311804
10	150	7.022314	3.432793	100	50	75	50
11	100	125	25	25	50	25	24.89671
12	75	20.59128	16.48499	6.359426	17.366	46.50725	25
13	100	50	25	50	50	50	48.12735
14	50	0.747393	25	25	25	2.98614	2.032679
15	125	50	25	1.447247	25	6.946556	14.45087
16	125	50	50	100	25	25	17.4886
17	125	75	75	50	50	3.17497	7.447965
18	100	50	50	16.00476	50	25	18.74666
19	100	125	50	10.92237	25	12.68868	25
20	125	25	50	25	20.93213	25	25
21	75	50	7.926238	19.05399	24.5551	50	25
22	100	75	1.941894	50	9.888203	46.31941	21.24798
23	25	25	50	25	25	50	15.96089
24	75	25	3.249085	10.50947	25	20.09008	19.22085
25	100	50	25	25	25	0.155325	25
26	75	50	50	50	75	50	4.521424
27	100	50	100	23.00909	10.20887	30.22682	6.686555
28	100	75	50	75	25	18.58797	50
29	75	100	50	18.16678	19.42274	14.06017	12.44405
30	75	125	50	25	75	7.351057	7.128673

Table A.5. Simple Inventory Model Total Cost with DT_AvgProcessingTime = 29 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	50	75	25	50	25	25	25
2	100	25	75	75	28.21027	25	25
3	75	20.33722	50	25	50	50	4.03237
4	50	35.08441	22.93171	22.25477	12.81824	75	75
5	75	25	4.652248	22.49623	23.95399	25	50
6	75	75	25	8.928655	25	16.70265	14.46296
7	100	50	8.758933	33.59524	23.7719	38.57678	25
8	50	17.09589	12.0422	10.94534	50	17.90996	25
9	25	50	25	50	25	50	15.23488
10	25	50	30.5846	50	25	13.60373	25
11	50	5.993678	1.997857	16.5293	25	3.214085	37.03578
12	50	50	75	25.85048	30.54087	75	58.06038
13	75	50	35.16013	75	25	34.2655	25
14	100	13.98479	21.25895	20.95646	8.8606	15.84962	9.870845
15	75	12.15382	50	50	16.20444	25	21.87191
16	25	25	7.541668	50	25	25	25
17	75	25	10.81386	50	25	0.920318	7.197002
18	75	23.99812	25	50	75	19.03892	23.4266
19	50	50	25	75	19.63666	14.76334	25
20	75	22.87538	25	50	50	25	100
21	50	27.8138	2.296312	50	25	25	6.94653
22	75	25	30.72571	17.12224	11.02445	12.9135	25.38015
23	100	25	25	25	25	50	50
24	50	19.07134	21.19114	75	15.51496	25	25
25	125	25	11.73224	25	25	4.976639	19.53141
26	100	50	25	7.219416	50	100	12.06332
27	50	22.96298	50	14.96431	24.26644	17.12053	25
28	75	50	25	25	19.56146	25	25
29	50	25	50	9.308346	25	25	16.70423
30	50	25	50	27.08129	25	7.768003	5.238429

Table A.6. Simple Inventory Model Total Cost with DT_AvgProcessingTime = 30 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	24.7727	3.080302	25	50	25	0.111501	25
2	25	25	25	6.612018	50	25	50
3	25	50	25	5.99681	75	50	25
4	24.7194	35.43175	25	29.59163	11.3249	50.45191	13.82799
5	50	12.44519	6.371981	8.385947	0.098532	12.748	22.69428
6	50	25	2.749233	25	23.21201	25	10.63374
7	2.509766	67.64039	17.47568	43.94974	25.47021	50	25
8	0.679061	0.395382	4.338604	15.99262	19.34536	25	16.74732
9	25	25	16.35348	4.197263	48.66205	3.482071	11.25971
10	25	14.54764	25	30.48148	50	9.65383	25
11	16.93448	12.15621	2.077549	29.11672	35.92235	50	6.970961
12	50	25	25	17.95698	17.24767	25	25.44578
13	17.58539	50	25	11.93123	3.499601	9.645884	25
14	75	25	75	5.73655	75	2.03206	50
15	75	6.536951	25	75	50	18.22852	51.86406
16	25	21.03005	50	2.158341	43.27504	50	50
17	50	12.26143	11.59079	14.56774	50	25	4.817347
18	19.97995	25	11.86643	7.6099	24.09129	26.8423	50
19	1.10794	2.704875	10.86165	25	16.0945	70.68241	10.18124
20	25	14.27753	25	40.37514	2.804062	40.81407	25.18624
21	9.595174	4.461152	25	25	22.41894	15.93906	18.78089
22	50	2.911718	37.69905	33.34288	25	3.360399	25
23	8.670416	19.61574	5.548081	25	25	25	21.69472
24	23.31742	50	1.546825	6.152762	50	20.20563	21.44828
25	25	25	19.23471	11.05854	75	50	25
26	25	50	25.26839	75	25	18.45456	25
27	50	15.31081	26.44993	25	25	4.851245	25
28	50	25	26.53428	50	25	15.41675	2.155219
29	75	6.799908	16.16027	48.06695	12.75886	25	14.18374
30	25	0.48399	13.25368	7.245848	8.612071	25	4.894377

Table A.7. Simple Inventory Model Total Cost with DT_AvgProcessingTime = 31 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	23.38449	29.41535	25	25	7.545107	50	25.64859
2	43.47359	25	25	25	33.15611	18.71242	10.18537
3	92.88686	59.22135	6.276846	66.3284	50	22.64538	7.096773
4	35.96197	12.78752	25	25	25	31.43376	5.850044
5	10.40554	50	19.96143	25	25	75	39.19485
6	24.56789	13.61524	25	5.474529	25	26.57209	25
7	1.030049	25	23.06133	25	68.25862	16.4583	60.63704
8	31.44858	10.39803	13.72663	0.10679	24.95399	8.740822	25
9	30.827	20.5309	25	2.064636	45.49891	16.8425	12.50527
10	60.49456	17.93728	23.15892	31.13644	2.736354	22.14816	50
11	46.13294	5.262871	18.2981	58.4093	5.384624	4.49817	25
12	20.65294	12.56839	8.770267	106.2338	23.35219	56.73036	1.101321
13	2.64783	27.60806	42.05216	25.16971	7.748467	10.55565	75
14	26.35002	46.0108	0.458654	49.95203	17.07159	1.091212	50
15	6.102578	35.16269	25	20.43479	7.14624	49.0456	6.9978
16	45.18434	3.838864	14.12852	58.37591	11.06964	2.255135	11.50022
17	15.89303	18.41737	16.95448	22.66672	8.208868	14.90696	25
18	36.58195	14.52523	44.04652	25	20.10836	20.25772	25
19	12.67713	25	50	53.07197	18.60513	81.98026	9.536601
20	17.31861	7.266205	8.600646	9.287087	4.05277	29.64059	44.58964
21	28.40805	9.641664	25	22.39917	75	50	22.61707
22	16.01577	47.03994	50	12.77308	17.97741	25.60823	33.53167
23	12.24365	25	11.64017	22.39995	1.583493	50	11.09357
24	7.648559	28.44597	4.514731	9.492571	50	40.09335	30.04341
25	24.31284	42.55182	25	22.43996	5.320862	33.56253	19.61678
26	19.02967	12.25185	13.04234	16.26073	25	23.86788	13.85787
27	11.36625	16.88309	25	22.89975	14.17006	6.488576	20.23164
28	6.026249	9.235262	74.99329	25	25	19.99674	5.557223
29	31.58177	21.98853	5.61012	39.04033	44.67019	25	5.87603
30	15.22079	22.9304	6.198027	26.9191	9.381247	25	34.78867

Table A.8. Simple Inventory Model Total Cost with DT_AvgProcessingTime = 32 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	71.55922	10.86836	25	21.94109	17.0483	18.20814	15.18825
2	107.372	34.32997	64.18906	32.11601	11.09747	23.99389	8.36087
3	46.61226	20.28104	52.44249	90.64921	29.13079	12.44501	19.37186
4	43.8124	25	6.356757	25	12.21764	50	25
5	55.96763	16.76421	23.7723	31.97527	16.24562	21.33667	17.438
6	57.47659	21.35486	13.89728	43.96415	43.33578	18.39584	0.293528
7	69.79061	14.33508	15.42189	35.82703	7.192118	7.549879	22.21505
8	70.66504	54.11087	6.634321	21.08058	23.80451	50	4.829206
9	34.59715	26.21918	8.306146	36.13449	12.22432	4.940915	22.04464
10	76.50601	71.58745	20.02611	22.15495	3.872012	28.76683	25
11	21.92186	26.55339	25	25	21.77397	4.82923	25
12	82.72312	47.73046	1.353114	46.03919	3.877318	19.54094	68.77868
13	26.70973	1.907423	50	50	25	25	16.50615
14	53.67373	3.753673	1.873317	54.15919	30.21637	36.03419	20.62792
15	46.95447	41.10366	50	2.273959	21.92704	11.22699	25
16	38.17383	39.5819	16.66528	1.013865	25	50	50.99128
17	67.99538	25.77965	0.575892	61.34047	25	4.092797	18.30422
18	61.80579	77.79265	7.702137	25	32.2588	50	21.91567
19	7.044287	25	1.533718	25	5.225614	14.80998	22.13007
20	31.10751	23.70908	0.728079	22.52039	18.08856	39.58396	75
21	65.46188	1.405809	25	23.30051	17.84822	34.65717	3.259034
22	62.25666	0.089195	54.58828	9.66496	50	50	25
23	36.34584	55.26338	27.85549	19.40095	19.38754	50	11.65292
24	85.60025	49.77302	85.34596	15.06192	9.808433	26.21814	25.77295
25	34.86801	38.88338	47.91459	35.4278	21.48602	63.196	25
26	94.28992	33.57241	25	9.803143	8.680947	13.63528	25
27	58.3475	30.29605	36.0933	50	1.879064	25	17.43682
28	43.72349	50.9395	19.90918	20.10014	33.01079	37.31476	12.38407
29	98.7867	25	3.255016	7.851225	11.28096	17.84907	14.65178
30	30.27706	50	50	11.41098	22.56985	12.21032	50.01726

Table A.9. Simple Inventory Model Total Cost with DT_AvgProcessingTime = 33 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	60.94186	109.6879	14.48967	27.68214	50	50	22.40316
2	69.79082	97.14107	54.54436	7.798765	25	90.43724	76.79039
3	78.22305	53.59562	7.598248	23.22081	14.72211	25	5.287347
4	98.72545	43.34047	78.14701	4.491772	10.89635	17.43332	27.5275
5	86.10225	62.17679	9.276081	49.55389	12.97866	67.07901	50
6	77.44449	2.718849	0.475466	19.41792	29.07634	25	11.73341
7	73.02091	12.84052	11.61366	9.823673	26.59719	16.70011	25
8	92.97374	103.3098	62.78545	17.16798	44.37743	25	51.84754
9	98.86146	30.52546	25	21.77282	5.538648	21.13678	10.75456
10	133.0372	60.49454	36.66515	7.160533	75.13172	50	15.24382
11	72.64299	47.41398	32.10478	26.36907	21.75485	2.819418	31.21653
12	102.259	53.59934	49.36955	42.51844	35.72627	26.56029	21.59497
13	104.0009	28.31709	25	50	6.378476	12.10534	10.21046
14	75.55598	62.59482	29.91159	7.089281	6.643295	5.72583	17.13189
15	84.7847	52.67127	56.33472	17.31977	17.87115	15.34448	50
16	141.2261	2.3767	15.26498	23.52967	26.3645	1.018617	14.58363
17	85.54952	22.81181	5.208443	71.61499	28.44891	31.15738	72.26958
18	117.0185	64.18163	23.57376	30.14346	25	15.3274	25
19	109.8719	48.95603	51.47397	9.675045	64.55959	4.339013	25
20	109.8571	15.32124	6.917311	10.12512	7.07314	4.134384	25
21	64.22901	23.51061	28.08925	32.2855	50	9.144919	8.492073
22	81.19011	78.0921	25	14.65592	20.93932	2.240234	27.69427
23	65.13745	122.8001	59.85756	42.70577	21.97306	27.52252	25
24	99.39813	44.2459	25	25.19512	49.07948	27.21864	67.52502
25	52.42494	52.99984	22.11764	41.25708	32.26273	25	17.82175
26	99.9532	13.94461	75.42221	9.265714	36.14614	18.17187	13.16995
27	89.89893	19.5384	40.65236	25	13.37548	13.09674	75.60441
28	133.3424	41.15416	5.691662	7.857989	0.972079	25	8.915368
29	73.22035	19.88542	6.385971	6.012928	12.67066	50	10.49041
30	91.88225	21.36096	15.23269	36.07762	10.76417	50	21.154

Table A.10. Simple Inventory Model Total Cost with DT_AvgProcessing-Time = 34 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	134.5472	24.36144	113.0007	15.18342	55.26938	12.17434	25
2	142.7649	108.42	61.66832	34.20934	21.37631	50	35.91075
3	131.9081	39.22588	59.56916	93.77664	43.68308	21.07973	5.665964
4	123.6098	12.57642	45.23154	75	36.41189	2.97215	10.15438
5	140.898	92.48942	71.384	31.53847	35.66986	7.923677	14.11823
6	122.1929	59.20031	68.49324	122.3316	12.77573	17.12229	92.91311
7	138.2264	51.838	77.7026	6.783746	34.05644	6.380308	10.45293
8	140.6821	26.91085	15.93409	22.30928	21.88926	24.9654	53.20528
9	170.4944	68.30557	39.23552	81.42617	14.40665	5.341484	34.40878
10	100.8022	68.88446	10.05785	69.31506	28.73299	75	25.114
11	146.8135	68.40157	58.08657	36.71993	75.81015	10.0827	45.38475
12	154.2184	65.26068	26.03992	7.69191	25	25	30.54807
13	159.1282	12.46789	49.89479	24.65657	53.21572	30.09352	19.35381
14	162.9639	108.1769	18.09065	34.02604	21.47963	40.64228	75
15	109.8488	104.791	56.6987	11.49429	49.62345	58.73815	19.70856
16	140.2918	64.50277	56.56341	35.15727	40.44156	52.23801	54.68374
17	134.1096	67.08542	88.3203	44.08358	80.74948	66.03011	17.00839
18	140.0625	67.91084	47.13199	25	4.400556	2.243194	54.37077
19	111.025	64.43281	74.98244	13.36806	9.356661	57.82179	26.22683
20	134.0252	81.51551	56.85979	11.13247	36.02159	17.28146	12.24332
21	138.871	75.21357	40.29896	7.939671	41.22592	38.92287	78.48851
22	71.79992	28.34735	69.34591	56.2081	25	42.01132	6.371069
23	110.0807	69.5633	1.52479	25	6.10129	25	14.14193
24	137.1738	37.73449	31.43968	25.40817	44.48043	25	8.032556
25	129.7449	74.98458	88.21425	27.51777	23.35909	92.71813	15.69383
26	143.1474	53.91873	44.88166	22.57675	36.34568	2.184876	23.88903
27	111.5318	105.5751	11.99236	53.5035	23.80102	63.63972	2.616512
28	109.2731	89.35367	30.10191	25.42725	21.60676	25	50
29	149.1857	51.8414	41.32998	67.61091	16.53475	11.7557	25
30	106.3986	60.89925	19.67137	25	30.95074	22.98178	7.650956

Table A.11. Simple Inventory Model Total Cost with DT_AvgProcessing-Time = 35 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	133.5739	95.27256	63.70256	50	23.80271	44.7592	1.943793
2	129.9003	43.30732	59.6092	44.93914	11.66726	8.511499	72.35702
3	165.2437	59.51065	54.29284	34.23156	12.66876	62.37404	51.36398
4	161.034	78.56513	57.74661	28.95504	6.372118	47.32253	6.919661
5	180.2992	71.54562	61.69883	5.030975	43.09581	33.28124	14.69695
6	162.9448	25.19375	62.71119	20.20209	89.95814	25	25
7	166.1637	112.0748	51.70839	17.3976	20.64355	21.08718	14.68235
8	159.0903	71.92556	38.4707	22.02919	21.15367	3.404699	25
9	219.2245	58.91821	29.88234	3.446947	28.68064	34.11092	8.002014
10	184.1298	64.9111	55.11585	37.92314	4.062541	21.1726	13.93434
11	155.8791	67.46377	36.98398	37.8842	11.90594	1.413193	1.383469
12	192.1563	98.24573	109.285	20.20026	75	75	1.092485
13	152.5777	99.14338	25.11009	54.39814	37.39966	22.22007	45.48312
14	149.0167	39.77017	64.94883	43.32514	51.66063	0.10924	13.24784
15	145.8259	67.34254	6.482508	28.915	40.91921	3.141345	4.198915
16	153.1221	120.9869	85.6592	4.080767	43.26124	50	23.00675
17	144.1471	71.6536	50.14637	40.99134	64.03318	4.779423	38.99355
18	162.2692	48.15103	4.178164	28.72468	50.25915	4.567349	23.01595
19	164.1562	96.00066	68.94397	54.45613	50.25927	1.300031	35.42314
20	187.7104	16.35123	12.08614	11.97375	29.9055	14.47783	25
21	194.233	61.06399	64.79977	118.2462	9.64637	64.99933	90.62604
22	183.3282	66.67479	38.31953	41.57302	9.309226	2.958954	11.2432
23	139.4453	66.54375	83.57491	78.0075	70.06607	14.63805	25
24	163.1984	112.5605	25.65375	59.36133	17.93478	12.58344	16.82703
25	103.6467	111.5211	94.21894	14.31834	25	36.42885	1.927116
26	109.9642	96.15361	61.01556	17.79406	63.02019	44.4614	35.04849
27	156.1495	60.06591	21.1509	64.2909	38.72903	26.7421	25.68841
28	158.6226	77.18369	56.09492	10.83258	31.85387	25	16.01871
29	176.2605	45.21214	64.98951	11.54167	26.56646	27.98427	22.49724
30	147.1249	65.9652	2.613194	8.731744	24.46496	17.13919	25

