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WORKFORCE PLANNING MODELS FOR DISTRIBUTION CENTER OPERATIONS

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by

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ABSTRACT

Customer order fulfillment at distribution centers (DC) is increasingly necessitated by innovative strategies to maximize operational performance that are primarily driven by cost and service level under supply chain variability. In order to better understand the trade-offs, in this thesis, a generic computational model is developed to estimate forklift travel times for DCs with any arbitrary floor space and loading docks. In particular, travel times are modelled as random variables and the moments of the probability distribution of travel times are estimated and used as inputs to analytical queueing model and discrete event simulation model. Results show that the analytical and simulation models are within 3% under different demand scenarios. These models are used to determine the impact of workforce capacity on key performance measures such as Truck Processing Time (TPT) and Labor Hours Per Truck (LHPT). The workforce capacity for different demand scenarios is determined using three different approaches - Target Utilization Level, Square Root Staffing (SRS) rule (adapted from call center staffing) and Optimization. The result from these models indicate that adapting workforce capacity to match varying demand can reduce cost by 18% while maintaining desired service level.

Keywords: Distribution Center; Decision Model; Workforce Capacity; Simulation

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DEDICATION

to my mother, Asha

CHAPTER 1

INTRODUCTION

1.1 Distribution Center Operations

Supply chain variability can be caused by product seasonality, batch production and transportation, product consolidation or value added processing. Distribution Centers (DCs) buffer the material flow in supply chains to accommodate this variability. Incoming items brought to the DC are unloaded at the receiving docks (receiving) and put into storage (storing). Outgoing items are retrieved from storage (order picking), processed and shipped to customers through the shipping docks (shipping). Resources such as space, labor, and equipment are allocated to different DC functions following organizational policies to achieve desired operational performance in terms of capacity, throughput and service at minimum cost. DCs can adapt to varying demand by adjusting workforce capacity to meet desired service level. The different DC functions are shown in Figure 1.1, [1], [2].

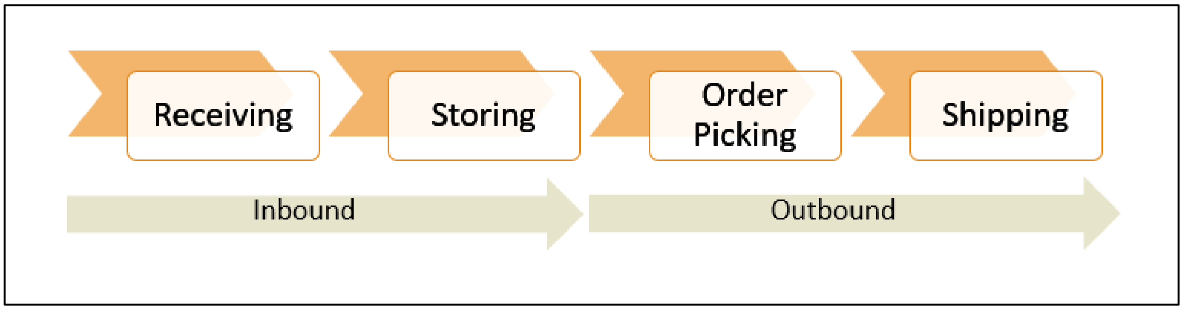


Figure 1.1. DC Functions

1.2 Literature Summary and Research Motivation

Several authors had investigated the effects of warehouse design and control on operational performance and developed analytical and simulation models for performance analysis. Pandit and Palekar (1993) investigated the effects of warehouse design on response time and suggested a method for optimal design based on response time, [3]. Chew and Tang (1999) presented a travel time model that evaluates performance of an order picking system with consideration to order batching and storage allocation strategies, [4]. Graves et al. (1977) evaluated warehouse performance for several sequencing and class based storage policies using continuous analytical models and discrete evaluation procedures, [5]. Bozer and White (1990) modelled the performance of an end-of-aisle order picking system by deriving analytical expressions and developed a design algorithm to determine the optimal configuration, [6]. Koster (1994) proposed a modeling and approximate analysis method for a pick-to-belt order picking system based on Jackson network modeling and analysis, [7]. Lee (1997) presented an analytical method for the stochastic analysis of a unit load AS/RS, [8]. Hur et al. (2004) presented an analytical model for the stochastic analysis of a unit load AS/RS without assuming any specific distribution for the travel time of the S/R machine, [9].

The existing literature is heavily focused on warehouse design & control using travel time models and performance analysis in terms of throughput, resource utilization and storage strategy for order picking systems. As labor cost can be a significant component of variable cost in DCs, it is evident that there is a need for research to explore the impact of workforce capacity on DC performance by considering cost and service level trade-off for varying demand scenarios.

1.3 Overview

The thesis develops a decision model that integrates critical operational performance measures to evaluate DC performance and workforce capacity policies under varying demand scenarios. The framework for workforce planning models is shown in Figure 1.2.

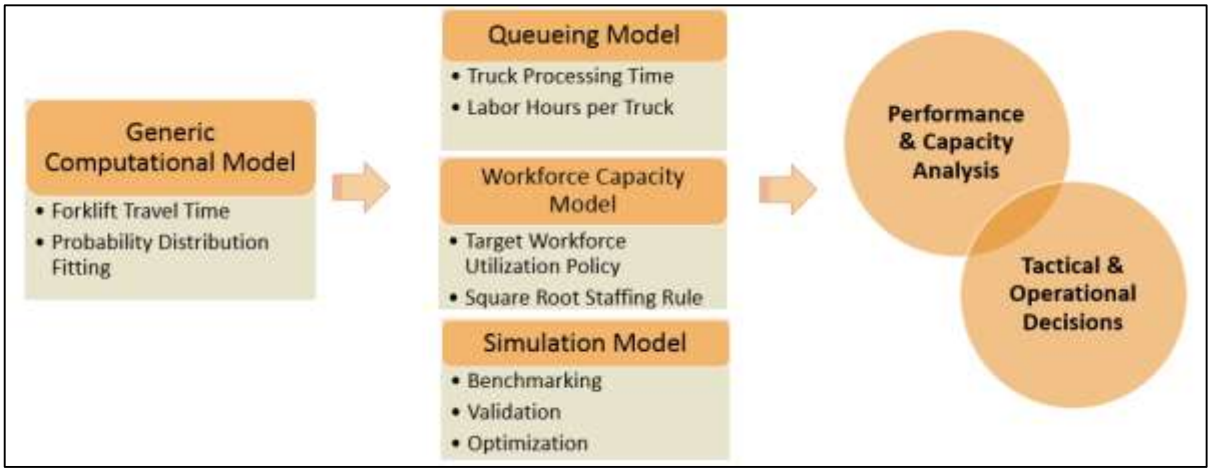

Generic Computational Model
• Forklift Travel Time
• Probability Distribution Fitting
Queueing Model
• Truck Processing Time
• Labor Hours per Truck
Workforce Capacity Model
• Target Workforce Utilization Policy
• Square Root Staffing Rule
Simulation Model
• Benchmarking
• Validation
• Optimization
Performance & Capacity Analysis
Tactical & Operational Decisions

Figure 1.2: Workforce Planning Models for DCs

Generic Computational Model

Labor cost can be a significant component of variable cost in DCs owing to variability in demand. The desired service level in DCs are also to be met for different demand scenarios. In order to better understand the trade-offs between cost and service level, a large scale, non-automated, rectangular DC is analyzed and a generic computational model with length (L), width (W), aisle-width (A) and number of docks (N) as parameters is developed to estimate forklift travel times in DCs. The skewness profile of forklift travel time distribution against L & W and distance from center dock is investigated. The travel times are modelled as random variables and the moments of the probability distribution of travel times are estimated and used as inputs to analytical queueing model and discrete event simulation model.

Analytical and Simulation Model

The analytical and simulation models are used to determine the impact of workforce capacity on key performance measures such as Truck Processing Time (TPT) and Labor Hours Per Truck (LHPT). Results show that the analytical and simulation models are within 3% under different demand scenarios. The workforce capacity for different demand scenarios is determined using three different approaches - Target Utilization Level, Square Root Staffing (SRS) rule (adapted from call center staffing) and Optimization. The target utilization level is taken as 70% for DC workforce capacity analysis. The SRS rule is applied for efficiency driven, quality driven and quality efficiency driven operational regimes in DC. Multi-objective weighted optimization and pattern frontier optimization are used to determine optimal workforce capacity scenarios in DC. The result from these models indicate that adapting workforce capacity to match varying demand can reduce cost by 18% while maintaining desired service level.

1.4 Organization

The thesis is organized as follows:

Literature review on warehouse design, control, performance evaluation & operations, queueing models in production systems and service engineering in call centers is presented in chapter 2. The travel time computational model, investigations on skewness profile for forklift travel time distributions and the DC queueing model are explained in chapter 3. The performance analysis results obtained from the queueing model is provided in chapter 4. The workforce capacity estimation results by the application of SRS rule is produced in chapter 5. The benchmarking and validation results from the discrete event simulation model are detailed in chapter 6. The conclusions arrived at from the research are presented in chapter 7.

CHAPTER 2

LITERATURE REVIEW

2.1 Warehouse Design and Performance Analysis

2.1.1 Travel Time Models for Warehouse Design

Pandit and Palekar (1993) investigated the effects of warehouse design on response time and suggested a method for optimal design based on response time. The multi-vehicle material handling system in an automated rectangular warehouse was modelled as an M/G/K queueing system. An expression for waiting time in the queue was approximated after computing first and second moments of the service time distribution. The optimal layout design for the warehouse was determined by modelling a nonlinear integer programming problem that minimizes response time and solving it by Generalized Reduced Gradient method. It was concluded that the effect of door location on optimal layout design was significant. Using a simulation model, it was concluded that congestion does not have a significant effect on response time, [3].

Chew and Tang (1999) presented a travel time model that evaluates performance of an order picking system with consideration to order batching and storage allocation strategies. The order picking system for a rectangular warehouse under general item location assignment was modelled as an E_k/G/c queueing system. The exact probability mass function that characterize the tour of an order picker was determined. The first and second moments of expected travel time, its bounds and approximation was derived from the model as a performance measure. The expected bounds and approximation for turnover time was also derived as a service level measure. The travel time model was validated using simulation. It was concluded that skewed item location performed better that uniform item location for a given batch size, [4].

2.1.2 Performance Analysis under Class-based Storage Policy

Graves et al. (1977) evaluated warehouse performance for several sequencing and class based storage policies using continuous analytical models and discrete evaluation procedures. Operating performance was measured in terms of expected one-way travel time, expected interleave time and expected round-trip time. It was established that significant travel time reduction was obtained from dedicated storage over random storage. It was also determined that class based storage with relatively few classes yields travel time reductions comparable to dedicated storage, [5].

2.1.3 Performance Analysis of Order Picking Systems

Bozer and White (1990) modelled the performance of an end-of-aisle order picking system by deriving analytical expressions and developed a design algorithm to determine the optimal configuration, [6].

Koster (1994) proposed a modeling and approximate analysis method for a pick-to-belt order picking system based on Jackson network modeling and analysis. It evaluated performance measures such as system throughput, picker utilization and average number of bins in the system based on factors such as the speed and length of the conveyor, the number of picking stations and the number of picks per station, [7].

2.1.4 Performance Analysis of AS/RS

Lee (1997) presented an analytical method for the stochastic analysis of a unit load AS/RS. A unit load AS/RS was modelled as an M/M/1 queueing system with two queues (storage and retrieval) and two different service modes (single command and dual command). The performance of AS/RS was evaluated using analytical expressions for system throughput, S/R machine utilization and turnaround time, [8].

Hur et al. (2004) presented an analytical model for the stochastic analysis of a unit load AS/RS without assuming any specific distribution for the travel time of the S/R machine. A unit load AS/RS was modelled as an M/G/1 queueing system with two queues (storage and retrieval) and two different service modes (single command and dual command). The performance of AS/RS was evaluated using analytical expressions for the probability distribution and the expected number of commands waiting in the storage and retrieval queues, [9].

2.2 Queueing Models in Production Systems

Wallace and Mark (2001) defines a production system as "an objective-oriented network of processes through which entities flow." The "objective" is to generate revenue; "process" include usual physical and ancillary production processes; "entities" comprise parts produced/processed in the system and information used to control the system; "flow" describes how materials and information are processed; production lines connect individual processes and the overall system to create a "network" of interacting parts, [12].

2.2.1 Little's Law

Littles' law (1964), provides a fundamental relationship between three long-term average measures of performance of any production system and can be applied in queue length calculations, cycle time measures and inventory planning.

$$\text{WIP} = \text{TH x CT}$$

where,

WIP: Work in Process, the inventory between start and end points of a product routing

TH: Throughput, the average output of a production process per unit time

CT: Cycle time, the average time from the release of a job at the beginning of the routing until it reaches an inventory point at the end of the routing (i.e., the time a part spends as WIP)

2.2.2 Variability

Variability is the "quality of non-uniformity of a class of entities", [12]. It has a significant impact on the performance of any production system and is a critical measure in production management. It can be caused by the process owing to cycle time fluctuation, outage or setup change or by flow during transfer of parts from one station to the other.

Coefficient of Variation (CV) is a relative measure of variability of a random variable and is denoted by,

$$\text{CV} = \frac{\sigma}{t}$$

where,

σ: Standard Deviation

t: Mean

A random variable can have three classes of variability: (i) Low Variability (LV), if CV is less than 0.75; (ii) Moderate Variability (MV), if CV is between 0.75 and 1.33; (iii) High Variability (HV), if CV is greater than 1.33.

2.2.3 Queueing System

High levels of variability cause waiting and waiting time is mostly the largest portion of cycle time in a production system. “The science of waiting” is called queueing theory, [12]. A queueing system comprise of an arrival process, service process and a queue. The part can arrive individually or as a batch and can have identical or different characteristics. Inter-arrival time and process time can be constant or random. The parts can be processed by a single machine or several machines in parallel following a queueing discipline such as first-come-first-served (FCFS), earliest due date (EDD), shortest process time (SPT) or last-come-first-served (LCFS). The queue space can be finite or infinite.