Table A.12. Simple Inventory Model Total Cost with DT_AvgProcessing-Time = 36 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	182.1381	106.5755	103.6285	59.40309	50	15.58007	25
2	157.3778	105.0494	65.5714	95.65442	40.76611	94.59658	17.01315
3	169.9062	67.39486	56.05686	38.80826	11.74886	6.702713	46.94139
4	217.9565	87.25272	57.80268	32.59188	8.900833	24.21967	41.92149
5	206.6544	50.24728	78.10933	78.74235	18.55119	55.33766	60.58943
6	176.6063	114.02	32.84119	46.97712	25	17.9834	25
7	236.2092	97.53936	75.20567	48.5023	31.83263	3.792508	48.33747
8	209.5685	64.01922	39.91478	27.75375	28.9246	25	72.09452
9	215.5353	120.0146	17.20135	0.834051	25	1.714094	39.07174
10	215.0162	141.9963	46.75423	14.85044	3.834946	23.26821	34.87819
11	137.461	81.0464	93.0199	75.88899	74.90554	23.25246	99.53108
12	202.9382	109.8058	73.01745	25	49.9849	12.91377	13.00592
13	190.3729	123.4617	21.22365	52.34102	24.38955	16.47743	25
14	188.5671	79.32385	25.04978	110.6975	2.747657	72.54442	58.1903
15	156.2908	99.11353	107.3151	50.58104	18.38982	40.20298	18.67185
16	199.1694	93.66821	110.1812	45.08648	57.39457	76.87676	38.0346
17	154.3747	97.63633	35.48834	3.531516	10.27207	48.92646	14.72307
18	175.3474	42.22531	42.70638	33.13155	14.52955	7.483371	27.91499
19	154.7704	58.65114	56.30172	25.52951	15.62559	4.147204	5.30511
20	165.4141	110.3003	43.99006	66.20469	62.9936	13.15649	21.80793
21	182.6181	105.9351	58.96887	19.25386	70.84775	24.47668	12.3636
22	219.7415	80.16466	48.74319	42.60606	22.14284	28.0187	11.49655
23	218.4775	78.15304	74.51767	18.2305	35.94606	51.75106	51.45236
24	196.809	82.32631	41.55137	8.035072	41.35046	67.69693	29.67674
25	150.4581	54.84009	25	33.40637	10.64591	8.702745	25
26	164.8342	97.29476	95.56035	59.52458	39.74004	13.25793	22.30475
27	187.9279	73.88674	73.48379	54.46584	38.74079	39.02384	44.80436
28	200.191	95.12385	102.8196	29.35149	3.524042	25	15.05986
29	161.5251	36.87589	68.40056	42.67881	31.73013	5.039676	25
30	200.2688	94.6198	73.7335	19.07771	30.22949	23.37025	48.996

Table A.13. Simple Inventory Model Total Cost with DT_AvgProcessing-Time = 37 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	219.5682	131.5969	46.01783	33.22106	51.60513	62.5647	11.52709
2	185.0889	57.53228	25.63101	16.89939	9.596772	8.570468	18.72888
3	162.7386	79.54586	72.46286	30.22295	24.80497	5.612246	70.59665
4	236.7522	72.77667	38.8151	38.39481	11.90649	25	21.81372
5	243.3226	78.9359	114.4015	32.39961	57.29398	12.19309	26.86769
6	223.0015	105.5618	36.80396	41.19687	47.16938	8.756039	25
7	248.5727	42.92874	84.44873	100.5816	50	20.82003	50
8	248.2523	85.50972	100.5124	62.02865	18.52843	2.95146	17.64572
9	197.6162	90.1694	26.57621	1.142494	50	26.68806	1.156716
10	180.556	96.33987	31.63602	56.27718	49.25037	5.57787	22.553
11	221.3308	98.15084	44.83245	60.97571	76.11613	7.437365	19.16681
12	217.0629	100.8086	51.5065	34.2259	68.16603	81.92836	16.28538
13	208.2337	35.36101	10.69129	43.88061	5.574456	44.77616	0.002163
14	186.3746	80.73794	70.27808	31.1544	25	19.95485	90.08019
15	230.683	103.1352	129.9707	37.90457	96.55342	78.51286	46.97983
16	217.2076	25.50959	102.4866	47.62533	54.66555	26.04843	16.96818
17	174.7498	93.66117	32.42307	30.82224	2.94136	6.317496	9.16487
18	188.4099	81.25067	47.84835	86.25259	16.64334	15.73972	50
19	184.7796	126.1828	75.92526	47.35064	31.14475	25	4.278764
20	178.9533	75.98481	17.03948	20.71272	14.33216	43.74672	22.12482
21	225.1001	77.7079	55.08882	68.09769	13.92732	15.54447	9.196831
22	189.7497	71.0435	101.8305	104.3392	20.17584	7.015123	1.151855
23	183.0444	115.538	98.2003	62.69218	24.24918	30.85741	24.4901
24	225.6095	115.9888	32.54699	71.65455	2.643661	58.37803	15.03694
25	213.6809	122.4544	50.7509	3.232148	24.34075	50.19692	33.32481
26	206.9774	58.47578	33.74861	11.2032	52.14872	77.17505	72.41341
27	221.734	107.7158	76.96619	25	60.94534	10.85221	87.41118
28	188.3672	124.252	30.77691	16.05535	37.58929	25	50.16983
29	203.0748	73.71558	3.761395	30.10923	93.92645	3.223807	40.84406
30	203.483	84.7914	49.08566	24.00007	54.34797	24.23032	16.44089

Table A.14. Simple Inventory Model Total Cost with DT_AvgProcessing-Time = 38 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	282.8279	99.34245	84.49154	71.62559	15.19993	12.7986	41.72378
2	237.2895	93.81837	37.46364	42.25811	65.26719	5.239048	56.86952
3	245.558	153.3158	122.9503	7.777772	25	57.95572	1.790338
4	242.0703	121.0694	4.550865	55.21071	25.20834	44.67535	5.575728
5	230.4727	112.7121	91.74035	24.07022	56.97702	9.479081	78.05523
6	232.517	70.2903	84.83352	25	29.53442	60.33834	25
7	252.7883	86.31876	31.90743	47.63181	37.07963	25.6916	16.94646
8	256.3008	105.5529	69.21808	95.22809	33.66299	21.00327	2.164379
9	287.6238	107.2814	158.4878	8.855311	25	16.87792	35.05679
10	240.5245	98.0204	13.79203	6.864236	38.42132	14.88065	57.5383
11	231.8562	142.9126	83.8012	85.23818	26.54106	50.82991	14.27059
12	259.1028	152.1919	91.54424	82.35096	4.832474	145.0435	38.41565
13	208.3856	93.36227	52.0316	12.09704	2.080841	27.82744	40.28545
14	244.704	105.2477	52.88704	60.40019	14.13506	8.045792	10.54711
15	309.4674	135.8028	102.3196	103.2251	16.00014	25	18.5179
16	210.1995	107.2937	63.88799	7.923454	41.60012	25	22.67048
17	225.3272	140.6754	80.07846	53.11722	27.25285	4.258998	23.36296
18	258.8694	102.9404	90.09397	5.469856	42.42408	30.00977	48.40315
19	211.4828	117.0458	43.9273	57.70578	101.8481	48.34026	39.23404
20	232.2585	75.36739	89.28469	9.579783	61.51417	4.454253	5.550837
21	283.1744	53.16866	136.4825	77.72909	36.05813	44.69688	19.59691
22	262.5515	47.65394	54.29435	86.94744	14.33543	1.655577	1.810209
23	182.8126	115.3163	44.66802	5.16547	65.8565	42.12949	18.86665
24	246.5316	127.5929	40.90506	4.323606	27.42498	15.40672	49.46811
25	202.0843	66.63608	89.36709	45.69277	30.38217	5.288283	55.4518
26	212.2898	136.178	102.3923	44.67511	9.712735	51.94208	3.968295
27	233.6049	141.0708	123.5914	79.24324	21.52909	8.463086	0.182525
28	232.6298	136.4578	69.22438	86.59104	5.464497	29.75025	21.50047
29	223.3927	97.08603	54.0619	48.25745	66.47395	22.14809	1.30176
30	248.492	95.51578	68.73811	45.04033	19.21388	31.40996	34.41331

Table A.15. Simple Inventory Model Total Cost with DT_AvgProcessingTime = 39 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	279.5423	111.4998	118.9118	100.8426	72.46588	61.52553	31.07062
2	226.0296	127.9106	66.8594	94.2557	25	79.38086	15.52619
3	292.6157	66.55059	55.72396	49.44089	9.833439	56.60504	14.69781
4	246.3073	128.9612	51.26322	78.90642	59.64662	75.50083	32.58132
5	290.4114	96.14424	47.76978	33.32459	119.6198	56.23522	66.90636
6	292.1617	170.2532	118.342	77.77916	42.66735	37.08821	99.25538
7	280.1652	103.4311	75.72793	74.88909	85.22057	84.12659	25.86355
8	253.5688	85.44354	55.34231	73.72932	43.89537	114.8398	24.45424
9	277.4297	95.98607	92.67466	78.11551	56.55031	17.26925	44.626
10	229.9872	154.186	82.69291	8.244871	53.61706	79.97728	33.41929
11	239.8227	115.557	80.5131	32.36887	32.65338	36.15797	28.16766
12	242.0496	76.29809	83.21018	20.10445	83.54291	16.20643	22.19621
13	275.2492	36.06626	71.41618	67.14765	25	52.56381	1.53346
14	279.627	110.0581	106.0107	3.780397	21.29084	36.83146	3.318693
15	271.5404	121.2354	88.18295	44.12004	25.12796	69.40351	62.98212
16	256.6094	135.129	88.94653	51.19676	95.65204	12.09631	25.06078
17	286.1763	155.3988	80.64094	33.9268	33.14947	25	14.63573
18	252.1592	73.85728	102.4724	76.66006	42.65401	24.17765	48.05253
19	270.2616	147.9744	61.69533	50.90635	6.192076	35.3655	66.72205
20	226.0401	119.0392	61.60086	19.89793	17.20572	33.83142	56.12661
21	301.4935	137.5149	91.68034	12.02835	50	29.9582	53.07831
22	292.1428	123.2233	121.0903	92.14082	22.26889	43.93985	16.47405
23	271.2795	127.2144	76.54559	34.70987	35.11679	24.78223	43.67892
24	301.1486	107.8901	25.9296	53.9065	10.76709	111.0102	25
25	313.411	146.2588	179.865	56.94557	51.80846	67.7767	74.36348
26	295.8657	99.83264	157.6844	27.64378	77.60009	57.49095	28.46188
27	259.8037	129.0451	60.55136	71.64931	52.03541	29.18569	21.80871
28	262.0966	86.68307	137.8103	13.87189	3.003264	17.45374	34.39934
29	274.2109	127.6005	44.43391	63.15866	46.04313	20.24055	18.65209
30	210.8485	124.2447	23.9485	39.13538	16.74623	25	36.62302

Table A.16. Simple Inventory Model Total Cost with DT_AvgProcessing-Time = 40 minutes

	n, Update Frequency						
Replication	1	2	3	4	5	6	7
1	317.5846	122.1955	90.06707	52.28087	59.09467	42.75147	45.31005
2	306.0117	156.0923	129.7879	13.95029	11.61034	78.23343	6.114127
3	306.7421	145.5571	72.71123	101.0452	79.1105	67.7737	25
4	286.7403	164.0576	71.43583	13.2152	125.7216	8.368202	46.92163
5	267.6115	175.3907	97.86058	42.93656	133.4023	48.45879	109.56
6	230.0401	111.6519	81.34164	63.30106	29.72652	83.60926	38.53245
7	287.5761	158.6225	72.98581	45.52768	108.1086	45.74548	10.52871
8	311.3263	124.8196	107.0526	49.3889	59.89229	25	35.94865
9	344.4752	187.0173	142.9944	112.6333	83.41532	48.35075	4.741992
10	269.1769	115.8448	113.3438	4.769749	7.556476	40.64314	31.97892
11	292.4407	148.8524	77.88265	37.11457	49.91512	43.12367	18.00055
12	279.9271	139.2551	78.66102	65.8508	57.10637	30.8739	50.41781
13	306.0228	147.2252	75.04252	31.36658	22.59976	65.60609	31.41175
14	276.6566	152.1341	71.63362	44.09561	13.86649	13.8911	56.91519
15	278.2889	155.6655	115.9085	122.7582	88.56743	39.89085	53.8894
16	288.5114	169.6633	64.0331	109.4301	40.97552	99.61175	10.32718
17	309.8511	145.9964	67.8096	101.1495	99.23184	61.03121	44.13539
18	300.1978	142.6436	53.39393	110.8603	48.21051	64.548	63.0602
19	292.2125	122.1297	83.38183	74.52491	15.92517	20.79069	11.90823
20	288.3544	149.7398	112.8277	79.65104	58.16432	43.16871	40.07683
21	301.1769	187.5163	98.25506	96.72045	41.77747	19.58571	39.63138
22	271.7892	149.7791	90.49902	120.5687	13.52029	36.77217	11.29789
23	273.9765	67.89606	80.75473	126.9826	54.9401	43.69888	32.04505
24	309.4515	96.01539	136.2404	89.89787	18.8864	64.35967	25
25	280.7475	95.16834	78.94619	21.66318	43.63739	55.50484	37.16194
26	299.3995	131.5398	149.5837	46.37684	20.94357	18.20685	24.77434
27	283.4923	141.5699	51.08468	42.79791	41.00935	37.90696	66.3942
28	267.9917	211.1299	95.58163	92.88947	94.25051	129.7293	123.2584
29	311.9073	106.9853	64.20985	17.81404	40.36433	18.22001	17.44114
30	271.8444	100.3636	79.34812	81.1985	28.58689	37.08448	61.47274

Table A.17. Complex Manufacturing System Average Late Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for SSS Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	5.587862	20.10957	3.563586	7.871626	13.50087	8.516364	5.624869
2	11.0138	7.785878	5.964366	4.493826	13.88877	18.47221	10.11134
3	15.84322	7.81554	7.421999	6.676936	8.469513	12.7957	3.713488
4	27.26478	12.48505	4.950406	7.183422	17.47459	9.263528	11.45455
5	15.41561	7.129421	7.166619	5.718117	12.94442	10.70611	6.342479
6	9.851081	13.98412	3.496531	11.25172	10.02062	9.604199	4.650096
7	19.65739	10.9544	6.84214	6.736939	15.83081	10.53004	7.215365
8	16.92626	5.306234	5.115188	3.780715	12.84179	9.333996	8.369185
9	18.89694	21.58848	5.910291	12.64311	9.37759	13.59886	7.670449
10	9.87626	8.219481	5.290379	10.3886	6.946248	6.967991	6.492563
11	7.777773	6.033772	5.401698	6.714574	10.86262	13.05917	3.303923
12	7.663284	8.460348	6.194825	4.21065	26.85593	7.038587	8.662809
13	7.806358	16.28813	8.351744	10.32442	24.92875	8.136652	5.731214
14	9.393058	11.78276	5.532734	9.956886	8.689621	10.59379	4.911362
15	8.419613	5.961769	7.179845	5.067193	11.96602	26.77173	4.273179
16	9.354864	5.095102	6.14627	10.48712	23.64154	8.188603	5.063101
17	14.88283	8.676112	6.519534	11.58661	17.82028	21.2445	4.769126
18	9.907577	6.302977	5.859517	6.102469	7.539272	7.723667	11.48403
19	14.86167	8.83211	9.095565	6.317086	21.93418	9.256014	6.687562
20	13.83036	5.189746	4.113359	3.196653	18.24462	9.123056	5.667249
21	6.66514	11.48134	8.753027	6.144157	8.830228	16.91258	7.023469
22	10.22324	27.31748	6.312944	5.94396	8.890589	5.188939	8.006172
23	9.238548	12.40227	6.448438	6.315263	6.525283	15.11351	10.02835
24	6.484938	4.863072	7.365815	11.8244	13.63437	8.502556	5.0106
25	8.014334	6.674729	12.97775	7.848222	17.08046	21.8803	3.726966
26	9.782406	4.854793	4.649518	4.410655	13.56529	5.988483	10.97782
27	16.44616	7.576517	7.246506	10.69898	20.1826	7.634256	8.225927
28	8.283122	12.24561	5.086453	5.377838	11.84719	17.50891	9.118386
29	9.336931	7.562128	5.833044	7.488572	5.183078	15.87471	15.07493
30	17.03276	28.66298	5.182316	5.165853	16.60153	9.982315	11.97064