2.2.4 Queueing Notation and Performance Measures

The following parameters are assumed to be known to apply queueing theory and analyze the performance of a system, [12]:

r_a = Rate of arrivals in parts per unit time

t_a = Average time between arrivals (in minute)

$\frac{1}{r_a}$

c_a = Arrival CV (Coefficient of Variation)

m = Number of machines available for a process

t_e = Mean effective process time

c_e = CV of effective process time

The performance of a queueing system is characterized by the following parameters, [12]:

u = Utilization

$\frac{r_a}{m}\ t_e$

CT_q = Expected waiting time in queue for a process

CT = Expected time for a process

$CT_q + t_e$

WIP = Average work-in-process level at process

TH x CT

WIP_q = Expected WIP in queue

r_a x CT_q

c_d = Departure CV

$\sqrt{c_e^2\ u^2 + c_a^2(1 - u^2)}$

2.2.5 Kendall’s Notation

A queueing system is described by Kendall’s notation as A/B/m/b.

where,

A: Inter-arrival time distribution

B: Process time distribution

m: Number of machines available for a process

b: Queue space

A and B can be a constant (deterministic) distribution denoted by D, exponential (Markovian) distribution denoted by M or general distribution denoted by G.

2.2.6 M/M/1 Queueing Model

M/M/1 queueing model assumes an exponential inter-arrival time and process time with a single machine for the process that follows a FCFS queueing discipline having unlimited queue space.

$$\text{WIP (M/M/1)} = \frac{u}{1-u}$$

Using Little’s law,

$$\text{CT (M/M/1)} = \frac{\text{WIP (M/M/1)}}{r_a} = \frac{t_e}{1-u}$$

$$\text{CT}_q \text{ (M/M/1)} = \text{CT (M/M/1)} - t_e = \frac{u}{1-u} \quad t_e$$

$$WIP_q\ (M/M/1) = r_a \times CT_q\ (M/M/1) = \frac{u^2}{1-u}$$

2.2.7 G/G/1 Queueing Model

G/G/1 queueing model assumes a general inter-arrival time and process time with a single machine for the process that follows a FCFS queueing discipline having unlimited queue space.

By Kingman's (1961) equation,

$$CT_q\ (G/G/1) = \left(\frac{c_a^2 + c_e^2}{2}\right)\left(\frac{u}{1-u}\right)(t_e)$$

2.2.8 M/M/m Queueing Model

M/M/m queueing model assumes an exponential inter-arrival time and process time with m parallel machines for the process that follows a FCFS queueing discipline having unlimited queue space.

By Sakasegawa's (1977) approximation,

$$CT_q\ (M/M/m) = \frac{u^{\sqrt{2(m+1)}-1}}{m\,(1-u)}\ t_e$$

2.2.9 G/G/m Queueing Model

G/G/m queueing model assumes a general inter-arrival time and process time with m parallel machines for the process that follows a FCFS queueing discipline having unlimited queue space.

$$CT_q\ (G/G/m) \quad = \qquad \left(\frac{c_a^2 + c_e^2}{2}\right) \left(\frac{u^{\sqrt{2(m+1)}-1}}{m\,(1-u)}\right) (t_e)$$

2.3 Service Engineering

Service Engineering “develops scientifically-based design principles and tools that support and balance service quality, efficiency and probability, from conflicting perspectives of customers, servers and managers”, [13]. Contact Centers are service organizations for customers to request service via the phone, fax, e-mail, chat or other tele-communication channels. Call Centers are a type of contact centers that primarily serve phone calls. Call center operations can be viewed as queueing systems.

2.3.1 Operational Regimes

It is imperative to have the appropriate balance between service quality and efficiency. The operational regimes for a queueing system can be a Quality Driven (QD) with emphasis on service quality over efficiency, Efficiency Driven (ED) with emphasis on efficiency over service quality or Quality Efficiency Driven (QED) regime with trade-off between quality and efficiency.

2.3.2 Square Root Staffing (SRS) Rule

Operational preferences can be set by determining service capacity relative to service demand. The Square Root Staffing (SRS) rule is applied in call centers to determine the appropriate staffing levels (n) for an offered load and quality of service and is approximated as:

$$n = R + \beta\sqrt{R}$$

where,

R: Offered Load, the amount of work that arrives in the system in unit time

β: Quality of Service parameter

The value of β reflects the service-level and operational efficiency trade-off and signifies the operational regime of the system. Larger the β value, better the service level, [13], [14].

2.4 Chapter Summary and Conclusions

- The existing literature is heavily focused on warehouse design & control using travel time models and performance analysis in terms of throughput, resource utilization and storage strategy for order picking systems.

- It is evident that there is a need for research to explore the impact of workforce capacity on DC performance by considering cost and service level trade-off for varying demand scenarios.

CHAPTER 3

MODEL AND ASSUMPTIONS

3.1 Travel Time Computational Model and Analysis

A generic computational model with length (L), width (W), aisle-width (A) and number of docks (N) as parameters is developed to estimate forklift travel times in DCs. The model is capable to evaluate DCs with a size between 60,000 sq.ft (small scale) and 500,000 sq.ft. (large scale) and up to 45 docks. A probability distribution is fit to the forklift travel times and moments of the distribution is provided as input to the DC queueing model, (see Section 3.2).

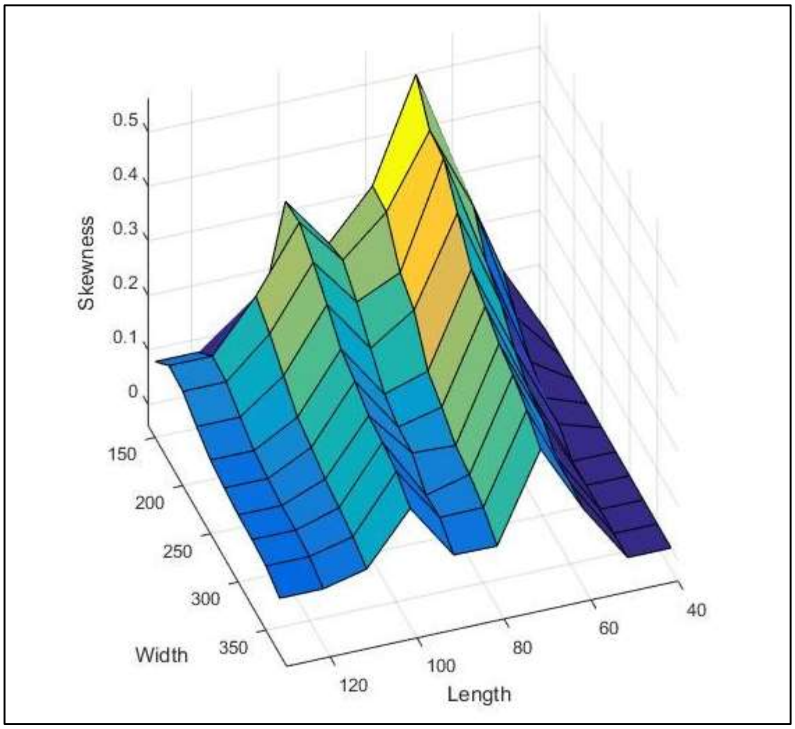


Figure 3.1: Skewness of Travel Time Distribution against L and W of DC (view 1)