Table A.18. Complex Manufacturing System Average Late Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for SSF Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	12.63412	60.38498	65.32822	57.80497	4.075389	30.01038	11.55945
2	15.17964	39.83812	40.18409	73.97517	5.970904	36.86632	17.46926
3	14.5909	16.56548	86.94146	72.96332	18.85948	9.42935	32.66375
4	4.775273	21.85887	89.28482	60.43685	22.25916	16.75953	9.157717
5	14.43502	13.90752	53.24294	74.04082	13.2022	32.00643	9.56237
6	22.89585	35.53642	65.81341	67.79409	18.06094	18.6205	26.26442
7	25.2757	22.92475	34.32522	70.16477	10.96468	20.23169	10.92856
8	18.87776	15.83672	63.81807	119.78	23.26733	16.61321	23.65521
9	12.98554	29.61003	61.57612	51.31446	18.58681	9.391585	21.38196
10	37.46103	18.44014	69.32949	37.81889	40.20579	14.49544	3.011035
11	19.12482	16.74945	68.28004	46.85411	12.23447	23.14502	14.83039
12	20.17534	10.13948	52.27011	68.3486	30.90908	38.4415	28.53662
13	8.718807	10.14653	48.79919	43.18619	26.13974	14.7287	10.48353
14	8.896166	7.595093	74.93102	61.56962	12.29213	22.91375	12.09249
15	6.838474	13.76895	56.92617	87.12582	21.40601	6.606697	23.89657
16	12.08622	25.51607	94.82744	53.93561	16.77174	9.818322	2.47853
17	27.15542	9.619756	57.23512	57.85359	39.01193	24.66503	15.5002
18	16.76209	10.18758	53.73291	98.38668	17.43169	21.46773	26.675
19	11.2376	15.10463	54.01699	47.48727	20.6277	9.659604	18.18763
20	10.87104	39.82156	88.96452	76.37011	17.27186	10.63227	9.975209
21	16.71382	31.32212	55.9012	103.9599	20.47495	18.10734	12.14011
22	12.16572	28.10325	62.29063	56.02586	9.660608	22.59085	28.47478
23	10.01564	2.798888	56.34553	67.58136	6.724705	7.140292	16.20659
24	22.36743	40.43155	74.2349	37.17143	14.1431	6.416682	10.49477
25	38.90119	24.3521	61.58918	60.15572	18.8301	24.57651	26.75173
26	11.94489	15.35307	76.22501	79.26557	10.04869	11.03951	13.61124
27	28.30436	31.01921	42.55173	63.68269	17.85721	19.86116	35.4805
28	12.70666	20.62312	84.23659	78.23613	20.9442	4.672107	23.66991
29	12.70728	23.43003	80.6807	63.87713	12.13182	15.47585	15.95984
30	16.01056	21.95486	43.33977	83.24345	20.16698	4.960487	19.30888

Table A.19. Complex Manufacturing System Average Late Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for SFS Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	8.985777	12.41999	75.18134	71.77243	11.32544	7.215562	24.84959
2	6.340179	31.6566	64.52363	57.20541	9.983863	38.12966	14.73671
3	7.037889	16.87306	63.26326	37.3746	12.24212	16.86998	15.0722
4	21.43031	16.96782	52.63731	78.73471	21.04536	12.73065	10.9502
5	18.19514	20.16565	52.87865	74.18945	9.702397	8.820068	11.84518
6	31.93469	27.13969	43.44905	68.80569	5.10094	11.04513	20.01013
7	18.83584	16.02957	48.39051	54.22202	19.28141	27.96035	4.363358
8	16.79321	7.743964	76.16307	36.9107	10.10069	9.624081	1.633108
9	4.995042	36.59814	38.53017	120.8006	4.843952	17.20637	9.617777
10	11.38394	5.938472	51.47284	51.29629	16.79945	24.06894	4.136382
11	16.16181	16.22732	63.57884	68.42341	17.04392	11.25667	24.54005
12	4.508342	15.33068	64.71657	77.53901	13.02432	18.6518	11.78144
13	6.906546	15.71681	104.9085	84.47434	22.62143	17.4822	15.48947
14	11.32822	3.33565	27.47176	71.04113	16.47201	21.98233	15.31737
15	6.364236	7.42748	107.8291	55.23626	17.98825	6.339636	22.78192
16	34.4541	3.518499	67.78526	67.18588	9.558921	22.71962	7.629323
17	13.2493	34.06642	41.90971	105.8342	8.133078	6.549988	10.31084
18	11.25752	12.52694	68.65576	45.2324	15.73273	4.453112	18.02656
19	10.84464	7.56903	64.83845	42.22007	2.277171	16.32866	9.223
20	11.00384	14.40731	65.3574	67.27932	18.12356	10.59769	20.27702
21	18.13675	12.52662	67.6391	37.04787	3.059123	29.53095	13.83525
22	13.94909	22.36064	43.20814	70.53994	5.848031	15.13417	5.982843
23	15.70951	10.99648	53.50945	79.94265	2.110732	9.192932	5.32378
24	20.47453	7.637508	66.18461	55.19888	6.438922	14.3728	8.3574
25	19.74937	20.63517	39.38763	72.72725	4.633699	4.719297	18.76785
26	13.36283	2.938067	60.08991	46.32301	20.51432	17.79622	11.64507
27	17.17565	12.77311	70.31924	48.60903	9.688737	7.098795	3.38085
28	7.465638	12.83013	90.44548	59.99109	18.49337	19.49988	25.9532
29	7.90098	4.792086	56.13878	31.8529	15.00364	4.886156	2.57508
30	8.328122	14.38014	56.66433	60.18979	21.91924	11.9929	6.772747

Table A.20. Complex Manufacturing System Average Late Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for SFF Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	24.40193	15.3968	67.08923	50.53821	51.59264	24.02573	46.04829
2	45.92282	24.66801	69.70065	73.49629	37.44703	30.6727	46.49415
3	37.68095	35.59469	65.85901	57.38674	22.31481	30.52854	31.06225
4	36.64558	23.63989	68.37832	85.67653	36.17738	22.72547	24.97951
5	9.915781	65.59701	59.44232	95.32175	20.19167	29.28717	35.50457
6	25.97269	51.63261	51.74865	78.84855	26.21227	30.33596	17.75777
7	27.0375	32.31243	69.42849	103.16	42.30686	11.35876	31.35858
8	23.4607	36.73973	66.25813	71.90069	21.12801	34.33261	26.11143
9	23.66251	30.15133	60.70737	83.1754	34.47597	15.96841	32.24023
10	48.39253	16.02339	57.57643	69.54303	42.16296	31.96597	42.21661
11	38.33786	17.79779	47.37372	48.35043	19.78187	34.59443	51.49844
12	33.83237	33.07137	89.96996	57.59615	18.74146	12.38744	29.53599
13	44.96367	36.85591	59.00744	77.22816	37.58729	18.16033	28.15031
14	34.76927	33.42934	69.2926	59.6722	32.7465	40.35619	30.49554
15	33.04108	14.44246	79.34463	81.1594	41.58042	24.19536	27.19842
16	15.78052	36.58498	56.24152	52.94114	22.85841	59.72892	47.05667
17	25.97276	37.2609	73.88987	104.87	41.68086	47.17266	41.17475
18	39.10768	43.45996	65.65694	82.39576	40.83894	29.35939	33.02608
19	19.3921	30.37639	76.27829	84.29523	33.51482	52.67089	34.97288
20	24.5732	31.49751	57.21471	82.71679	15.81726	19.35779	21.51037
21	38.88199	27.91076	90.1432	78.98042	34.45835	33.60784	14.4067
22	28.9102	36.78013	113.3215	80.03852	28.06532	16.30572	31.41189
23	39.81404	23.978	112.9212	79.37624	32.09604	32.80442	23.31168
24	23.65737	45.64455	63.42021	103.8314	20.42162	46.29189	32.91849
25	37.98973	38.18286	67.75793	107.7907	21.36896	37.76806	26.13322
26	23.17642	32.93969	77.3378	63.72822	24.46264	9.120634	36.14634
27	18.76499	32.35265	66.85418	42.16675	34.36735	39.06814	7.604652
28	11.83962	28.7842	48.88392	115.1369	38.20294	21.74514	17.75966
29	36.17135	22.75534	70.66315	49.09669	25.28164	14.73351	16.13455
30	27.89808	33.77438	47.56569	97.94827	28.30994	34.32691	17.87896

Table A.21. Complex Manufacturing System Average Late Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for FSS Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	15.43826	41.32558	58.86535	78.86251	10.42684	28.89755	11.3313
2	19.25496	53.92542	69.75093	54.40768	14.69445	26.06092	7.609801
3	33.58074	36.91934	58.91265	44.44829	6.109655	27.4923	9.395386
4	14.02904	57.44029	72.44815	64.77813	9.923152	13.21609	9.27182
5	7.499092	25.87035	41.44373	105.8492	11.29807	24.87124	15.96717
6	9.833961	4.131726	63.07065	47.63077	14.87677	54.66286	23.36612
7	12.19458	26.65727	67.33027	75.51348	13.41339	29.52072	8.066956
8	12.63877	66.97605	71.9066	62.5111	9.061338	4.755067	12.05893
9	17.63675	36.16817	77.86355	52.78555	9.653678	18.69753	4.612589
10	9.81721	46.08874	58.23425	114.2887	28.14739	21.7334	23.51549
11	16.10053	32.3616	32.27507	48.39563	12.63142	28.10918	43.88159
12	8.847551	8.866432	98.48904	62.18177	8.682122	32.71906	11.81262
13	30.74712	18.83469	65.32706	32.00148	9.395908	26.09137	6.098964
14	7.445752	18.4561	44.10699	76.44974	9.985256	36.82433	6.075024
15	6.18745	37.6294	56.68748	75.06325	18.59733	31.21029	18.88959
16	5.753489	42.25682	98.04959	46.24832	7.495744	30.74542	6.732462
17	13.86419	14.24157	52.19564	90.15494	27.32416	13.78941	18.35015
18	8.910715	8.50795	90.84746	110.9628	7.442215	20.553	8.773396
19	16.44071	12.04551	56.18277	63.82637	19.60885	14.81713	4.721164
20	12.09307	17.83139	61.65415	50.92623	24.18692	21.69639	15.29695
21	24.40689	12.29914	61.11012	68.5708	11.84043	19.20666	26.21207
22	6.090873	16.33813	69.33503	79.01802	11.38557	31.40263	11.24209
23	34.04766	20.54438	87.95997	71.39515	17.10037	31.19621	23.77249
24	17.95946	46.3126	46.19761	30.75739	17.47306	34.50144	25.32744
25	16.18343	22.27415	53.0188	46.8309	5.615137	43.84802	20.38234
26	6.757086	17.24953	33.843	68.38646	9.10216	36.95936	14.4177
27	12.94587	28.99132	38.83677	53.84667	16.66105	39.43532	7.110612
28	18.78346	13.59267	69.41496	51.85067	11.17683	17.7943	30.80387
29	20.75556	21.00789	58.51427	62.11456	13.78524	8.087383	4.692993
30	23.68697	29.94384	61.84342	94.54888	14.88521	16.17624	8.870929

Table A.22. Complex Manufacturing System Average Late Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for FSF Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	44.42438	92.0622	63.49536	108.5372	40.23124	93.21215	22.62064
2	29.93162	35.54234	62.74651	74.80023	36.63891	22.61271	40.62892
3	34.90976	68.72884	64.86722	120.3679	34.23765	93.92885	74.00632
4	22.91892	77.55162	69.48367	67.2376	40.21743	35.31503	33.33954
5	44.15356	49.28113	65.17903	85.77124	24.46277	84.62007	24.7063
6	43.60438	48.82249	58.06281	76.63519	35.47685	47.85308	35.83553
7	21.09953	64.1052	101.4268	68.31521	41.92113	58.64073	33.63674
8	40.67743	39.9054	84.82356	73.05487	37.08188	58.76742	34.50696
9	29.94952	66.59348	69.34489	77.41924	27.32328	47.90843	36.82754
10	49.54999	62.95984	85.9665	78.76081	20.77379	53.56522	13.01434
11	33.7804	50.46838	78.82344	147.6263	29.01522	44.63806	41.92998
12	30.36818	59.73043	61.48004	82.86456	42.24155	43.08653	28.17909
13	36.83697	89.21125	57.71274	93.41706	34.76955	73.3074	38.9571
14	16.60964	11.69545	56.23439	140.1928	48.21749	75.64114	36.38291
15	42.45821	42.54947	57.73771	56.43895	16.44905	40.94446	23.54423
16	29.51823	45.47655	87.53671	123.4621	32.18243	72.93147	72.78553
17	47.726	42.32833	52.39772	106.8137	27.03587	52.82883	62.91097
18	28.82081	62.48159	67.46071	68.19653	42.5397	54.70605	70.3055
19	43.63465	13.50022	98.5093	49.79296	38.81158	19.86882	18.81511
20	21.2379	62.58278	69.25384	59.8471	22.8508	28.93705	21.57745
21	39.14372	51.47897	51.43283	76.2727	14.06158	41.97228	25.70397
22	27.7525	54.48971	67.93293	38.37974	41.78615	51.25166	17.74199
23	29.53113	43.06376	58.64201	70.26328	46.52919	23.54343	54.97847
24	37.57474	84.39848	61.65727	58.5034	35.23185	32.22771	72.71882
25	35.56511	75.29819	103.6982	47.475	43.43728	71.33763	49.35346
26	24.66381	39.7237	58.86933	47.96149	20.68076	49.05557	42.24803
27	45.75697	50.31907	74.94515	48.41573	35.90928	50.87592	29.92074
28	42.27848	60.86413	41.81746	70.9957	34.35745	43.2133	41.60865
29	33.04089	55.11641	60.37089	70.63431	34.5017	63.08825	66.17758
30	35.61713	33.29364	47.12887	94.68913	22.17873	69.50411	36.71444

Table A.23. Complex Manufacturing System Average Late Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for FSS Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	37.89622	49.02039	59.32522	94.56909	16.93305	42.6632	19.28007
2	22.41275	66.93518	112.3874	72.68804	20.58456	24.22141	33.50131
3	27.48174	34.87393	62.41811	119.4121	11.79725	81.47277	26.34438
4	20.16642	36.36593	68.62112	63.80227	58.90284	14.92363	26.78204
5	25.40874	71.05457	43.49145	62.76231	18.87357	68.1852	38.19056
6	43.43199	21.1002	56.57782	123.2475	49.03504	59.24137	19.65845
7	31.64747	18.50435	48.85451	144.3233	12.42568	41.05713	13.38385
8	31.38479	36.043	49.1256	94.30256	37.37475	50.72407	16.68032
9	39.74055	28.89909	49.84388	130.8025	47.05992	23.28389	31.5681
10	36.77685	38.88704	124.1763	69.13464	31.0453	47.11311	33.1773
11	15.73446	40.05487	46.79609	92.96847	15.41259	51.15954	47.18144
12	43.05451	32.84178	86.16316	113.702	50.92532	65.80575	28.03417
13	37.19618	42.20822	55.38299	91.54033	24.25925	62.57383	47.24114
14	31.08919	36.21339	65.92749	85.92978	8.740287	33.3733	19.95587
15	20.46869	41.60478	61.80501	114.9571	28.63447	20.19106	13.76878
16	19.4783	38.89457	50.71286	53.438	29.57011	34.03606	13.63751
17	41.8774	38.61501	42.39473	75.08877	12.34958	66.35837	16.72434
18	19.75118	8.748518	51.61241	91.18278	7.535935	49.39485	29.82889
19	25.15196	67.89937	66.97266	94.88175	37.46709	43.35125	39.30173
20	15.6671	61.59695	53.61007	43.16186	23.55542	60.86878	13.48519
21	19.12989	66.82045	51.45835	46.4764	22.89222	78.23831	21.51195
22	24.43813	63.70845	59.54055	77.36329	36.0857	44.19235	19.5986
23	14.84032	19.71959	46.41307	162.2756	15.97802	62.41769	23.66228
24	33.48496	35.20423	65.18516	73.87958	56.75384	44.73095	49.6827
25	14.24934	49.45595	78.76468	137.7086	12.12051	26.46729	77.66861
26	16.2392	46.22142	62.95709	40.45133	16.72777	52.619	35.8811
27	13.33585	43.45687	50.84609	73.22419	30.94457	54.71355	20.42187
28	39.90273	36.94844	52.4615	51.06549	14.57533	45.9959	30.67409
29	24.85067	40.57946	64.18085	82.3812	12.59842	17.79821	52.26743
30	18.73703	57.31134	65.93064	83.19568	21.37283	33.51457	15.15045