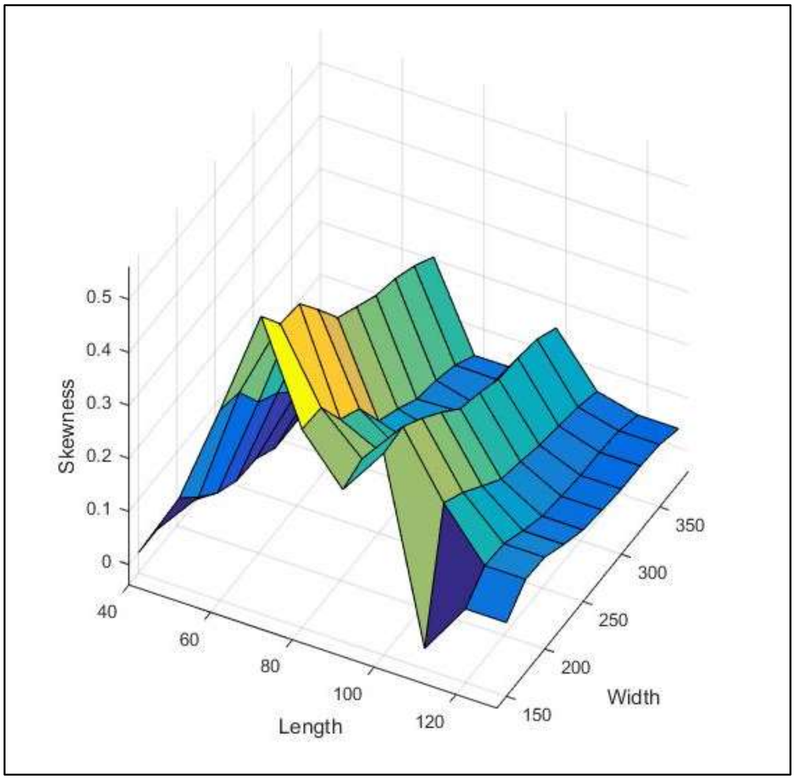


Figure 3.2: Skewness of Travel Time Distribution against L and W of DC (view 2)

The skewness profile of forklift travel time distribution against L and W is investigated. It is observed that for a given W, skewness profile is represented by a series of peaks and valleys with decreasing value as L increases. Similarly, for a given L, skewness profile remains nearly constant as W increases. The skewness profiles are shown in Figure 3.1 and 3.2.

The skewness for forklift travel time distributions fluctuate significantly from dock 1 (end dock) and becomes negligible towards dock 23 (center dock) and remains negligible from the center dock to dock 45 (end dock) as shown in Figure 3.3.

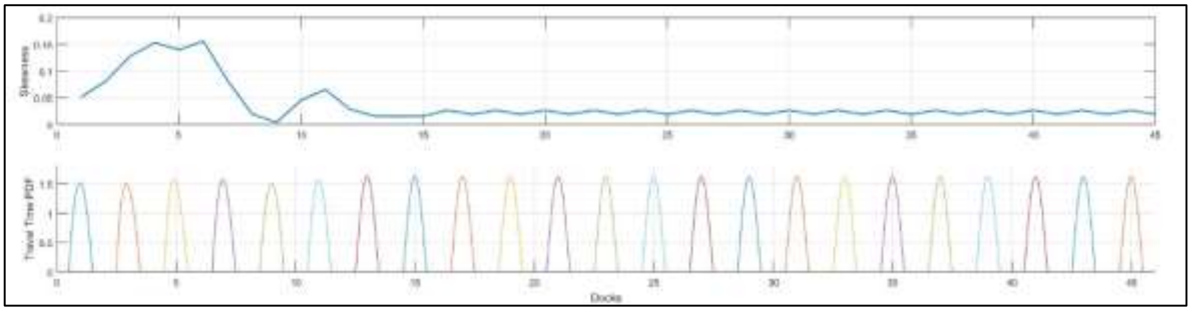


Figure 3.3: Skewness for Travel Time Distribution with Distance from Center Dock

3.2 Queueing Model

A large scale, non-automated, rectangular DC is analyzed. A rectangular shape is the optimal geometrical shape for storing rectangular units such as pallets, [10]. The storage locations are characterized by single-deep racks and drive-in racks. The racks are arranged back-to-back, to form a block, parallel to the dock of the DC, such that space between blocks form aisles. The blocks are arranged in a rectangular grid to form a network of aisles through which material handling devices travel. The DC layout is shown in Figure 3.4, [3].

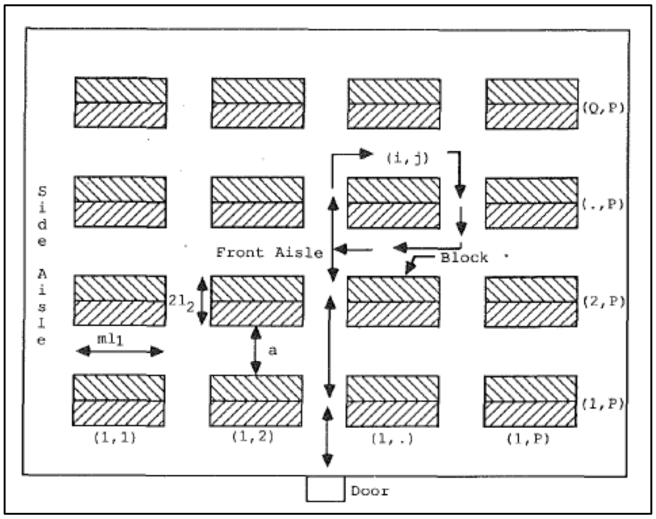


Figure 3.4: DC Layout, [3]

The outbound operations in the DC begins by “accumulation” of customer orders from storage area as pallet loads in the dock to form a truck load. The pallet loads then undergo a “wrapping” process to secure items in the pallet after accumulation. After wrapping, pallet loads are “inspected” to verify that items in the pallets have completed all processes before loading. Pallets are then “loaded” onto the truck for shipping. The process time associated with accumulation, wrapping, inspection and loading are denoted by Accumulation Time (AT) or Forklift Travel Time, Wrapping Time (WT), Inspection Time (IT) and Loading Time (LT) respectively. The process time for a truck load, denoted by Truck Processing Time (TPT), is the sum of AT, travel time taken by forklifts to retrieve a truck load from storage area to the dock; WT, time taken by wrapping team to wrap a truck load; IT, time taken by inspection team to inspect a truck load; and LT, time taken by loading team to load a truck load to a truck for shipping; TPT = AT + WT + IT + LT. The operational productivity is expressed by a metric called Labor Hours Per Truck (LHPT). The movement of pallets are done using forklifts and pallet jacks. It is assumed that forklifts perform only accumulation operations and pallet jacks are used by wrapping team, inspection team and loading team to perform wrapping, inspection and loading operations respectively. Fork lifts, pallet jacks, wrapping team, inspection team and loading team are shared resources in the DC. The queueing model is shown in Figure 3.5.