Table A.24. Complex Manufacturing System Average Late Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for FFF Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	68.73941	78.76218	89.83501	93.00012	50.44616	86.32191	69.94373
2	33.33787	59.1688	41.09674	67.9764	56.09712	57.2576	72.34811
3	41.69948	76.63628	38.94674	51.93389	55.26468	70.63367	87.72304
4	45.79776	66.4462	47.45807	83.58553	43.40568	109.2613	56.99834
5	72.00984	69.96017	137.7516	61.58896	49.67375	88.77844	67.98564
6	34.94327	81.17607	43.42838	60.81575	41.75941	78.2841	50.71033
7	38.80123	66.47132	47.66718	87.72732	41.73116	61.29887	62.25571
8	46.11938	75.93107	50.70864	107.7965	44.29425	49.42811	49.0978
9	37.47965	80.8108	50.6858	55.49111	46.19258	50.38757	51.244
10	49.08798	67.77249	53.80928	103.581	61.42365	62.47173	74.34127
11	26.80084	42.71542	49.72768	115.2769	39.76718	57.70047	44.15082
12	48.77921	90.0385	67.16665	134.5901	62.48259	52.40226	47.76692
13	39.3096	45.92159	95.87519	50.70601	74.93868	58.10472	69.99952
14	43.54148	75.83207	82.04343	63.80361	51.70928	95.42697	38.22262
15	48.58594	51.88919	102.206	58.86538	47.73927	73.89462	71.45973
16	64.03397	133.7124	68.73774	50.34172	39.51947	51.92942	42.25865
17	41.13984	65.86628	50.66227	66.4301	58.61172	72.41369	35.33754
18	46.13984	57.8356	46.89699	55.52293	41.96388	96.49151	36.48103
19	58.1166	81.80235	63.79737	90.1356	53.64844	69.47122	50.60992
20	42.78144	63.82019	62.62935	88.24748	38.68134	92.39878	32.96726
21	51.21306	33.86963	42.68029	90.8835	30.08867	60.9233	80.68384
22	40.15984	73.97705	79.29851	128.4187	29.45087	50.76328	80.854
23	16.48219	63.38404	67.91924	97.97437	77.38827	63.13021	100.873
24	50.20466	59.97187	69.44588	98.88905	57.66867	60.40449	81.03668
25	62.94106	104.7857	67.67775	74.09606	54.11893	78.11387	38.85644
26	43.06097	83.94268	87.4787	46.31593	19.35794	58.75651	58.58237
27	62.89711	65.05978	42.91216	54.46488	60.85437	80.76467	66.22352
28	41.69079	86.42135	53.31019	72.98085	34.53508	62.33047	94.12539
29	44.59917	62.11986	73.84865	67.65172	71.42169	52.85757	97.58159
30	54.10309	103.0307	62.66218	49.78466	72.56007	49.2092	93.94113

Table A.25. Complex Manufacturing System Average Waiting Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for SSS Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	5.587862	20.10957	3.563586	7.871626	13.50087	8.516364	5.624869
2	11.0138	7.785878	5.964366	4.493826	13.88877	18.47221	10.11134
3	15.84322	7.81554	7.421999	6.676936	8.469513	12.7957	3.713488
4	27.26478	12.48505	4.950406	7.183422	17.47459	9.263528	11.45455
5	15.41561	7.129421	7.166619	5.718117	12.94442	10.70611	6.342479
6	9.851081	13.98412	3.496531	11.25172	10.02062	9.604199	4.650096
7	19.65739	10.9544	6.84214	6.736939	15.83081	10.53004	7.215365
8	16.92626	5.306234	5.115188	3.780715	12.84179	9.333996	8.369185
9	18.89694	21.58848	5.910291	12.64311	9.37759	13.59886	7.670449
10	9.87626	8.219481	5.290379	10.3886	6.946248	6.967991	6.492563
11	7.777773	6.033772	5.401698	6.714574	10.86262	13.05917	3.303923
12	7.663284	8.460348	6.194825	4.21065	26.85593	7.038587	8.662809
13	7.806358	16.28813	8.351744	10.32442	24.92875	8.136652	5.731214
14	9.393058	11.78276	5.532734	9.956886	8.689621	10.59379	4.911362
15	8.419613	5.961769	7.179845	5.067193	11.96602	26.77173	4.273179
16	9.354864	5.095102	6.14627	10.48712	23.64154	8.188603	5.063101
17	14.88283	8.676112	6.519534	11.58661	17.82028	21.2445	4.769126
18	9.907577	6.302977	5.859517	6.102469	7.539272	7.723667	11.48403
19	14.86167	8.83211	9.095565	6.317086	21.93418	9.256014	6.687562
20	13.83036	5.189746	4.113359	3.196653	18.24462	9.123056	5.667249
21	6.66514	11.48134	8.753027	6.144157	8.830228	16.91258	7.023469
22	10.22324	27.31748	6.312944	5.94396	8.890589	5.188939	8.006172
23	9.238548	12.40227	6.448438	6.315263	6.525283	15.11351	10.02835
24	6.484938	4.863072	7.365815	11.8244	13.63437	8.502556	5.0106
25	8.014334	6.674729	12.97775	7.848222	17.08046	21.8803	3.726966
26	9.782406	4.854793	4.649518	4.410655	13.56529	5.988483	10.97782
27	16.44616	7.576517	7.246506	10.69898	20.1826	7.634256	8.225927
28	8.283122	12.24561	5.086453	5.377838	11.84719	17.50891	9.118386
29	9.336931	7.562128	5.833044	7.488572	5.183078	15.87471	15.07493
30	17.03276	28.66298	5.182316	5.165853	16.60153	9.982315	11.97064

Table A.26. Complex Manufacturing System Average Waiting Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for SSF Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	17.99827	75.39947	9.466854	8.608343	10.72814	44.08791	10.9419
2	20.40937	53.86553	5.439171	11.39941	16.51768	45.63368	7.931409
3	19.19541	28.33888	12.54697	11.33839	29.31663	20.22316	10.44306
4	10.64071	28.56483	13.48206	9.163266	31.47705	25.62093	5.994711
5	26.6106	25.75818	8.366844	11.59164	20.53354	38.18809	8.3308
6	33.61015	46.66199	9.866065	10.25494	29.10694	28.48166	8.605858
7	36.01133	26.79299	5.442784	10.88061	18.42381	29.83577	13.19023
8	32.09155	23.72542	9.32162	16.72279	31.33515	29.04003	8.960645
9	21.33405	44.78663	8.387216	8.01316	29.93259	13.56084	9.340864
10	48.34371	30.42469	10.32055	6.354245	49.96816	24.68588	9.392162
11	31.46106	24.07579	10.94201	7.692688	20.53607	34.91317	11.28783
12	22.95145	12.73192	6.84882	10.41951	42.91083	52.97292	7.582612
13	18.4607	19.16504	7.925044	6.832585	37.86146	22.04954	9.835372
14	19.382	14.02118	11.69238	9.411234	23.96217	33.58594	10.77424
15	13.74909	25.66514	8.410794	13.08402	32.21009	14.59542	8.981701
16	21.91498	38.12938	12.88162	8.532015	28.84602	19.78815	14.55396
17	40.46058	17.21887	9.129171	8.522373	41.7949	31.87003	8.800131
18	24.01759	17.68763	8.655256	13.77386	24.98773	34.80864	5.51272
19	15.5945	25.77578	8.316955	7.677595	30.54864	18.84267	9.172084
20	20.70522	42.85832	11.87487	10.59929	20.32864	17.75116	14.35132
21	28.77381	41.31974	8.01806	16.16138	30.84104	30.83537	5.234857
22	21.15455	40.98673	9.404134	8.510928	14.69235	30.1157	8.207915
23	16.25056	5.312233	8.333492	10.57787	17.69497	13.63424	6.630065
24	30.15372	54.77947	9.992354	6.261352	24.58598	15.22431	7.457115
25	47.20488	35.60132	8.333971	9.639387	27.23613	39.48761	8.201862
26	19.47599	26.03583	10.58336	12.10295	19.19976	21.70178	12.57746
27	35.49601	46.3084	6.545537	10.31352	24.61356	32.72045	10.67512
28	18.70203	22.58261	11.85013	11.90345	35.02583	11.4896	6.100075
29	22.6812	34.78709	10.61313	9.658685	20.7129	28.05777	10.52833
30	23.15841	31.24509	6.147755	11.08115	34.08755	14.5018	8.295923

Table A.27. Complex Manufacturing System Average Waiting Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for SFS Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	12.19876	22.42871	11.34324	10.59396	22.67977	15.40952	7.000703
2	14.74959	45.54667	8.254859	8.884669	17.0853	53.14419	12.10057
3	14.76834	27.73525	9.486524	5.807023	23.64633	28.75326	5.958967
4	31.46034	28.54094	7.603603	10.98691	33.02542	22.70144	12.27059
5	29.38394	33.59073	8.081507	10.63745	17.90621	17.10333	5.846177
6	45.24845	35.98906	7.087977	10.10226	12.43866	22.82488	7.001748
7	26.37082	20.47375	5.861461	8.994435	31.49022	39.34439	9.503904
8	22.40137	15.07116	10.52986	5.760731	19.49431	19.50228	8.357481
9	7.497551	49.0853	6.037212	15.90249	12.75729	25.56273	7.024157
10	20.07808	10.29107	6.569378	8.312307	30.91111	35.1791	7.366669
11	23.36617	24.95315	8.184167	9.438193	22.23884	16.2406	9.286085
12	10.72603	23.26838	9.658043	11.82743	20.01824	31.81769	9.15443
13	14.04962	27.54009	13.74493	12.92267	34.29176	28.25675	6.930465
14	22.49049	8.047257	4.483733	10.42927	23.14583	30.01923	10.8529
15	11.84408	12.70533	14.57452	8.003986	28.02385	8.399914	11.84305
16	48.55654	9.175472	9.362027	9.436328	19.66394	33.07617	9.317767
17	23.90307	48.10831	6.672182	15.45178	18.93475	13.36169	9.517077
18	17.96101	16.56045	10.07058	7.120356	27.73846	9.182654	10.85428
19	13.96585	16.69905	9.861656	5.944056	9.061881	19.77772	7.169103
20	18.64249	21.00797	9.276874	10.14364	31.68553	17.30569	9.318091
21	26.11934	23.8847	9.691214	6.342138	8.339184	43.80419	8.046705
22	24.8478	36.1411	6.315928	10.53417	14.71677	21.76371	9.259775
23	26.60891	19.59313	8.794558	12.03273	11.51947	14.79799	9.974631
24	29.60989	13.39503	8.456721	8.282398	16.42538	22.69226	8.676401
25	31.78404	29.90464	6.215953	10.82339	15.70783	14.36205	6.870766
26	19.87014	6.047962	8.975277	7.111234	24.29489	25.67018	11.13764
27	30.41657	16.54174	9.461473	8.261736	15.76209	13.8191	8.134705
28	17.14139	24.354	13.09364	9.647616	24.5515	23.22024	5.153332
29	17.84514	10.78229	8.362485	4.64485	27.78814	7.208396	10.08254
30	17.29503	22.7111	8.615678	8.80287	31.92964	23.27156	5.231231

Table A.28. Complex Manufacturing System Average Waiting Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for SFF Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	36.78553	25.92512	10.01489	8.579241	66.90354	38.73255	8.966366
2	55.79432	33.16217	9.561611	11.36282	52.3247	45.14599	8.354134
3	47.90451	47.08528	10.3011	9.151431	33.03757	42.8351	7.360039
4	50.36138	35.88145	10.07196	12.08099	48.93977	34.07729	9.689074
5	19.58425	79.29375	8.571701	13.44783	30.85741	42.25233	7.155923
6	35.1769	61.35082	8.027471	11.08442	40.71601	42.87982	10.0925
7	38.20915	46.41019	10.53874	14.69413	53.17511	21.44212	8.179198
8	30.71168	45.5745	10.02485	11.31997	29.58749	47.38771	10.59668
9	28.84718	42.97406	9.367861	12.30408	44.60852	27.32044	9.136554
10	63.21097	29.1332	9.128735	10.50855	52.29131	42.30633	8.548367
11	46.44809	27.65396	7.86405	7.87907	28.84009	46.4603	9.232785
12	48.59151	42.39413	11.51543	9.527414	30.77893	23.25519	9.403504
13	56.85816	44.21977	9.228877	11.84113	45.68941	30.14443	7.846949
14	49.04699	46.78217	9.843539	9.723398	40.50165	52.4315	10.34831
15	42.47563	25.60585	11.13103	11.99366	51.13906	32.21968	9.390229
16	23.13465	44.72108	8.637331	8.805896	32.2102	75.12132	14.4825
17	37.71348	50.26886	11.37	13.79715	52.42215	60.55558	8.985136
18	45.85062	52.89319	9.741566	12.21133	53.43044	38.20875	8.139411
19	27.89401	37.70531	10.88034	12.13645	48.65689	54.67914	12.23032
20	33.6088	42.99389	8.765403	11.98001	26.50615	31.9535	7.508084
21	51.78465	35.48062	12.496	11.50883	49.70533	45.08481	10.63004
22	40.2445	49.70825	14.98622	12.56295	34.74438	29.71396	14.35533
23	47.76931	33.08794	15.31597	12.37257	44.29149	38.1673	8.851642
24	36.01295	59.01145	9.618778	14.49476	32.15211	60.51048	12.7021
25	52.11082	53.04106	10.14546	14.18866	31.95122	47.24956	11.1356
26	28.3856	44.59985	12.09958	9.794275	35.83652	20.85113	14.8272
27	30.00371	35.9606	9.504497	7.542223	45.98801	53.90079	11.90726
28	13.18195	39.05494	7.517382	16.85946	47.11983	33.61312	9.530559
29	49.14797	29.03137	10.44625	8.24969	37.38633	22.01894	10.61729
30	41.20515	34.45489	7.892833	14.9354	30.15954	37.14687	14.96921

Table A.29. Complex Manufacturing System Average Waiting Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for FSS Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	24.57377	54.30768	8.432975	11.11786	12.94555	34.77345	6.909405
2	33.13871	67.53677	8.822014	8.14282	23.81553	28.23049	10.06921
3	45.53504	50.09865	7.413517	7.095159	13.18926	39.71298	8.016483
4	17.46701	71.33573	10.32835	9.836452	19.48102	21.06376	12.23608
5	15.84759	35.67106	5.775588	14.58967	24.65408	36.48764	7.957598
6	20.60879	7.130147	9.080097	7.605225	28.18427	68.38008	8.607772
7	23.94525	36.07115	9.892682	9.950716	22.78385	38.728	9.834198
8	24.44751	80.24109	10.06153	9.269754	20.93284	6.769121	7.172614
9	29.31405	49.11918	10.64461	8.07748	22.49244	28.01378	8.930067
10	19.99495	58.29771	8.566265	14.42104	41.51016	31.73454	4.5004
11	24.64891	44.84367	4.70752	7.680259	24.20224	38.08332	8.230686
12	19.45647	10.49604	12.44642	8.49423	16.21806	44.43141	10.61483
13	44.56278	23.28179	8.964941	5.406509	21.55995	36.31892	10.19442
14	13.66479	28.27172	6.931211	10.9432	19.57116	47.08909	12.10058
15	11.1235	49.75106	7.945714	10.83133	30.809	42.36844	11.63593
16	11.71817	54.3388	12.63151	7.297934	13.11477	34.20385	4.682961
17	25.36008	22.16719	6.491906	12.8532	41.74406	21.88129	6.918336
18	14.82993	12.72564	12.59068	14.64052	9.588513	16.9151	14.44146
19	27.28767	18.49425	7.367479	9.08087	32.68243	20.38924	6.914996
20	21.38662	19.6979	8.246731	7.056477	37.3035	28.75567	7.526831
21	37.58206	17.60366	8.324887	9.565326	20.52286	26.414	8.89825
22	14.15971	21.77919	10.05871	11.86852	18.02339	40.55152	10.6048
23	43.05655	29.80177	10.95389	9.875711	28.85849	39.79857	4.751343
24	31.58164	58.93772	5.947075	5.136303	28.56024	47.53659	8.054758
25	29.47075	29.12455	7.632405	7.523138	12.96418	57.16512	10.81295
26	14.31096	24.98225	5.148565	9.775396	15.54132	50.00524	9.567261
27	20.07824	35.98023	6.11276	8.07147	27.27686	52.63812	10.3045
28	31.87707	21.06779	8.544375	8.136975	23.11892	25.78134	15.04114
29	34.65342	26.88032	8.010653	9.233245	26.4541	12.19536	6.2359
30	32.68211	38.49111	8.590751	12.95357	16.98705	21.60922	16.1276

Table A.30. Complex Manufacturing System Average Waiting Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for FSF Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	58.80761	107.0817	10.02868	14.65757	48.13781	108.3925	16.70576
2	39.83996	46.77313	8.638957	11.24351	51.20981	28.24362	8.041445
3	48.50051	83.21403	9.099274	15.82773	48.72311	107.8582	9.20257
4	36.67218	91.45472	9.748316	10.52468	54.30305	47.70394	10.42489
5	57.3926	62.21441	8.944006	12.40738	38.53956	99.87192	12.22623
6	55.39118	60.8934	8.123304	11.31424	49.39474	58.35257	9.636988
7	31.29395	78.54828	12.77654	10.75263	55.53358	71.50166	7.902091
8	55.08064	49.94498	11.28834	11.54699	51.20518	73.53187	7.764281
9	44.05708	80.90027	9.948093	11.02557	42.02796	58.25272	10.51786
10	63.84823	77.23055	10.90593	11.43013	34.59959	64.63804	8.195915
11	47.36363	63.11411	11.20183	17.79138	43.06282	56.67832	9.392126
12	44.45974	70.13639	8.606527	11.53214	56.44305	54.17573	10.01003
13	51.51854	104.215	8.308036	11.97543	49.41932	87.93407	9.021815
14	27.16617	16.86441	8.704954	18.49602	62.85546	88.95909	9.190448
15	56.57083	55.30169	8.628144	9.311882	29.4676	53.60569	6.558283
16	40.9439	58.12014	11.08981	15.31218	46.92675	87.76146	10.20831
17	62.26359	54.75948	7.718297	14.70047	40.89861	67.73466	16.81618
18	41.59943	76.58074	9.381205	10.26282	56.45857	68.34486	7.590241
19	57.28707	19.27605	14.20865	7.899899	53.50856	25.56943	7.166027
20	32.95855	76.84609	9.875935	9.02223	36.77764	36.76634	10.95728
21	51.07765	64.55251	7.610075	11.18328	22.68557	56.54613	7.680369
22	39.71754	68.68922	9.457184	7.091989	56.37155	65.19231	7.893855
23	42.67857	55.60092	8.945428	10.31464	60.61724	30.66318	7.601021
24	51.17933	98.91583	8.828194	9.015751	49.7599	38.43372	11.36339
25	49.8172	88.36367	13.07353	7.842131	57.69263	85.58785	6.290073
26	36.89708	50.76075	8.518596	7.04421	33.80593	54.38762	11.00161
27	58.36295	62.78454	10.42895	7.781946	47.10793	65.47611	10.74064
28	56.29334	75.37234	6.471338	10.44044	48.8047	53.76802	6.24625
29	43.76076	68.39761	8.967694	10.57809	49.09509	72.86737	10.71743
30	49.54621	43.53184	7.790009	13.31813	35.1481	84.6804	8.583359

Table A.31. Complex Manufacturing System Average Waiting Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for SFF Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	52.43208	62.03319	8.477782	12.56815	28.02898	56.66278	9.221624
2	33.39361	81.21412	14.32011	11.08133	34.74749	33.12344	10.38331
3	41.73762	46.28493	9.032412	14.96723	25.59759	95.16896	9.315701
4	32.94632	46.79937	9.171607	8.984231	73.51089	21.6	8.772182
5	37.45223	84.51505	6.623216	9.733	31.49842	82.85216	6.624258
6	58.05443	20.40392	7.988867	15.96062	63.45414	71.5397	7.721391
7	45.45988	25.8048	6.469837	17.98325	24.36782	50.88099	9.209208
8	43.58019	47.36644	7.648202	12.13831	51.33214	63.59297	12.93506
9	48.5054	37.11094	7.888595	15.85246	61.26666	34.32198	9.280953
10	47.92769	49.10265	15.94131	9.774405	45.3939	59.20018	10.53427
11	24.91474	52.04308	7.351524	11.96813	29.40729	64.5789	9.59151
12	57.12039	45.06088	10.77995	15.889	64.62102	80.09894	10.35662
13	45.03839	53.54246	8.245736	12.93336	38.047	76.40907	7.131113
14	41.57425	48.55936	9.529806	11.71225	15.43099	41.31073	6.460827
15	33.23916	52.2418	9.017345	15.58824	42.75502	27.7047	15.52082
16	31.25999	50.45596	7.97447	8.42536	42.87682	43.20214	13.44094
17	55.07319	45.28577	6.781345	10.36506	23.55352	80.34231	9.495098
18	31.72492	14.24347	8.196183	12.14569	17.79075	61.07389	8.943138
19	32.968	82.01488	9.111798	12.86154	51.35615	48.34677	7.571457
20	25.11418	75.08058	7.959957	7.203888	37.17814	74.42568	13.44301
21	32.82909	80.53505	8.091606	7.199563	36.43377	92.30078	7.781608
22	37.82786	77.12663	7.955941	10.29753	50.42838	54.68367	7.645853
23	26.43582	27.07417	6.882536	20.78506	24.16139	75.7531	9.015994
24	45.25473	46.7525	9.420968	10.94682	71.59999	55.36693	6.719194
25	23.9681	62.15063	10.3261	16.84259	25.78321	37.80058	8.341666
26	28.71811	59.45319	8.707235	6.982204	26.84734	62.70732	8.843089
27	22.48473	54.48165	7.833456	10.20286	40.34946	68.73544	9.058946
28	48.28792	48.75797	7.552177	7.662365	22.96496	60.29801	8.119469
29	37.78196	51.32154	8.640487	11.42035	26.50523	28.20938	7.732141
30	29.1132	68.13061	10.03265	11.41237	35.37492	42.3544	6.314801

Table A.32. Complex Manufacturing System Average Waiting Time Performance Measure For Unadjusted Fabrication Processing Times Without Information Exchange for FFF Arrival Rate

	Policy and DT						
Replication	P1	P2	P3	P4	P5	P6	DT
1	83.17637	92.47056	11.58232	13.35762	65.05481	100.2833	11.9369
2	47.84356	67.40566	6.402706	10.15493	70.58438	71.16511	13.12325
3	56.22287	90.94722	6.298053	8.368729	68.51207	85.45776	7.971296
4	58.04473	79.91101	7.268541	11.55404	58.13113	124.5182	10.30043
5	86.63798	83.78711	17.92564	9.362844	64.19168	103.5138	8.685665
6	48.49563	95.07241	6.799265	8.988237	56.26783	92.36088	10.91493
7	52.07393	80.45799	6.987958	11.55479	56.51104	76.27704	8.226748
8	60.65107	88.46883	7.67877	14.90689	57.97564	63.81288	11.32595
9	44.63914	94.01344	7.766539	8.857415	60.87595	64.35391	15.5212
10	63.53095	82.3741	8.026786	14.40184	75.94646	75.63928	7.138048
11	37.81464	53.36716	7.471308	15.50304	52.44011	71.73973	7.726201
12	63.3648	104.6218	9.421148	17.14874	77.25484	66.41837	10.93169
13	52.64818	55.98086	12.81364	7.986942	89.65049	72.66824	9.746196
14	57.54483	89.60822	10.99042	9.4685	66.47735	110.0653	11.61873
15	62.17432	63.55324	12.36212	9.043599	62.45503	89.06793	10.2697
16	78.61001	148.894	9.058201	8.479293	54.28581	63.34245	12.03197
17	55.48186	78.54892	7.840436	9.608658	72.42508	86.98638	8.651207
18	60.52444	71.05696	6.947996	8.679502	55.87314	111.4753	13.66646
19	71.81722	94.83548	9.418058	12.37561	68.21429	84.12007	14.4198
20	56.75023	76.88565	8.467872	12.14435	52.88867	107.4822	8.210746
21	64.80694	45.22989	6.837231	12.9296	43.75291	75.85406	8.312499
22	52.50186	87.46214	10.99893	18.32621	43.71901	64.7309	7.183916
23	26.35628	77.57733	9.505473	12.69556	91.86516	77.77933	10.51295
24	64.82455	71.85417	9.656036	13.9952	72.02378	75.12863	8.42081
25	77.31648	119.88	9.42181	10.22231	68.88446	92.93541	11.47739
26	57.05696	98.85815	11.52827	7.730734	16.24936	71.54218	9.540847
27	77.44356	77.29408	6.97766	8.708922	75.521	95.12449	12.48367
28	55.65196	100.5838	7.643801	10.73717	48.81664	76.19751	9.174278
29	57.01453	75.95233	10.11281	10.0923	86.00843	67.02223	8.564688
30	67.66939	118.228	9.294426	8.019536	87.45605	62.02795	7.772632

Table A.33. Complex Manufacturing System Average Late Time for Each Replication Using DT and Adjusted Fabrication Processing Times for SSS Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	3.060158	1.234046	10.49356	16.04115	15.1209	15.23634	36.57218	37.77622	19.36012	36.05986
2	4.261509	13.41953	2.4357	2.443748	19.25885	29.98497	30.74396	20.656	43.27651	35.95502
3	1.485399	6.583028	2.126505	2.31083	20.75724	25.07484	33.51311	27.32822	39.91541	19.19902
4	2.291784	9.281208	6.096993	2.332183	13.81024	27.71784	18.20535	20.13168	50.37157	42.22006
5	47.01257	6.170351	2.705899	2.133973	8.352029	24.44506	47.55722	24.4177	40.35222	38.80216
6	0.756168	11.47708	13.94702	5.07441	7.566123	36.25572	44.79565	23.99103	27.78706	31.02778
7	3.94159	5.868451	8.868514	2.744091	19.51614	24.33129	36.34741	21.18876	26.08527	59.93794
8	11.75793	5.964968	3.829114	2.433985	4.439341	21.65664	15.15385	20.92075	31.188	27.63655
9	5.829595	2.014752	0.813386	5.777532	18.09964	30.66087	15.52139	42.42931	40.95359	23.63835
10	6.904437	12.26612	0.351839	3.747969	30.95875	24.85416	24.91127	50.50162	35.29796	38.83106
11	13.91962	11.51749	1.306078	0.795444	12.39172	13.52733	28.2842	20.63919	32.24223	42.87442
12	6.666099	3.081173	0.625306	7.170504	17.80185	18.41096	28.72538	13.30837	60.17184	63.57867
13	43.59442	1.122336	14.59636	1.949168	17.09434	29.62017	26.76526	37.96777	31.44269	29.05005
14	4.25178	1.802777	2.694792	7.20129	8.96332	31.94419	35.00864	14.47158	38.00646	44.59926
15	7.231607	5.594406	8.565195	3.886439	7.297798	15.90007	32.74641	20.60637	41.91029	33.99165
16	33.05579	5.997746	6.937405	2.879443	6.752834	16.14659	45.61082	39.17042	21.73413	57.15714
17	15.69419	3.482537	8.246614	1.78687	10.61939	26.14589	21.71429	52.35546	31.95603	72.77688
18	7.351856	3.726653	14.42095	18.71485	15.00179	26.99837	29.99656	39.90399	19.73354	51.27645
19	2.076292	4.190666	3.327756	8.039667	6.30306	15.91799	18.55213	34.17603	26.89927	19.38267
20	4.54258	12.66001	4.637404	3.556527	14.78707	32.5038	32.64994	41.68931	28.16245	29.01016
21	2.545307	15.52836	6.576201	3.133857	12.03552	14.50339	35.6052	32.94449	36.16995	20.88706
22	25.44778	3.957834	8.769657	12.65195	14.79701	40.46473	17.0198	25.96647	38.5845	35.40016
23	17.84663	5.299699	2.319212	4.233284	8.358187	44.9947	19.15704	19.64057	65.08164	32.91394
24	7.011456	4.498734	2.573633	4.195834	14.37294	23.67889	35.11541	17.53241	55.94441	42.91239
25	32.02122	8.573679	9.378876	4.782218	20.93066	20.79393	30.3425	46.25886	14.44637	20.52483
26	25.21811	1.616147	2.565506	0.784797	12.1778	23.60543	11.04837	18.1465	29.86014	35.54897
27	5.441792	10.54591	11.23449	5.15426	13.69746	18.46347	14.11146	29.46851	20.44921	25.07758
28	15.13337	1.351241	16.84128	16.55389	30.8827	34.94304	19.1317	30.78713	51.89799	68.53711
29	9.50257	1.053624	6.637225	7.890533	6.680293	29.49877	40.40442	21.7196	44.94751	37.68825
30	1.742112	20.84682	13.05319	12.85686	12.50544	25.80492	34.85729	12.68307	36.01092	29.58688

Table A.34. Complex Manufacturing System Average Late Time for Each Replication Using DT and Adjusted Fabrication Processing Times for SSF Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	32.95187	39.27571	9.334711	17.99602	15.72115	22.39226	49.61126	33.33579	23.09134	24.63286
2	52.6838	47.09772	35.75867	11.58486	12.12932	43.26679	29.13564	44.14975	50.88751	33.12186
3	63.58392	13.57152	17.40703	5.27664	20.61081	29.13823	71.05805	19.01028	49.60141	44.93981
4	14.39686	7.71129	58.52111	25.43255	30.62198	34.00806	64.243	22.89871	56.68819	42.9666
5	30.83424	19.43931	44.96147	17.41223	15.19037	37.95013	21.07219	24.14479	31.8963	56.23302
6	91.61893	13.85222	13.27122	7.69496	33.03278	26.61009	36.74441	32.92616	21.26155	26.60576
7	11.01465	30.36763	16.06308	10.2679	13.85062	44.63415	51.81097	20.53026	48.38045	42.83808
8	19.10956	18.69287	13.77616	19.38701	29.37993	25.55923	48.85893	50.22437	20.87362	51.34349
9	22.69088	20.5638	15.21552	25.1588	11.46197	28.57167	51.58833	27.22981	38.37357	25.94069
10	28.84608	11.75973	20.7796	3.785802	18.07734	32.83757	31.75196	27.34205	22.04228	38.7379
11	42.99069	21.8449	7.032539	22.06393	27.58538	29.97997	83.42339	33.22156	51.13123	44.77898
12	39.86545	34.13225	46.4586	29.08201	12.9253	22.17714	31.52599	43.70666	23.62101	44.34057
13	7.126574	20.26189	18.353	11.67775	21.18049	43.91803	26.94964	31.23028	23.67195	29.24384
14	53.67865	37.53098	18.77407	16.6387	19.49137	28.51843	19.84551	43.94638	40.46251	35.75807
15	11.50456	13.16259	21.69778	42.05488	21.51627	36.02422	48.19199	33.96121	32.3133	28.00515
16	19.59022	36.36537	5.282009	7.283804	12.12253	28.43304	56.49363	23.23595	17.11836	67.75876
17	43.50539	12.49858	36.59435	8.640072	26.75235	18.61565	25.68916	46.01813	55.05083	53.75807
18	23.21936	10.55322	37.43406	7.519823	17.11233	38.87244	30.29706	24.78272	52.01813	38.72357
19	26.99127	44.91433	22.62014	5.024625	25.61913	22.2435	47.14768	24.58402	49.83839	22.97791
20	33.82901	54.48001	9.525882	5.148709	35.21977	24.52017	43.33067	30.81405	26.70661	51.91333
21	69.43133	13.20008	20.98826	28.29461	17.62805	24.94683	36.3789	24.60504	17.53424	41.08387
22	24.64173	10.31066	23.58132	12.62581	22.79118	28.17546	25.2079	67.73899	24.8289	36.57724
23	15.2003	22.39865	11.07482	19.09721	23.55763	40.48049	69.58982	26.71145	21.24737	46.54447
24	15.10032	38.61042	22.5973	31.61912	20.61649	23.3885	27.77986	22.83792	39.76844	45.05551
25	46.24861	20.66619	24.72837	9.996401	18.04617	29.32831	28.6294	17.47495	44.83971	30.3676
26	16.86534	16.60855	19.43737	10.26299	20.78511	34.62981	47.16884	35.63076	23.44371	27.8746
27	18.95093	19.54535	56.88788	6.375717	13.07252	30.77947	37.46794	29.46064	37.14537	35.1381
28	45.2153	32.48906	11.12872	2.032052	18.58188	38.92306	53.79257	23.14311	48.79158	40.42928
29	26.90743	32.47592	24.99912	18.24011	31.41584	23.02245	44.05693	28.79447	25.36121	28.58182
30	62.67641	16.48655	28.84339	8.92478	15.18217	27.59621	33.83078	20.29899	30.63986	40.50461

Table A.35. Complex Manufacturing System Average Late Time for Each Replication Using DT and Adjusted Fabrication Processing Times for SFS Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	44.72129	6.547482	9.011525	1.566542	25.11652	37.06504	70.97241	28.15153	47.60547	34.82097
2	50.57689	27.5027	11.52167	18.39283	11.76777	25.64466	58.11222	34.03069	23.29222	29.12284
3	21.55414	13.73231	3.222494	15.95958	10.43573	37.23368	39.8153	39.38116	27.05905	20.97604
4	33.14072	12.31776	9.172507	11.32696	29.60632	30.78661	27.91455	25.50662	43.40058	22.7871
5	44.35606	10.5463	46.23245	5.342628	10.28189	27.33906	40.57937	71.46998	34.90573	42.83742
6	12.98719	33.52576	9.143499	19.21675	24.37592	25.26181	41.9214	31.874	17.67027	40.72564
7	28.64889	27.48046	31.04985	3.398223	15.85329	26.54029	30.68865	25.68156	35.00729	33.23337
8	17.11882	31.74067	7.016053	3.222141	10.10337	28.26632	17.44922	47.63462	41.22814	21.79013
9	49.65379	8.355435	7.926178	44.883	29.33275	27.95359	38.12931	28.82136	22.52028	49.54267
10	20.98647	13.06655	10.63581	17.08292	17.13777	18.65753	31.4862	15.61616	20.33195	71.44165
11	24.35672	5.236923	36.85812	6.229763	6.918507	15.54869	15.54291	19.23369	39.11005	45.36324
12	30.76764	4.567466	18.12709	32.00697	14.74549	22.51677	21.69665	22.18128	36.54552	21.20249
13	30.54008	16.52883	0.87416	7.352032	10.66875	29.21534	12.49698	24.69018	41.89268	54.03919
14	16.43904	26.17481	12.85543	17.96397	6.062831	35.14407	30.80419	27.57547	53.1603	30.82618
15	29.29628	32.36489	34.41989	17.59228	21.3771	22.88358	32.40728	24.00157	33.67518	21.77863
16	40.53048	28.42759	13.0045	7.040431	17.74805	18.15529	57.06044	14.62023	45.38255	40.17276
17	3.907566	5.670322	12.98979	28.73193	18.69347	10.07769	25.14625	23.70374	11.40479	28.34712
18	44.98583	11.00534	40.41004	9.351581	35.2025	23.0486	26.03413	45.10695	38.29161	45.7264
19	1.978608	41.64815	39.21258	25.76163	13.86431	40.03778	43.89818	24.17612	33.37213	23.75827
20	39.63436	51.12404	5.948948	4.353786	9.646001	20.60363	30.27556	38.60347	33.10517	45.92082
21	33.69596	14.34829	7.556228	8.713871	15.98951	15.00095	39.33293	33.41389	34.25433	62.78797
22	13.62009	21.50418	30.45337	8.205753	8.783029	37.43446	31.71698	62.95257	42.96221	65.19075
23	52.17259	4.165148	1.559742	21.93308	29.76171	25.50471	53.8581	38.90792	34.49273	44.82274
24	17.77813	2.711897	33.99102	6.751968	16.65836	20.53501	26.87225	13.15951	28.23896	24.47688
25	45.04693	25.55101	8.443328	5.447684	22.21515	29.80874	21.7823	38.77282	66.83946	36.17763
26	39.2021	13.98711	17.7606	17.26606	20.00194	27.8125	44.17267	17.40887	21.07658	45.52828
27	18.72802	9.414707	13.40186	8.609549	6.901736	33.64055	31.40327	36.04443	34.82844	37.4777
28	57.78868	26.24357	2.911289	27.49506	11.45481	30.64499	39.62229	16.88597	21.61348	35.41976
29	16.56593	12.43038	12.17364	19.78016	27.74682	24.6454	38.42311	24.72383	26.63908	55.64072
30	2.053816	22.70522	8.915136	7.924536	24.31201	32.71995	25.97926	30.43742	17.08062	32.96559