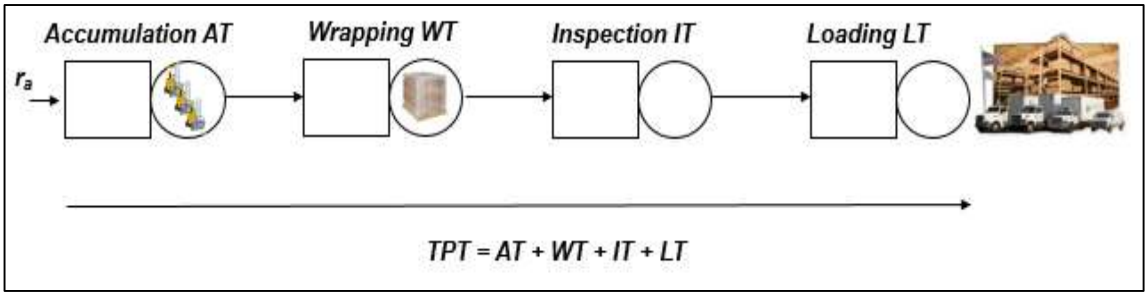


Figure 3.5: Outbound Queueing Model

The outbound operations in the DC can be modelled as an open network queueing system with a First Come First Serve (FCFS) queue discipline and an infinite queue space. The customer orders for accumulation arrive at a rate r_a in the form of palletized truck loads. Forklifts, wrapping team, inspection team and loading team act as servers. The system is characterized by a series of G/G/m queues for accumulation, wrapping, inspection and loading with general (non-exponential) inter-arrival and process time distributions. The model facilitates development and evaluation of workforce capacity policies for the DC for several demand scenarios by providing a performance estimate for each policy-scenario combination.

3.3 Performance Measures

The following parameters are provided as input to the queueing model: r_a - rate of arrivals in truck load per unit time; t_a - Average time between arrivals (in minute); c_a - Arrival CV; c_d - Departure CV; m - Workforce level in a process; t_e - Mean effective process time (in minute); c_e - CV of effective process time, [12].

The performance of the queueing system is characterized by the following parameters and are considered as the output from the queueing model: u - Workforce Utilization; CT_q - Expected waiting time in queue for a process (in minute); CT - Expected time for a process (in minute); TPT - Truck Processing Time (in minute); WIP - Average work-in-process level at process (in truck load); WIP_q - Expected WIP in queue (in truck load); ATL - Average Truck Load; LHPT - Labor Hours Per Truck, [12].

3.4 Chapter Summary and Conclusions

- A generic computational model, with length (L), width (W), aisle-width (A) and number of docks (N) as parameters, is developed to estimate forklift travel times in DCs, which is capable to evaluate DCs with a size between 60,000 sq.ft. (small scale) and 500,000 sq.ft. (large scale) and up to 45 docks. The travel times are modelled as random variables and the moments of travel time distribution is used as input to analytical queueing model and discrete event simulation model of DC.

- The analytical queueing model facilitates development and evaluation of workforce capacity policies for the DC for several demand scenarios by providing performance estimates, particularly in terms of TPT and LHPT, for each policy-scenario combination.

CHAPTER 4
PERFORMANCE ANALYSIS

4.1 Performance Analysis using Queueing Model

Table 4.1: Queueing Model Output

OUTPUT					
	Process Time		WIP Levels		Workforce Utilization
Process	Waiting Time	Cycle Time	WIP Waiting	WIP	
Accumulation	0.30	295.54	0.01	12.76	50.98%
Wrapping	36.21	89.68	1.56	3.87	76.94%
Inspection	43.81	164.03	1.89	7.08	86.49%
Loading	3.82	155.51	0.16	6.71	65.48%
TPT		**704.77**	**ATL**	**30.42**	
LHPT		**357.34**			

The performance of outbound operations of the DC is analyzed for a given arrival rate, process time and workforce level using the queueing model. The queueing model output is given in Table 4.1. The TPT and LHPT is determined as 704.77 minutes and 357.34 respectively. It is observed that the expected waiting time in queue and workforce utilization for wrapping and inspection process is high (36.21 & 43.81 minutes and 76.94% & 86.49% respectively).

The performance of the DC is analyzed for several demand scenarios that range from an arrival rate of 0.01(low) to 0.09 (high) for a given process time and workforce level. It is observed that TPT / LHPT remains almost constant till an arrival rate of 0.04 (medium demand) after which it increases sharply as workforce utilization approaches 100% as shown in Figure 4.1.

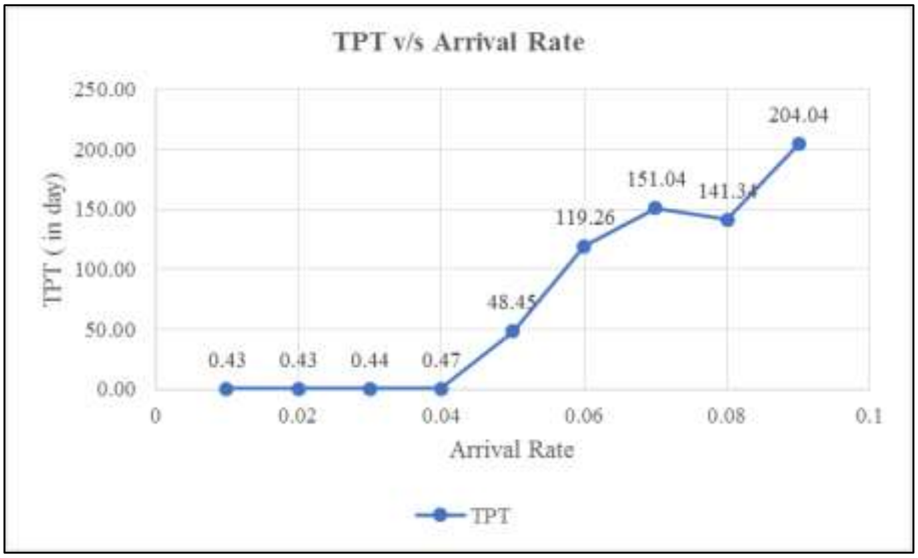


Figure 4.1: Comparison - TPT v/s Arrival Rate

4.2 Workforce Capacity Analysis using Queueing Model

The queueing model is used to determine the workforce capacity at different stages of operations to meet desired performance levels. The workforce utilization becomes an input to the queueing model and workforce level at accumulation, wrapping, inspection and loading process is the output from the queueing model. All other input and output parameters remains same as that of the initial model.

The workforce capacity of outbound operations of the DC is analyzed for a given arrival rate and process time at 70% target workforce utilization for all the process using the model. The workforce capacity model output is given in Table 4.2. The total workforce level (M) is determined as 37 for the DC with a TPT of 664.22 minutes and LHPT of 317.40. It is observed that the expected waiting time in queue for wrapping is high under the present target workforce utilization.

Table 4.2: Workforce Capacity Model Output

OUTPUT					
	Process Time		**WIP Levels**		**Workforce Level**
Process	**Waiting Time**	**Cycle Time**	**WIP Waiting**	**WIP**	
Accumulation	7.17	302.40	0.31	13.05	18
Wrapping	20.49	73.96	0.88	3.19	3
Inspection	8.56	128.78	0.37	5.56	7
Loading	7.39	159.08	0.32	6.87	9
TPT		**664.22**	**ATL**	**28.67**	**37**
LHPT		**317.40**	**M**		

The workforce capacity of the DC is analyzed for several demand scenarios that range from an arrival rate of 0.01 (low) to 0.09 (high) for a given process time at 70% target workforce utilization for all the process. It is observed that TPT decreases steadily as M increases and LHPT increases linearly with M as shown in Figure 4.2 and 4.3.