Table A.36. Complex Manufacturing System Average Late Time for Each Replication Using DT and Adjusted Fabrication Processing Times for SFF Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	79.41491	37.80172	31.3424	56.85709	25.73256	58.68952	65.28509	46.78736	54.29707	62.12436
2	40.45222	76.56766	30.24999	52.75018	54.66845	54.71105	40.16347	24.42701	32.12603	58.43082
3	92.34576	44.44286	64.20554	36.31192	58.78315	42.95149	109.2381	65.8729	52.16128	59.66935
4	52.07969	52.34972	56.62667	55.57214	70.09468	43.11825	47.89015	38.3682	56.57211	44.0743
5	36.98794	52.66442	26.31595	55.05928	40.5506	39.4255	66.64924	20.02751	54.87226	40.46458
6	59.47335	74.22842	36.14346	34.11004	20.60194	33.87109	111.7125	84.2795	58.53898	60.21152
7	97.27399	24.13829	11.93858	81.2689	19.69266	41.45467	79.22382	27.17106	21.7872	50.97687
8	42.82659	34.90059	41.81582	26.73601	35.69633	49.00208	39.4564	59.70657	59.24101	79.63934
9	69.05729	30.18621	45.70059	35.69348	26.36143	50.84958	70.46096	55.85733	38.49994	46.0891
10	39.98537	47.08029	33.05544	16.52917	44.99432	71.59415	79.65994	62.41097	29.06663	62.42459
11	54.61554	49.06492	64.46443	47.32773	22.91774	40.66581	44.85643	52.18618	67.77166	51.84367
12	112.4733	22.25378	28.03703	36.2854	44.31389	37.69914	55.82141	26.82899	50.92353	59.46712
13	108.1355	55.82689	33.66391	36.87766	40.45304	42.76608	50.49638	30.76591	69.59893	54.98568
14	73.57918	38.30687	39.05241	36.54456	28.56473	56.43165	57.76785	49.49698	52.88676	49.52181
15	110.7456	44.28769	53.25152	45.36232	28.0483	32.35103	39.79729	28.7974	57.30389	52.38107
16	57.37272	20.8349	39.62368	24.63926	32.55662	45.2864	83.35919	58.04233	78.63377	61.64441
17	54.87018	40.15038	66.88069	42.39397	61.52509	51.33372	62.85099	45.06548	72.98471	40.27089
18	36.91269	54.43212	18.38858	41.67013	28.36454	45.66582	52.19342	52.89781	63.41757	59.12757
19	87.8288	10.72088	12.48967	39.72922	32.30378	44.54349	54.48574	38.08666	69.06435	37.33578
20	95.72707	30.42918	25.86715	25.52355	29.74372	44.18235	56.47524	54.32061	42.50251	62.46271
21	68.27253	23.67517	34.32031	49.91334	26.97348	37.73617	69.91572	90.11705	38.77553	34.45393
22	75.88995	29.46332	43.96771	48.11445	24.48646	24.50732	26.1909	35.14097	24.43649	60.03793
23	28.91663	93.97818	15.66446	44.91764	59.95057	53.83787	72.57393	40.9718	40.32641	37.83208
24	27.62109	36.19436	27.70253	17.40403	29.97074	20.15899	52.47707	32.7418	48.14436	75.30159
25	41.51759	38.62348	35.93461	51.21587	37.62489	43.66329	86.06745	52.54217	41.07811	50.70674
26	49.11532	51.8047	34.64439	46.16544	36.47401	59.28281	68.90511	65.75135	47.79856	59.67474
27	39.63855	46.91605	8.796348	8.465529	38.68119	51.16282	117.4395	42.87767	48.05813	63.71145
28	36.92452	73.99581	38.73621	32.1838	58.10731	36.29295	71.53499	49.43972	72.11948	76.39704
29	84.76509	49.55734	45.35656	55.7782	40.92828	35.80872	109.4167	65.04165	50.90798	78.90674
30	46.70078	72.63861	19.29277	40.44036	24.09596	31.24835	79.35535	23.79565	28.40514	51.77986

Table A.37. Complex Manufacturing System Average Late Time for Each Replication Using DT and Adjusted Fabrication Processing Times for FSS Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	3.409335	19.55038	46.27413	32.6456	24.84903	40.36095	18.219	22.50773	18.83955	20.13724
2	7.435812	15.74321	10.8954	4.150544	28.65322	52.85494	30.22565	17.13503	32.16643	46.03501
3	9.405838	28.92601	8.117534	12.07845	11.05905	52.6969	22.61623	41.78168	28.4865	30.64944
4	3.620138	21.90481	18.47048	10.39091	27.5036	55.41295	66.89857	30.81366	56.98933	41.62752
5	11.04621	39.49495	51.72573	23.06465	15.85995	35.7362	35.52401	30.01455	32.47517	15.03826
6	10.67074	67.58591	2.865361	22.8482	13.46274	52.14938	49.06582	49.65866	30.65813	38.98535
7	49.27835	9.169918	14.09248	19.23202	21.98546	22.81734	43.69859	19.02543	51.30361	40.49765
8	40.00414	27.53183	21.46454	17.66993	28.19212	30.20211	11.15261	23.60566	36.94628	20.58131
9	5.537229	25.32575	25.99548	10.21052	34.13413	35.48031	35.00986	40.02406	31.96019	26.58872
10	12.24568	16.64784	4.964315	18.30202	20.66045	15.68194	12.10175	23.17273	31.71373	23.58479
11	2.885528	33.52792	22.49566	27.88138	15.68267	41.40299	65.13816	32.33778	37.12066	19.82319
12	24.39763	33.49518	7.68791	23.63435	26.55381	39.82151	23.50925	18.02731	20.72903	71.75804
13	60.97609	42.44053	25.91163	6.854097	25.85077	30.60513	35.00245	16.33913	42.60342	19.17296
14	16.20229	13.45282	35.38918	4.758295	30.68871	23.47342	35.11298	25.38089	27.09871	32.40901
15	10.91023	4.880977	18.90833	25.95776	48.80475	18.80925	41.76499	21.49144	16.55527	26.07024
16	62.08991	16.26446	7.604951	7.043504	64.72005	29.06281	53.30426	20.54966	25.79267	34.1152
17	45.29908	11.68878	7.407895	11.20719	19.45057	32.2231	36.26065	18.42743	15.13759	31.01883
18	6.76844	74.62522	10.87041	9.723887	26.28756	28.34886	31.31087	15.34115	30.97976	45.19248
19	38.14342	40.67161	37.89865	18.31974	9.037617	25.36463	21.33089	39.23527	53.48954	30.85381
20	1.049906	10.05394	30.80151	14.87653	17.29724	49.62884	13.22262	49.66573	40.01503	51.54368
21	4.702979	43.41802	12.17282	43.78828	48.83961	20.09277	40.62589	27.4634	31.40155	38.7267
22	21.53454	3.836943	14.38329	23.19506	43.06485	44.21898	15.40014	51.37259	32.59227	27.91756
23	104.0744	10.54675	24.38913	11.09693	14.93987	20.93536	41.55125	28.8001	27.83867	29.18634
24	5.814773	48.13545	16.61015	4.058922	37.33303	28.37519	22.23871	33.2434	35.43727	34.98678
25	38.45374	56.56188	44.68671	3.957114	11.40615	32.17818	35.81915	26.98754	34.31182	39.81272
26	26.37962	29.40417	5.47322	8.168617	17.67931	23.06505	41.03271	27.60839	14.44618	49.34757
27	25.51488	13.6058	42.81322	5.381245	33.60297	34.4904	13.56977	14.52531	18.87664	53.00316
28	40.69339	1.729827	30.25154	11.61041	10.31024	38.82686	43.99745	25.35177	29.55951	46.68433
29	37.30465	4.311262	3.129462	28.02427	15.68903	25.97835	24.31997	70.5142	29.65136	29.71037
30	47.56548	5.449225	14.38699	9.03634	19.12598	37.92307	23.31092	25.53693	61.31439	15.05671

Table A.38. Complex Manufacturing System Average Late Time for Each Replication Using DT and Adjusted Fabrication Processing Times for FSF Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	89.9538	54.55371	30.27728	56.83097	54.24826	69.60531	104.6709	48.15533	69.6875	52.45464
2	57.54783	46.76737	41.1564	27.7625	48.54044	43.7119	71.74318	61.59727	56.00052	66.49641
3	78.28497	64.30347	37.7562	53.58236	24.46271	64.04535	78.31712	46.88424	56.78448	47.06182
4	33.75316	45.81343	84.97039	46.50532	30.0082	34.70489	102.8317	82.53911	58.47978	91.04297
5	24.5389	64.65993	24.03369	31.67084	60.27019	35.13396	78.21346	32.63619	54.21553	92.66979
6	99.8727	41.14255	49.27449	81.24404	80.22014	88.32138	80.34365	46.79459	34.4892	43.81358
7	38.91665	35.012	48.25923	31.12739	83.82247	72.00765	77.88437	32.78047	36.82538	108.6234
8	29.78894	59.71861	72.64324	19.35071	29.06826	47.33065	103.8629	42.93747	52.76291	71.62816
9	52.22397	81.83027	58.92599	15.84505	61.7398	50.61567	94.47223	38.68462	77.78881	39.52756
10	68.86211	28.40091	36.51933	48.66045	76.85891	74.43077	52.49901	40.47356	84.24885	37.89662
11	44.48422	47.81078	55.88602	55.67306	63.80541	63.60439	75.74191	66.03739	95.58438	71.2819
12	58.24523	18.42767	99.64039	54.15994	28.8848	83.0693	69.25882	57.83436	95.28389	64.37407
13	45.63373	89.9463	51.30032	49.77391	30.03174	64.75657	114.8698	55.99608	64.48934	57.5602
14	48.2326	33.40646	87.88972	41.64863	48.15162	61.01059	58.12202	32.04721	58.6572	34.31683
15	53.01604	115.2775	68.45173	9.683576	25.09069	62.70449	66.89472	65.62764	59.95854	52.61434
16	45.68623	70.25561	90.33714	50.118	30.47876	116.2191	84.37471	71.23936	69.72605	77.53395
17	69.20041	46.76365	35.82723	24.39926	76.34593	41.50983	70.97617	33.10028	50.76487	99.06843
18	42.5049	71.93622	49.53817	48.97811	52.12689	67.89964	79.97063	59.35015	46.8125	63.27234
19	54.88659	29.42288	52.31806	49.05364	76.98159	67.83774	84.15952	57.17587	67.58064	33.99713
20	55.94379	29.21197	51.08609	91.58266	49.67327	93.98101	77.925	41.48042	22.84956	96.36831
21	32.95719	69.96414	63.70266	25.82263	47.89908	80.84923	94.21829	73.97826	95.83186	97.05833
22	48.81519	48.25727	60.84577	28.2011	31.13345	62.77701	55.89665	55.53724	64.35801	73.04067
23	41.49385	45.74292	64.76018	41.96055	78.18128	69.79136	18.95857	30.01143	57.01363	62.99347
24	72.15977	34.74082	33.11746	40.87329	36.68187	62.40777	103.3221	50.85078	67.68833	76.28437
25	54.83646	73.51756	110.0278	43.97546	52.75134	51.38396	78.65156	48.76155	78.16318	71.33148
26	59.01661	55.18833	75.47086	29.6776	34.02844	45.11854	81.83672	30.45578	29.67092	58.91808
27	44.68402	61.48897	29.26764	64.33835	51.881	72.88237	63.43099	41.43369	41.28942	74.82488
28	45.68068	37.58195	73.10197	71.92097	52.31768	45.15445	69.43954	54.38372	54.21161	53.22849
29	81.14363	45.76477	28.95141	22.10768	26.69655	43.74055	43.59771	44.89336	67.22846	70.35937
30	86.7491	26.24818	60.20616	19.0641	63.10465	46.3664	56.33245	60.57108	41.13528	90.9653

Table A.39. Complex Manufacturing System Average Late Time for Each Replication Using DT and Adjusted Fabrication Processing Times for FFS Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	73.32802	20.92823	82.68093	33.08704	57.55487	40.15002	47.279	43.9018	62.82433	41.32916
2	29.40798	45.30049	34.58468	52.80861	94.61988	74.75561	85.75515	21.81433	21.58063	29.43462
3	54.74469	7.7308	17.77976	33.64492	56.44584	27.57988	56.56993	68.8684	21.36222	18.87037
4	56.22585	5.567283	9.67899	60.65801	38.49219	59.44384	81.4646	20.20462	18.22969	44.69285
5	38.99312	13.68002	24.94476	57.95417	74.45588	67.8061	46.73535	46.91209	76.08234	46.15197
6	41.40673	50.01997	92.04481	85.31065	30.59377	75.83864	29.93185	35.99273	64.24251	44.81767
7	61.33021	67.1451	36.19854	30.64351	73.3338	40.0989	38.07951	49.18516	46.53547	52.47493
8	23.40598	72.29513	77.59601	57.95627	71.62628	47.9843	48.70402	56.95017	32.41442	21.5831
9	55.23222	34.01886	27.48453	33.69168	50.60394	51.00484	87.94831	36.15289	38.87624	82.37172
10	24.93256	60.74821	15.11473	43.19311	20.83164	95.28327	89.69214	55.8694	37.78751	57.78264
11	35.04785	41.499	68.98844	15.34075	33.97984	60.89992	18.47152	20.91707	30.94642	42.76842
12	35.44623	48.45629	49.06464	26.37686	70.39132	42.36623	69.00124	53.22913	76.98239	80.42562
13	41.85922	23.55256	49.49968	26.221	28.92649	38.16427	63.0724	59.83985	49.98438	56.70464
14	38.30247	23.36084	8.210409	63.53576	60.78018	68.4686	20.78063	83.57922	62.04685	97.016
15	25.77808	52.8805	24.37381	55.27104	68.12412	56.99143	67.73106	42.15248	44.41147	70.69003
16	44.90481	89.02397	29.61429	16.20511	21.87081	25.9559	46.07418	51.08973	55.23215	36.19511
17	45.98404	83.51819	52.57341	53.53775	62.72757	56.50692	59.84701	37.96723	34.14208	74.29261
18	19.42402	26.10451	21.79199	14.49781	59.8376	53.93332	34.22805	22.64851	91.10659	48.41398
19	52.80614	70.36039	39.98894	51.7854	29.94941	54.02295	68.88228	55.47495	39.14347	60.14796
20	32.82882	51.49741	49.4751	32.62107	84.96964	28.83585	89.7127	55.6648	41.76546	51.40545
21	28.29151	21.431	42.47826	58.51629	49.26194	24.08441	61.38824	19.99646	60.31635	54.44001
22	9.676174	4.75244	42.23312	99.43606	61.69357	65.97619	79.23261	26.01235	78.16914	23.80453
23	50.2159	30.44391	40.4037	44.57096	66.21143	85.34653	54.71708	61.56473	24.08278	67.1888
24	54.74063	116.8219	35.78988	65.77775	52.58867	37.75191	59.15523	31.38706	77.57461	53.28151
25	31.81859	65.33825	61.30749	40.07686	27.59104	73.12959	79.84594	30.49959	35.05437	51.86323
26	71.52922	28.54122	47.35976	43.2671	63.76162	27.95431	51.24465	19.61437	49.09003	60.96946
27	72.67634	31.88385	48.84901	12.36413	75.63785	32.78992	110.1198	90.32522	67.44981	64.72312
28	19.11708	52.37645	47.74366	93.64903	93.99271	66.03946	101.8773	41.06839	54.46122	35.07951
29	52.15635	79.34916	20.61158	14.80687	35.79221	67.84501	39.1926	30.89238	41.43526	37.54338
30	40.69911	65.79444	44.36965	76.65499	65.28785	57.23773	74.48229	47.88166	21.24417	81.31911

Table A.40. Complex Manufacturing System Average Late Time for Each Replication Using DT and Adjusted Fabrication Processing Times for FFF Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	93.07309	41.19403	99.28023	53.60903	83.69787	74.16949	133.3492	68.7753	72.18036	99.38478
2	33.36166	123.9451	89.22284	87.8266	115.4377	79.47732	95.18568	42.55857	61.71908	83.44349
3	77.59102	57.82623	65.23805	90.28321	87.4592	104.8476	125.1806	62.46663	82.74803	117.9894
4	44.15299	38.17103	51.67102	39.59835	91.76107	70.87877	119.3472	57.99488	103.1059	157.4103
5	73.05791	124.4954	62.54465	72.14218	91.73615	72.81448	86.87906	67.35541	103.116	88.1224
6	26.10692	57.68729	67.89228	58.55202	81.90141	61.37519	101.4316	67.42101	76.26244	103.2244
7	36.7256	83.39197	48.98343	76.52134	108.2076	61.86173	120.5204	59.21188	55.04548	93.04319
8	38.90725	66.41073	43.76442	122.9593	65.74791	88.67173	106.8435	65.8209	87.90226	115.0375
9	35.86838	54.89871	72.75237	61.01822	129.0508	89.52968	85.41881	74.3862	81.12163	138.4148
10	27.83525	69.70479	44.69475	72.97868	98.20963	75.64441	78.61935	47.03013	58.89612	83.26211
11	67.47468	45.21958	29.24926	67.69249	63.69098	120.4112	103.7428	60.84655	60.25432	122.9084
12	73.10609	58.73957	99.25592	40.30407	76.0225	68.17308	84.34152	73.48802	84.89431	106.1324
13	33.80403	62.31545	100.1924	50.61882	103.1138	79.92057	127.9149	57.90501	95.45739	52.96805
14	33.08632	53.19734	86.70856	55.28829	104.6826	88.47328	80.69294	91.59658	85.86253	126.0645
15	72.40674	53.77891	91.42021	68.61589	96.2481	85.41269	72.62064	74.43906	102.4424	110.4453
16	23.33835	43.83837	74.71912	76.39916	79.41715	33.0907	134.2966	61.20735	82.37239	90.43245
17	73.8371	100.3178	65.05503	97.24905	69.59227	92.57462	127.5176	61.73165	105.4655	75.46053
18	55.27467	68.4766	76.41107	87.90598	57.75332	87.01056	99.83049	46.28055	134.3371	59.60963
19	54.56809	27.23451	91.4671	130.3891	108.3291	100.9323	78.76701	89.00335	72.30759	115.6145
20	88.85506	58.43714	51.7502	102.6533	69.79534	113.592	91.25758	68.97876	116.6778	89.61475
21	45.77029	46.73141	43.50508	104.1075	79.80048	36.98009	67.80431	56.59362	95.00404	78.84222
22	63.24312	66.68608	96.5349	82.19934	80.56209	84.54937	100.4343	32.04902	100.4422	89.26834
23	30.7592	51.80794	80.74662	96.22297	127.7131	107.1312	86.32065	77.74054	103.6758	151.6194
24	45.44752	60.12866	144.1749	96.39966	108.6182	89.81619	102.5047	75.72366	124.6484	96.05239
25	72.13368	50.76375	73.24545	79.78521	70.86892	66.90837	68.82578	69.88044	85.68106	104.5316
26	57.33513	52.51221	55.49623	105.19	116.6157	73.59277	98.84141	66.72396	108.777	138.643
27	48.85755	85.5217	47.03794	49.07448	68.95051	81.0258	115.8043	43.78255	92.99085	88.32654
28	51.11398	42.72747	79.21283	58.1188	106.9897	85.39591	154.17	85.87804	87.28763	72.47586
29	28.83731	41.64955	69.02174	46.05511	60.40736	78.31546	104.4661	70.33316	59.76666	95.04614
30	98.70939	38.11337	63.1518	103.3195	117.9256	91.91076	79.76192	88.64023	91.56382	44.35828

Table A.41. Complex Manufacturing System Average Waiting Time for Each Replication Using DT and Adjusted Fabrication Processing Times for SSS Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	5.958401	8.590343	4.119995	6.794556	6.257442	6.501445	8.801699	4.136546	9.532402	10.3584
2	5.812821	3.307336	12.49334	5.672616	4.741408	9.046885	6.28655	5.832463	5.284665	6.582944
3	8.899492	6.754093	4.516716	5.843028	9.585407	6.651083	5.403854	8.852284	7.620302	10.05856
4	3.695039	9.415361	6.84971	10.64719	7.444193	5.56246	3.016433	8.496002	5.582371	5.074087
5	8.663588	4.144272	5.894618	8.547445	7.181394	5.209936	8.998911	5.589782	10.81018	5.496584
6	9.849181	6.486325	5.246363	8.222171	8.295924	6.876365	4.104638	7.410052	7.62113	4.048194
7	6.345474	8.192156	3.627028	8.724404	8.596827	8.722008	6.065849	10.24062	6.306763	7.331622
8	5.009012	8.220005	8.61926	6.215534	7.472205	5.913414	4.115031	8.559967	14.76774	3.591018
9	5.64479	6.45008	9.300727	5.266253	4.659766	5.204534	5.264182	4.27057	4.582125	5.557256
10	6.416794	6.310363	7.177936	5.181678	8.557999	5.720047	6.521768	8.514635	4.339965	5.413064
11	3.616971	8.486828	7.707757	5.545228	5.11872	7.83621	3.600259	8.59689	7.92661	5.648848
12	7.060417	8.205217	5.227883	8.867357	3.751495	4.932483	6.214071	6.168643	6.35721	7.211417
13	5.508099	5.930809	4.955523	6.81189	9.734584	6.184163	6.530142	6.43907	5.928089	4.177507
14	10.40467	4.190256	7.699797	10.11895	3.905432	6.635732	5.015244	5.012997	4.861865	4.894326
15	10.01217	6.497307	2.658754	13.46602	5.614365	8.26542	4.885306	5.979052	4.440473	4.665344
16	6.752768	5.573932	5.541792	3.61654	11.41173	11.26831	5.956516	11.25037	6.813186	7.364671
17	8.031063	6.857606	5.22708	7.055559	9.590396	6.186314	7.832625	6.915205	4.702971	9.572734
18	4.052758	4.899921	6.420208	7.199287	6.602919	7.81778	5.961337	4.447147	10.03005	7.07266
19	7.178387	3.585766	3.822285	7.865023	6.174704	5.696748	4.006229	7.784579	5.749459	7.53257
20	4.715125	6.472666	5.261014	8.876302	8.859326	12.71464	7.398296	7.508717	9.007134	9.868493
21	6.647236	3.822137	5.539556	4.37465	7.816071	3.494963	6.513279	5.366818	5.646594	6.892042
22	7.687599	6.290098	6.077458	7.508195	6.499296	3.645502	6.300125	5.652919	3.996638	6.633265
23	6.312771	9.532294	15.40774	8.13913	4.647454	7.407381	7.402503	6.023659	5.660575	5.720604
24	5.847687	8.79057	4.253321	7.420374	7.040367	11.30217	6.448361	7.650778	5.971633	6.671537
25	5.905137	11.16346	10.67065	4.19332	4.710923	7.045086	10.7623	8.865927	6.997763	7.888603
26	11.48786	5.524599	11.10105	12.05619	10.55545	7.489023	5.281864	4.835337	3.896308	7.999643
27	6.064887	6.882086	5.681509	6.302987	5.158099	12.19297	5.101234	4.067365	9.913156	6.254768
28	7.554915	5.592649	5.273368	9.801217	8.772384	5.763366	4.016412	8.183293	8.846714	9.725646
29	9.344803	4.821282	9.447956	6.731542	7.695295	5.449869	4.032675	6.704341	4.775586	5.510501
30	4.623495	3.944502	6.132402	9.116003	8.577768	6.767977	7.358021	4.591141	4.242465	3.412828

Table A.42. Complex Manufacturing System Average Waiting Time for Each Replication Using DT and Adjusted Fabrication Processing Times for SFS Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	7.330373	11.3902	9.147844	10.22952	6.945324	8.316715	10.79222	5.974727	8.642742	9.023193
2	6.678942	7.957097	10.0315	8.161952	10.41688	10.19965	7.360973	7.410333	9.241925	8.741781
3	11.34781	12.8609	7.161682	9.866367	15.48033	8.371332	11.59951	6.356415	6.975495	7.491118
4	13.3402	10.82577	9.655885	13.10253	7.371459	12.51056	8.89258	7.712991	6.755795	8.468571
5	4.752956	12.23996	12.16028	7.752643	5.295229	11.37043	5.727524	6.348351	7.422411	8.316555
6	12.45003	8.090642	8.45651	11.02423	8.646978	9.33084	7.742527	7.687094	6.641119	9.000827
7	6.69817	11.4783	6.221413	8.405223	7.006124	9.599419	7.735015	7.146502	9.501281	5.484415
8	7.656112	11.07125	4.856791	12.13855	9.844769	5.888035	9.375994	12.62449	8.568237	7.391354
9	10.33444	6.67594	6.719699	10.68166	11.4017	8.943014	10.60098	9.638934	9.966869	8.818795
10	8.190779	6.497924	7.086359	8.959073	8.96666	8.056645	10.4661	6.364647	8.419139	9.532044
11	13.51081	12.05635	8.029875	7.387768	6.718297	6.158209	6.158334	10.0141	5.427471	6.184048
12	6.283036	7.015095	6.010644	7.853884	7.856706	12.17439	6.850368	8.087909	9.457699	9.637901
13	8.689174	6.949544	7.197289	8.668211	7.321365	9.029187	4.895983	9.524207	8.48924	7.938002
14	9.719303	8.917179	9.113003	7.587874	10.66313	8.140637	9.236209	8.55135	5.589048	5.933095
15	11.11711	11.35219	9.592959	7.243989	8.874141	7.322885	7.914399	8.450397	6.408275	6.626384
16	8.703992	5.043456	8.047164	8.99464	7.799202	6.577396	7.422618	7.376967	14.55703	7.848573
17	13.08139	8.051041	7.530609	13.51441	7.019066	10.81284	5.040883	9.673829	6.985867	7.935335
18	6.562254	8.330696	7.171692	4.639103	8.394641	5.564643	8.458323	5.509419	10.20886	8.286118
19	7.914891	8.180718	13.44136	11.6474	10.30618	9.445586	8.020771	6.477409	8.963312	7.039189
20	8.938233	4.336039	10.0946	5.444472	8.083102	7.374202	9.395357	11.05084	11.26344	10.15795
21	8.685264	4.741622	9.778272	7.210109	7.563691	4.782113	6.776043	13.76613	7.307946	11.29604
22	8.346683	6.638585	8.590818	4.884057	12.0487	5.503793	10.81864	8.267237	8.787005	10.12397
23	9.215836	10.52418	6.114544	7.952609	11.62254	14.50602	8.092938	9.423351	6.858458	8.95858
24	7.892637	11.01179	11.67008	9.273761	6.66134	10.69059	8.036521	6.872627	9.757115	8.282661
25	6.485653	5.684161	7.032768	10.30251	9.45832	10.02089	6.380705	7.100941	9.014199	9.566689
26	3.815006	5.305435	6.424632	11.30223	7.306903	6.705269	10.47456	6.430174	8.399197	7.882281
27	8.596495	7.522185	10.37139	7.212869	8.500332	12.48371	8.389544	6.796524	8.388559	6.281393
28	7.642611	10.01959	7.435815	5.932611	11.71478	8.85363	10.36997	4.405202	10.22381	7.838877
29	13.86361	7.534479	6.819263	9.404389	11.58939	11.57262	6.630042	7.639439	10.45227	6.792223
30	7.007668	9.390842	7.436316	7.215821	15.93643	8.124195	9.236737	11.14059	7.215839	5.118024

Table A.43. Complex Manufacturing System Average Waiting Time for Each Replication Using DT and Adjusted Fabrication Processing Times for SSF Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	13.55284	8.138723	8.508779	9.349795	8.560712	7.461295	7.294338	9.27804	9.756448	9.01986
2	16.03936	7.45845	9.219263	5.424561	7.885385	10.30761	8.830221	9.877439	10.72223	6.037261
3	8.658007	7.416668	8.560793	9.722489	8.119351	6.210565	9.919929	7.0922	5.042416	11.54848
4	10.46021	14.86451	11.32361	6.659152	12.19766	8.109962	10.00936	7.510311	9.821962	13.03727
5	11.97196	8.39325	9.629412	8.410494	8.976734	9.984701	7.340452	9.683561	8.374057	9.84131
6	9.475347	8.129835	7.819235	9.002947	11.02574	12.2848	9.148237	8.695825	7.182656	7.863342
7	9.058887	6.998291	5.840756	7.121531	8.89875	7.883749	9.981396	7.654546	8.976172	8.944811
8	6.305184	11.05915	10.61542	10.83778	8.090639	9.323765	7.920237	10.6269	7.829692	9.000165
9	7.507981	11.78883	11.39364	7.514497	8.610554	10.00796	7.739139	7.649047	9.198111	8.111408
10	12.90172	10.64118	6.013639	8.083174	7.726456	7.216408	7.176556	8.792135	7.370166	8.387706
11	9.804152	12.25755	7.636264	6.92407	8.516094	7.921047	11.38333	7.277834	13.29793	9.280369
12	6.213336	9.571419	7.233362	10.02024	6.826366	9.811163	5.763585	6.19568	6.636245	7.835706
13	11.7716	7.814514	11.80538	6.65777	11.1381	9.527594	7.939913	7.348074	7.582263	7.352708
14	6.686519	11.34453	8.731148	6.410017	10.08456	8.329624	6.212321	13.22818	6.326988	8.686957
15	10.99235	9.868011	8.129657	9.493545	8.349986	9.800063	8.400314	8.991752	10.30767	9.43279
16	7.661861	6.951869	11.00466	8.004596	7.740858	8.491067	9.276413	7.251693	6.557425	8.387892
17	7.242595	9.456371	8.94684	14.62929	16.18963	7.465213	5.111274	9.782714	9.944993	9.745168
18	8.420055	9.516431	11.07618	10.95626	11.4323	8.08614	8.238929	6.710055	11.25566	8.247666
19	8.574796	8.508674	8.723644	11.68238	10.57516	7.195235	7.487306	11.58872	6.425975	6.339892
20	7.367569	5.484573	11.58396	6.746906	6.530076	8.814572	8.103523	8.03334	7.995229	6.336911
21	9.763637	11.58645	7.726161	13.39408	5.319001	6.623143	10.92244	8.080374	6.522222	11.31803
22	10.15075	10.9109	9.019655	9.93448	8.935486	8.775115	6.337565	11.56139	6.029833	7.788252
23	14.17823	11.99657	9.749066	11.30484	5.648545	10.65128	10.35652	6.858787	7.510663	12.97093
24	9.480351	7.944966	5.391802	5.057918	10.28537	8.648283	5.681691	10.32696	9.022474	6.834005
25	7.777042	8.733299	9.429102	5.730665	6.935991	7.630645	9.402177	8.086124	10.86426	5.829624
26	8.025612	9.47231	11.90651	9.537044	7.442463	8.803838	9.01593	9.569403	7.616932	7.551921
27	8.827834	11.39806	7.989042	11.51545	9.493834	8.80977	7.151612	8.195264	7.703547	9.497552
28	9.201061	9.600574	8.850759	12.35737	8.564449	6.968505	8.396039	7.993745	9.327418	5.982462
29	11.47374	9.077179	7.63956	5.959141	10.19153	8.597594	10.82831	9.757409	9.068865	7.281244
30	9.355934	9.308678	9.75263	10.46948	8.582155	8.974794	9.3875	6.423516	8.914612	11.29375

Table A.44. Complex Manufacturing System Average Waiting Time for Each Replication Using DT and Adjusted Fabrication Processing Times for SFF Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	8.529969	10.323	8.876445	8.896649	13.41712	11.89553	8.121385	9.557054	7.398985	10.30938
2	8.786596	10.58609	11.55091	8.968296	11.07464	11.47949	10.6523	8.37399	7.503641	9.301516
3	10.46132	10.35366	11.08188	8.569336	8.048995	8.017345	11.74155	10.6186	8.820291	7.409366
4	8.218989	8.710424	8.340977	10.93373	9.58552	10.0288	9.558434	8.46271	9.848661	8.096211
5	7.856323	13.43513	12.26979	12.44646	11.85805	7.104435	7.847607	8.130363	8.933971	10.41188
6	12.0154	9.905522	8.169805	12.30856	10.74489	11.1585	11.22099	10.46108	14.20656	8.230508
7	9.312455	11.0291	7.243083	8.481729	11.31927	14.29269	7.977642	8.078793	7.511376	7.521142
8	16.67899	10.1972	13.15545	10.29134	10.87881	7.184825	8.428963	11.51949	9.930777	14.0419
9	10.23046	9.148206	9.466581	14.35855	6.397272	8.783779	9.051193	10.66252	11.40694	8.795084
10	12.72653	8.876714	10.53487	11.56907	12.27208	9.774751	9.804047	11.84859	9.181473	10.47678
11	7.291578	10.62785	9.674424	11.63629	11.32562	9.048089	11.76221	9.526233	12.4214	8.847448
12	7.72931	7.845965	6.881213	8.804287	11.31123	11.29852	9.229876	7.906411	10.04485	9.207228
13	11.0061	7.362804	8.96017	8.50841	7.580937	8.845441	9.419261	8.059089	10.07728	8.374726
14	14.7484	12.73125	15.46701	8.184386	11.61218	8.716001	11.64054	11.89637	9.629289	8.129444
15	12.09101	7.211312	10.27202	9.192269	8.375965	7.42944	7.547492	7.562285	9.814048	7.853906
16	10.3868	7.442417	10.56143	7.353657	8.856377	9.989563	8.486087	14.92644	9.035157	9.355485
17	10.16647	10.19166	12.17565	9.71002	9.267725	8.985134	10.21937	11.13341	11.13227	8.049558
18	8.910039	7.507519	12.42892	8.96689	8.577633	9.875979	9.782386	12.1688	13.5241	7.464617
19	11.41137	10.29052	9.293204	8.185377	10.60959	11.39316	9.227082	7.942937	9.291283	9.921751
20	10.14747	8.915929	6.676741	11.58051	9.714712	7.2352	9.053403	11.89514	8.713063	10.16442
21	11.58641	6.598238	13.79523	15.43843	17.08643	9.479363	12.56482	8.782989	8.070708	5.788698
22	8.164955	11.78612	8.015346	7.829592	12.65831	7.980119	7.172441	10.72415	8.682358	9.153511
23	10.1136	10.04595	8.584505	10.63451	14.11832	11.44731	7.407924	12.74699	8.430869	8.542728
24	12.91175	13.58466	16.74884	9.435428	9.146378	8.242071	8.756079	8.043176	11.2966	14.55312
25	11.02701	9.010291	11.22852	10.48806	8.095809	6.654897	10.46418	9.910761	10.18824	10.88758
26	9.480252	8.71445	9.931643	8.406931	12.93428	11.1553	9.526916	9.725721	7.201685	9.913662
27	9.919329	7.702908	8.658513	6.505948	10.25193	13.04264	10.56578	11.73187	8.553877	14.31071
28	9.75246	8.332698	8.174278	14.78692	12.50252	7.997754	9.931302	9.47028	11.04751	8.756818
29	10.50615	6.396691	8.801245	8.102042	8.925173	7.975739	10.70468	9.865767	7.141412	11.04811
30	10.60765	10.63913	9.880892	11.76578	11.38449	8.85398	7.530407	6.637564	8.837457	8.051093