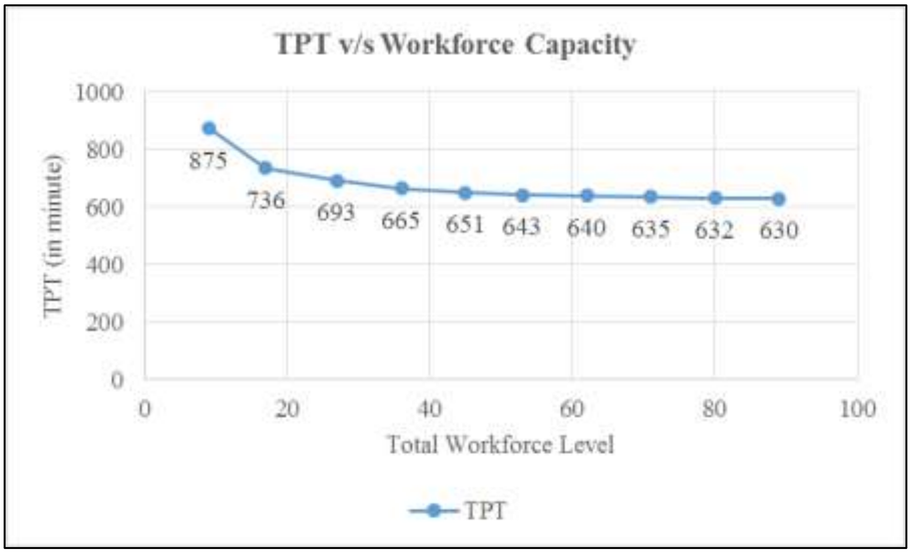


Figure 4.2: Comparison - TPT v/s Workforce Capacity

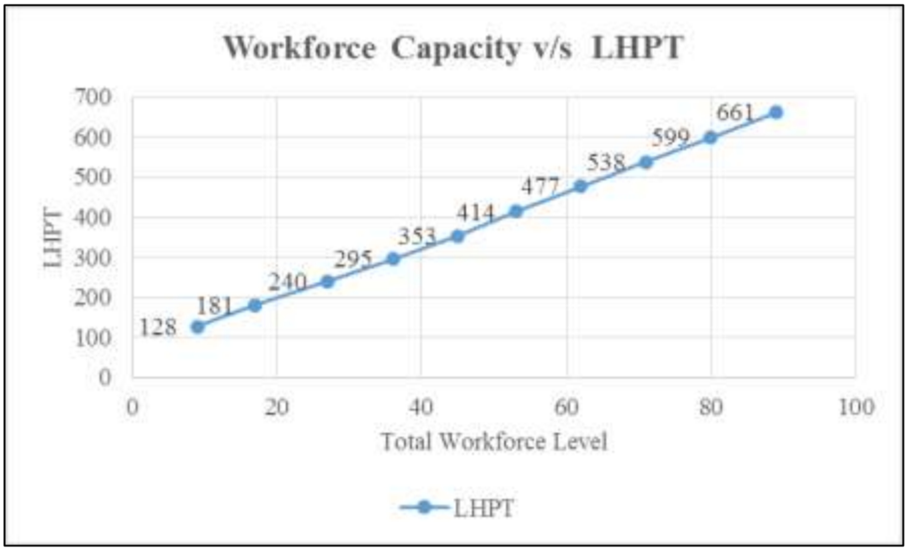


Figure 4.3: Comparison - Workforce Capacity v/s LHPT

4.3 Chapter Summary and Conclusions

- The performance of the DC is analyzed for several demand scenarios that range from an arrival rate of 0.01(low) to 0.09 (high) for a given process time and workforce level using the analytical queueing model. It is observed that TPT / LHPT remains almost constant till an arrival rate of 0.04 (medium demand) after which it increases sharply.

- The workforce capacity of the DC is analyzed for several demand scenarios that range from an arrival rate of 0.01 (low) to 0.09 (high) for a given process time at 70% target workforce utilization for all the process. It is observed that TPT decreases steadily as M increases and LHPT increases linearly with M.

CHAPTER 5

SQUARE ROOT STAFFING (SRS) RULE AND DC WORKFORCE CAPACITY

5.1 Workforce Capacity Analysis using SRS rule

The SRS rule is applied in call centers to determine the appropriate staffing levels for an offered load (R) and Quality of Service, (β) and is approximated as $R + \beta\sqrt{R}$, where, R is the amount of work that arrives in the system in unit time. The value of β signifies the operational regime of the system and can be a Quality Driven (QD) with emphasis on service quality over efficiency, Efficiency Driven (ED) with emphasis on efficiency over service quality or Quality Efficiency Driven (QED) regime with trade-off between quality and efficiency. Larger the β value, better the service level, (see Section 2.3), [14].

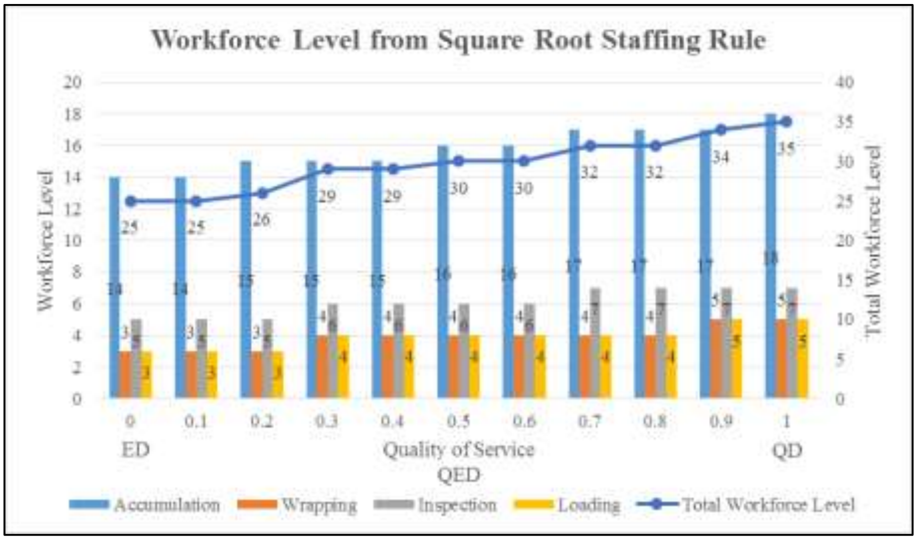


Figure 5.1: DC Workforce Level from SRS rule

The workforce capacity for the outbound operations of the DC is computed by the application of SRS rule for ED (β = 0), QD (β = 1) and QED (β = 0.5) operational regimes. It is observed that as quality of service increases, total workforce level increases as shown in Figure 5.1.

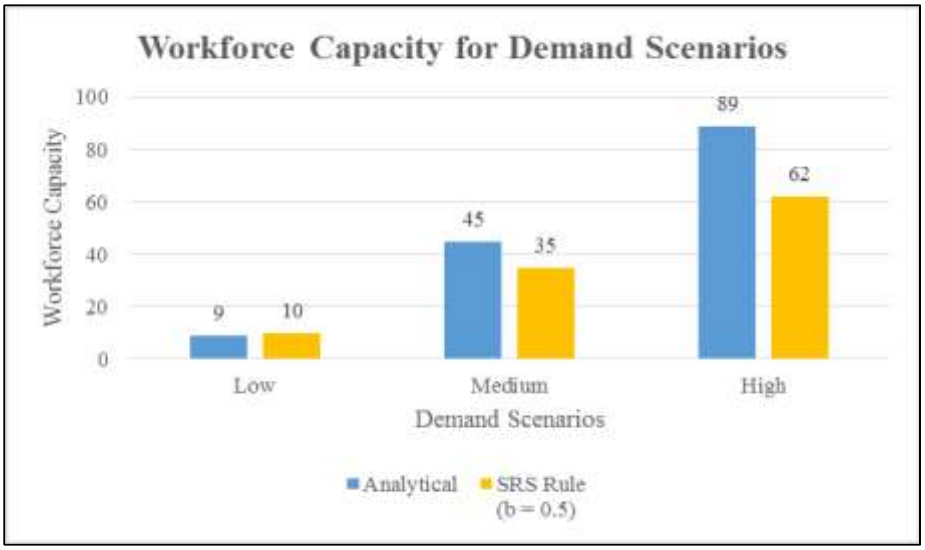


Figure 5.2: Workforce Capacity for Demand Scenarios

The workforce capacity for low, medium and high demand scenarios under analytical queueing model and SRS rule (β = 0.5) is determined. It is observed that workforce capacity determined from analytical queueing model and SRS rule are comparable only for a low demand scenario as shown in Figure 5.2.

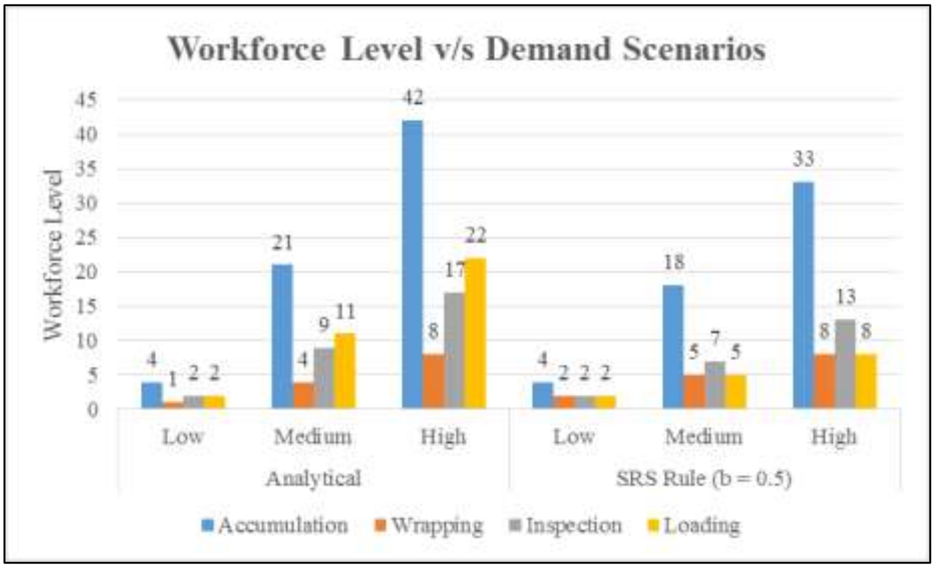


Figure 5.3: Workforce Level for Demand Scenarios

The workforce level at accumulation, wrapping, inspection and loading for low, medium and high demand scenarios under analytical queueing model and SRS rule (β = 0.5) is also determined. It is observed that workforce level for accumulation, wrapping, inspection and loading determined from analytical queueing model and SRS rule are comparable only for a low demand scenario as shown in Figure 5.3.

5.2 Chapter Summary and Conclusions

- DC workforce capacity is estimated by adapting SRS rule used for call center staffing. It is observed that as quality of service increases, total workforce level increases.

- The workforce capacity estimated using the analytical queueing model and SRS rule is comparable only for a low demand scenario.

- The workforce level for accumulation, wrapping, inspection and loading determined from analytical queueing model and SRS rule is comparable only for a low demand scenario.

CHAPTER 6

SIMULATION MODEL AND ANALYSIS

6.1 Simulation Model

The outbound operations of the DC is modelled using Simio simulation software for a given inter-arrival and process time distribution and workforce capacity. The simulation model is built using a "model entity" (which represent truck load) generated from a "source" based on customer demand and flows through "servers" (which represent accumulation, wrapping, inspection and loading process) to be destroyed at the "sink" when truck loads are shipped. Forklift, wrapping team, inspection team and loading team are the "resources" used in the model that the process can seize and release accordingly. The simulation model is shown in Figure 6.1. TPT, LHPT, CT & CT_q, WIP & WIP_q and u are the performance parameters of interest from the simulation model, (see Section 3.3).

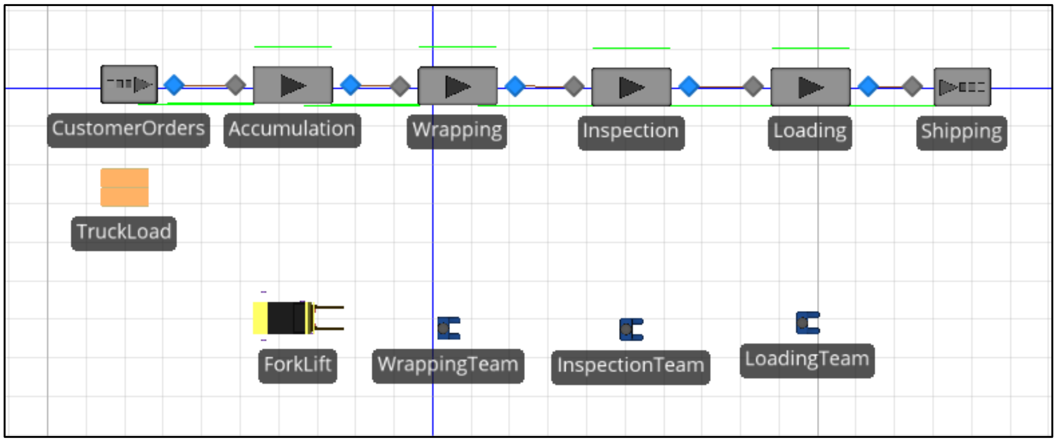


Figure 6.1: Simulation Model

6.1.1 Performance Analysis using Simulation Model

The performance of the DC is analyzed using the simulation model. The model is run for 500 hours with 30 replications after a warm-up period of 100 hours. The simulation model output is given in Table 6.1. The TPT and LHPT is determined as 683.39 minutes and 335.56 respectively. It is observed that the expected waiting time in queue and workforce utilization for wrapping and inspection process is high (32.30 & 28.64 minutes and 78.75% & 86.00% respectively), (see Appendix A.1).

Table 6.1: Simulation Model Output

OUTPUT					
	Process Time		WIP Levels		Workforce Utilization
Process	**Waiting Time**	**Cycle Time**	**WIP Waiting**	**WIP**	
Accumulation	0.05	294.99	0.002	12.67	50.76%
Wrapping	32.30	55.00	1.40	2.36	78.75%
Inspection	28.64	120.19	1.24	5.16	86.00%
Loading	0.26	152.28	0.01	6.54	65.36%
TPT		**683.39**	**ATL**	**29.2**	
LHPT		**335.56**			

The results from simulation model is compared with that of the analytical queueing model. The analytical and simulation model outputs for cycle time, WIP level and workforce utilization are comparable. The TPT and LHPT is determined with -3.13% and -6.49% error respectively from the simulation model with reference to the analytical model. It is observed that error levels for accumulation and loading are within acceptable limits though that of wrapping and inspection are outside limits as shown in Figure 6.2 - 6.4.