Table A.45. Complex Manufacturing System Average Waiting Time for Each Replication Using DT and Adjusted Fabrication Processing Times for FSS Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	8.48869	6.560169	7.650495	9.540092	8.92776	8.794181	6.510839	9.090076	7.660186	6.830408
2	14.07921	8.401667	6.495694	6.658384	6.241978	7.20248	8.691932	6.967	7.758447	7.549573
3	9.16545	6.829426	6.566699	7.481486	10.40269	11.65906	6.989114	9.233904	9.257316	6.731631
4	8.797373	7.874226	12.56122	11.20767	9.004753	9.832929	12.04147	7.435929	6.248907	7.545175
5	9.189358	5.947402	6.390906	9.336355	9.940383	6.864165	5.136208	7.004533	7.795517	7.67363
6	5.860455	7.848567	10.29342	8.898778	7.301825	10.52314	9.641775	9.237962	8.967779	9.658287
7	10.278	5.986976	10.30184	10.97609	6.989961	6.174137	6.457505	7.166525	11.83536	6.236669
8	7.907954	7.504296	7.760631	7.837089	10.69765	6.2315	5.840924	6.745611	10.65092	7.425174
9	8.718014	8.676197	9.502154	8.666159	9.56189	7.319366	5.789569	6.616438	8.709011	6.604649
10	6.203286	6.313016	13.20091	6.953402	7.038952	8.416241	4.298075	7.341574	4.773555	6.367046
11	8.259723	6.42954	7.725658	8.616403	7.366009	5.677619	11.62186	7.750793	4.542995	6.359582
12	6.625983	8.85044	14.61531	7.137719	8.589968	10.93917	6.672685	9.966899	5.755037	15.16065
13	9.087395	12.21905	6.086964	6.139023	11.34457	10.13893	6.715106	7.662464	7.928332	6.629753
14	8.846396	8.713698	8.716174	10.57673	7.091621	6.153708	5.689812	8.30633	7.965081	8.129459
15	8.358204	8.750339	7.712202	11.08947	10.45732	9.320818	7.367915	10.34069	6.298184	7.16693
16	7.077531	7.239701	7.543452	7.860828	8.113315	9.558143	8.53611	8.012292	7.511047	6.387112
17	9.125299	9.181978	5.781801	7.969013	8.219083	8.073901	8.792913	6.136564	5.97096	8.719552
18	9.223878	6.933719	6.641937	6.703092	7.491996	6.763294	9.024608	6.137628	7.608265	12.56263
19	8.049339	7.606947	8.120829	9.599977	7.484934	6.406964	10.39254	9.445459	8.204554	8.265451
20	7.476519	8.999597	13.8926	7.007392	16.66295	8.24478	6.297945	10.58556	8.495292	8.509177
21	12.40225	7.567155	5.906669	5.942546	6.545003	6.258366	9.949592	7.088589	7.43699	8.701828
22	9.157409	7.811297	5.597409	5.581683	10.58352	11.0523	8.189214	12.72457	9.190118	10.24228
23	12.96401	8.451006	10.85779	7.477355	7.007339	8.283045	7.456984	7.655085	8.039128	7.619043
24	6.772347	5.491927	8.227215	8.678391	11.3648	7.113073	7.519941	7.309597	9.829422	8.283352
25	9.209978	4.661539	9.560189	8.982065	6.3486	4.785779	9.002352	7.976979	7.699259	9.529284
26	6.912547	10.82348	7.831038	7.237131	6.712919	7.634042	7.595197	7.145533	7.462129	6.34033
27	8.957877	8.434818	9.98817	10.645	9.44504	11.37029	5.849783	7.44302	6.527606	8.507916
28	7.163086	8.696059	8.771407	12.2469	10.83264	12.16304	11.26205	7.170462	6.760509	10.73084
29	5.320838	8.941557	7.522605	6.622315	7.694186	5.286254	7.539848	8.875257	7.898855	15.35513
30	8.028212	6.343834	8.239818	5.637781	6.932221	6.949525	7.606088	8.939141	10.96071	7.944758

Table A.46. Complex Manufacturing System Average Waiting Time for Each Replication Using DT and Adjusted Fabrication Processing Times for FSF Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	9.768093	17.68248	7.739653	8.738062	10.07148	8.806721	10.40199	9.479284	9.443251	6.606573
2	8.521691	8.45917	11.56817	8.82231	8.370177	8.065288	8.334673	9.124697	8.345903	8.395374
3	11.56186	10.20785	8.120908	8.64435	7.599372	11.31058	9.424493	8.4417	7.458632	7.995773
4	9.175847	13.05324	9.608243	7.282589	10.05374	8.080057	6.643429	12.31924	7.521027	6.42457
5	11.92496	8.225852	9.017127	11.07574	10.79323	8.198603	7.068348	6.901883	10.09	12.63687
6	9.509131	6.841023	8.908705	9.744184	10.91727	10.5593	7.724205	8.559544	7.601151	8.979387
7	12.75814	8.224611	9.607817	7.1754	8.381703	8.822041	8.310668	10.65383	6.866347	10.08991
8	9.877752	11.92137	11.90381	12.12668	8.139087	9.499964	8.730191	8.224601	12.2204	11.67054
9	10.68898	7.064058	7.691798	6.60077	8.378631	8.482496	11.62562	7.857375	7.628863	9.093158
10	7.899076	10.24187	9.995373	8.438236	7.197732	8.549633	6.004799	9.222719	9.231132	9.994818
11	10.97597	11.08472	10.40932	7.755838	9.519487	6.792533	8.18942	9.904382	12.95516	7.123678
12	8.895763	7.590773	8.185148	10.59478	8.147482	8.702561	8.884109	7.647104	7.088342	6.015026
13	7.362366	12.98476	11.40436	9.3292	7.443631	9.018837	11.13236	11.10158	6.896378	10.29333
14	10.08619	10.6981	11.55296	8.924766	8.448894	7.748442	7.794654	7.856944	6.966789	7.447845
15	9.100165	7.562356	8.517569	11.03957	9.67074	8.743279	9.168508	6.917821	6.347452	9.199455
16	8.47411	7.969367	11.43463	6.720259	10.56341	10.27008	12.22285	17.86313	8.522431	9.3953
17	11.65106	8.907384	7.495563	7.526648	9.583283	7.877072	10.15183	6.394559	7.383252	7.025091
18	10.04109	15.00733	11.45994	11.11138	8.052059	6.053284	9.025448	8.640829	7.192759	6.925256
19	9.843447	10.93279	8.405746	6.719941	7.939581	9.191292	8.635754	10.3708	7.238945	7.358692
20	11.14627	11.90529	8.471587	10.23411	8.249728	10.59734	8.190299	8.178862	7.544181	8.391361
21	9.05928	10.85488	20.04097	8.86719	10.12962	7.708989	12.39054	9.282645	19.75323	6.621544
22	10.50178	7.593047	10.93558	8.62903	7.133405	8.443634	10.89127	10.11174	10.4802	8.648178
23	8.884384	8.334048	9.883458	18.84189	10.53807	8.938411	6.65523	9.42651	8.488117	8.270824
24	11.40677	8.51212	11.36067	10.72371	7.835019	13.69659	11.65248	10.86645	7.133581	11.53591
25	10.34946	6.869819	7.214208	8.798211	13.76582	13.09942	9.200671	10.1025	7.346187	10.12025
26	8.463586	8.277293	10.23418	7.901067	6.519943	8.490391	8.819761	8.19295	7.504364	7.429011
27	9.169602	7.764481	10.7601	7.922642	11.02562	11.19253	9.983685	6.737462	9.477986	7.071105
28	9.449498	8.967858	9.908087	9.113794	9.369188	7.833914	7.694856	8.395797	7.281347	6.502228
29	9.088945	9.04701	8.04602	6.891069	8.504606	9.55342	8.409097	9.995457	10.95613	7.732705
30	7.907863	10.7332	9.949794	7.955371	7.947136	8.188972	7.903385	10.37512	7.180732	10.20116

Table A.47. Complex Manufacturing System Average Waiting Time for Each Replication Using DT and Adjusted Fabrication Processing Times for FFS Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	8.602084	9.2014	8.895257	9.5875	7.033008	7.741407	8.680296	8.273018	7.685264	7.251364
2	8.413795	8.779206	7.502139	7.457513	9.555821	9.831965	9.654521	6.378147	6.718371	6.333675
3	12.16034	9.086695	9.178925	9.407452	8.645105	5.869149	11.0298	7.291907	8.246765	6.990898
4	10.08005	8.570132	7.754404	8.147852	7.286423	9.997475	6.338736	5.539824	7.333305	8.049794
5	8.847896	6.130707	7.869021	11.15865	13.65445	6.723741	6.854415	8.018408	10.44858	6.797295
6	5.834822	9.419841	10.17922	10.67653	7.928165	9.948185	5.6916	7.173323	10.27568	6.924923
7	12.72018	10.43127	8.806648	8.793144	12.0389	8.097907	8.60077	7.90148	6.239308	7.799453
8	8.014162	12.01533	8.797312	7.449988	7.818982	7.603106	6.067664	9.448253	6.662331	6.791627
9	13.24733	9.677324	9.191305	9.958558	9.993989	7.867052	10.90041	7.998832	5.854747	6.86945
10	10.20092	9.914367	7.148664	7.952641	7.612152	12.73001	8.812906	10.41336	8.37677	6.564017
11	6.532737	8.882543	8.311131	11.9236	7.82594	12.50242	7.699903	5.670167	8.746537	6.385878
12	13.82848	13.42005	6.961155	11.23599	7.234897	10.19227	8.573609	8.922851	11.17853	9.565189
13	9.275312	8.244457	8.576281	7.489253	8.023823	7.092911	8.12102	10.0689	5.21495	7.434596
14	10.30781	9.312025	8.561949	8.216673	9.285424	9.007192	8.074856	7.630837	7.221044	11.30984
15	8.465008	7.111468	8.517669	7.678282	10.98826	8.014849	7.46338	9.619011	6.163598	8.296735
16	9.570738	10.0869	8.425796	8.792236	9.48733	5.904893	9.430844	9.328187	7.908127	7.787513
17	8.246079	11.99724	7.533876	8.802583	10.64428	8.350243	7.768084	13.36622	6.543279	8.624168
18	10.07531	6.384221	7.720056	8.230402	9.146509	12.13697	7.750981	8.022541	10.04683	9.710767
19	9.213728	8.419753	7.969499	8.30257	9.581858	10.53131	7.797357	9.580568	6.864016	7.514043
20	11.66717	6.226763	7.142221	7.611468	11.52184	6.342594	8.554355	7.346549	6.299762	7.52928
21	8.141427	7.96983	7.994779	6.771908	8.206572	9.735929	8.399769	7.055465	7.702137	8.824512
22	6.706081	7.155754	7.465188	8.668902	8.551355	8.257971	9.484074	6.580454	6.762655	6.963745
23	7.034814	11.04942	7.382989	6.68627	10.44921	8.932137	7.578619	8.730332	9.200954	8.536204
24	11.72757	11.32535	6.152305	8.614712	14.24791	7.09959	7.957808	6.935312	13.3522	7.133191
25	6.412671	7.84007	8.620826	8.635702	8.659071	7.008985	7.977582	8.489271	6.354779	10.38105
26	9.241147	9.665851	8.588645	8.336293	8.618881	5.730387	9.279347	6.058687	6.648742	7.157363
27	6.626419	7.743377	6.012561	8.523718	9.203296	8.520529	9.282186	10.30078	11.09564	12.47701
28	9.625981	8.399252	10.27273	10.82389	10.17821	7.368448	12.43209	6.209091	9.414485	6.410553
29	8.198804	8.017292	7.902744	9.072816	7.361063	9.033606	5.696966	8.43545	7.196658	8.528439
30	9.815937	10.4783	7.629971	9.299995	9.255526	10.24915	8.371167	6.590601	9.044097	7.773602

Table A.48. Complex Manufacturing System Average Waiting Time for Each Replication Using DT and Adjusted Fabrication Processing Times for FFF Arrival Rate

	Decision Period									
Replication	30	60	90	120	180	240	300	360	420	480
1	9.232618	9.587507	9.660453	8.112427	9.117715	9.217944	12.3321	8.010461	7.584058	9.870271
2	11.23572	8.134393	9.474827	9.323393	9.027468	8.689683	6.645671	9.03798	8.665975	11.16217
3	8.080278	9.913654	7.381459	11.85858	7.473008	12.25699	8.814113	8.00846	7.948276	8.968596
4	9.927695	12.17411	9.166504	10.85001	10.7106	8.911245	10.34393	7.798131	8.706029	9.215752
5	9.501127	8.313442	11.48537	9.263374	6.596319	8.245795	6.925258	8.99929	6.253612	8.139329
6	15.67536	7.630385	8.520322	9.633116	8.155778	6.675296	9.467527	12.45865	6.548831	9.971438
7	7.263987	9.752977	9.282308	8.829195	7.883785	7.388305	8.598458	10.2075	11.17294	10.63448
8	8.998781	9.044075	9.622226	8.563868	7.448136	11.95058	9.289717	10.85404	9.790527	10.73462
9	9.367511	9.385161	7.513116	6.0699	11.15064	9.202449	9.109385	10.49427	9.717592	8.128384
10	7.664542	10.56754	7.926695	11.12576	8.592495	7.862876	6.878427	8.828566	8.803991	7.591079
11	9.190781	11.15547	11.23185	7.567098	9.154857	11.71646	6.972114	9.773882	9.735937	13.64205
12	10.96947	9.914059	9.310931	7.81899	9.521683	9.36541	9.152343	7.797585	9.832007	8.445534
13	11.74646	9.142035	8.605977	10.71027	10.22796	9.273736	8.445874	9.208368	9.570386	7.332481
14	9.977733	8.600868	11.07568	11.57193	10.95006	8.219041	10.99677	8.475964	10.98593	7.118042
15	8.613476	13.90297	7.97384	7.712202	11.70021	8.765891	7.377801	10.75523	6.989873	8.181907
16	11.6362	9.202215	9.737716	10.11846	8.777352	8.1056	9.337628	13.4278	6.02288	7.12843
17	9.743092	8.877534	8.278674	7.158376	9.163041	8.731217	9.53124	8.869424	10.29233	7.656658
18	9.163413	7.454011	10.27617	9.327339	7.881598	9.027942	8.635459	8.03336	12.56296	8.036934
19	12.14887	9.659229	8.421079	8.844454	10.14073	6.539791	6.242367	9.15106	9.008296	8.14571
20	8.403949	12.49019	9.248357	7.068533	9.704055	13.02987	9.193726	12.90961	7.917344	10.34744
21	9.750828	13.92102	7.463929	11.3615	10.01332	10.0376	7.862005	8.684064	12.09639	9.128451
22	7.468135	10.25585	11.2284	12.89623	8.813278	9.679482	6.504895	7.70539	8.738797	7.986798
23	10.44412	9.39124	10.87378	11.35408	10.93372	9.891269	8.581021	14.27497	14.46243	10.64998
24	13.5347	8.922177	10.59193	11.14485	10.05121	10.20742	10.88272	11.70077	9.48093	8.362331
25	14.30518	11.10346	7.613793	7.100254	10.32353	10.43098	10.53842	9.259679	8.059328	11.09081
26	9.359029	9.62565	6.913279	9.465021	10.07141	6.743135	7.717579	9.447577	8.556669	7.326066
27	13.38197	9.090607	15.12506	10.54512	6.80922	9.326336	9.440616	7.426493	6.619815	8.1152
28	12.68349	11.58912	7.999694	8.827732	8.655026	9.467512	10.83236	9.036061	7.319544	8.570426
29	10.61229	8.868713	9.506363	7.540024	11.12961	9.951626	10.77487	9.5473	9.194447	7.066045
30	12.1774	7.970681	6.986621	9.312975	9.629935	7.560255	7.364548	7.725296	7.235786	7.6619

VITA

Edwin S. Kim was born on June 17, 1987 in Northampton Massachusetts. He received his Bachelors in Operations Management from the University of Massachusetts Amherst and his Masters Degree in Industrial Engineering from the University of Massachusetts Amherst. He enjoys playing golf, basketball, bowling, watching movies, hanging out with friends, and trying new things.

His pursuit of his doctoral degree has given him the privilege of working with amazing scholars and meeting life long peers. Although the road was long, every moment was a learning experience and an enjoyable time in his life.