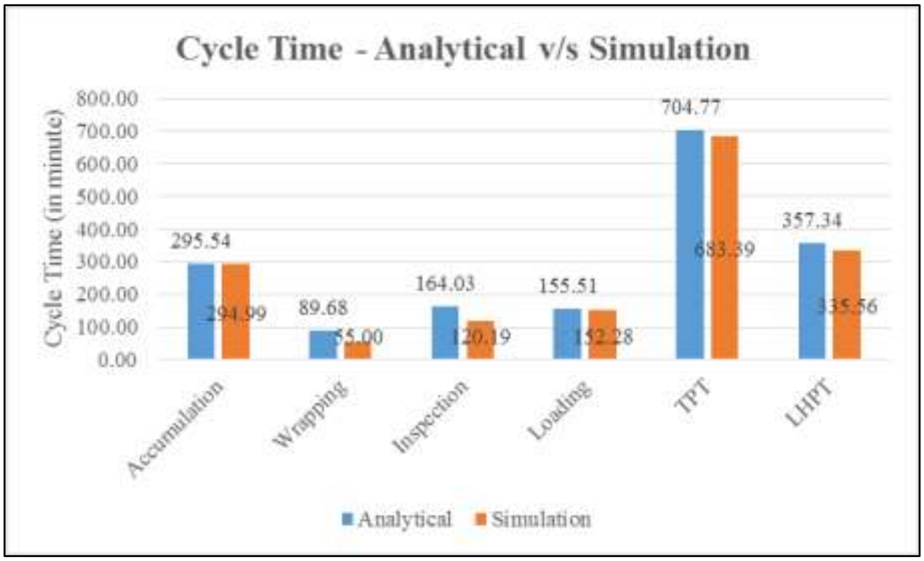


Figure 6.2: Cycle Time - Analytical v/s Simulation Output

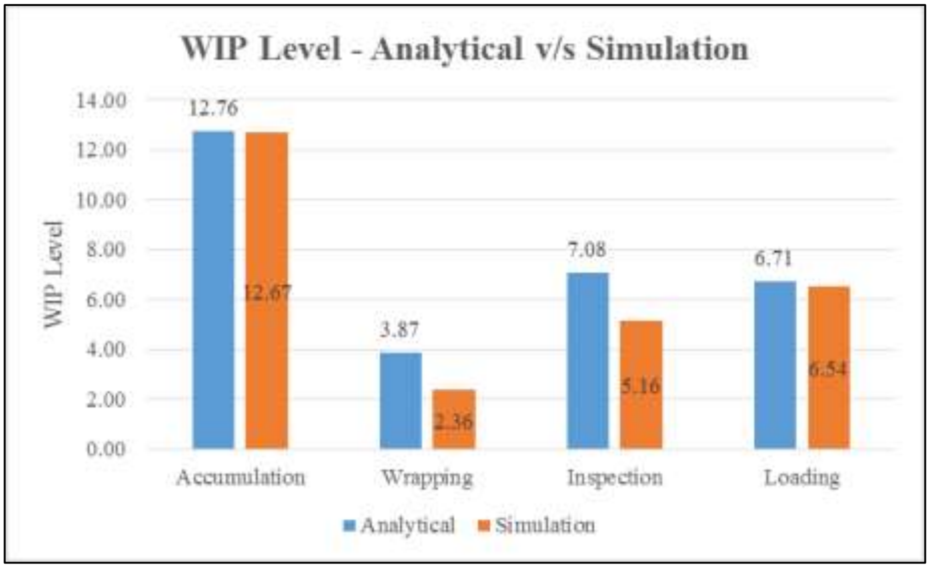


Figure 6.3: WIP Level - Analytical v/s Simulation Output

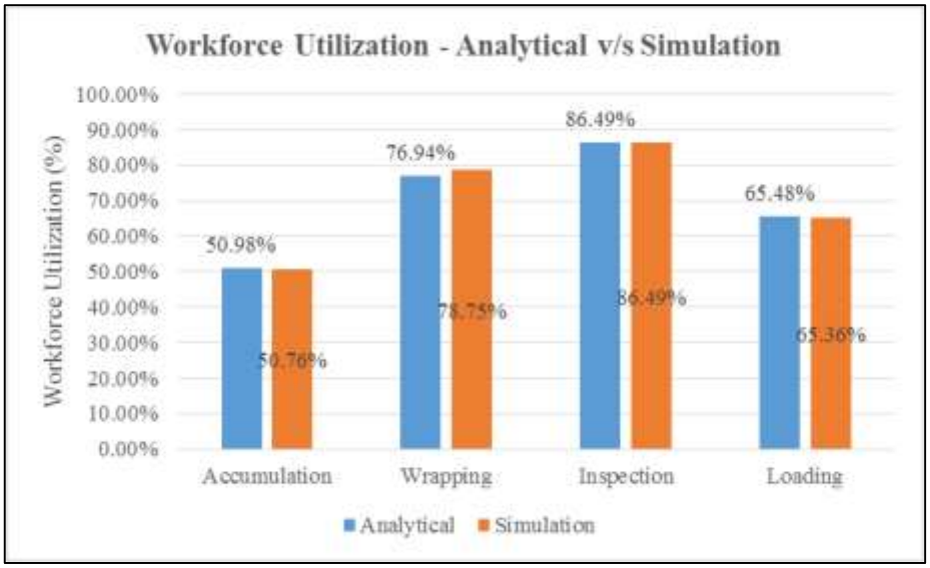


Figure 6.4: Workforce Utilization - Analytical v/s Simulation Output

6.2 Simulation-based Optimization Model

A simulation-based multi-objective optimization model is developed from the initial simulation model using OptQuest for Simio add-in to determine the optimal workforce capacity for a target workforce utilization policy by minimizing TPT and operating cost subject to constraints. The model is run for 500 hours after a warm-up period of 100 hours with 30 replications for 100 scenarios.

The optimal workforce capacity that minimizes TPT and operating cost is determined by multi-objective weighted optimization and pattern frontier optimization.

Minimize: TPT and Operating Cost

subject to:

1 ≤ Forklift ≤ 25

1 ≤ Wrapping Team ≤ 6

1 ≤ Inspection Team ≤ 8

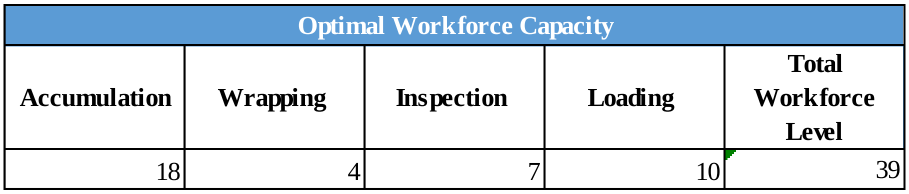
1 ≤ Loading Team ≤ 10

u ≥ 0.70

6.2.1 Multi-Objective Weighted Optimization

OptQuest optimizes across all responses considering each response's weight value to determine a single optimal solution. The optimal workforce capacity that minimizes TPT and operating cost is determined by multi-objective weighted optimization as given in Table 6.2 - 6.3 and shown in Figure 6.5, (see Appendix A.2), [15].

Table 6.2: Optimal Workforce Capacity



Optimal Workforce Capacity				
Accumulation	Wrapping	Inspection	Loading	Total Workforce Level
18	4	7	10	39

Table 6.3: Optimal TPT, LHPT & Operating Cost

TPT	LHPT	Operating Cost
641.04	294.44	$ 5,502.30

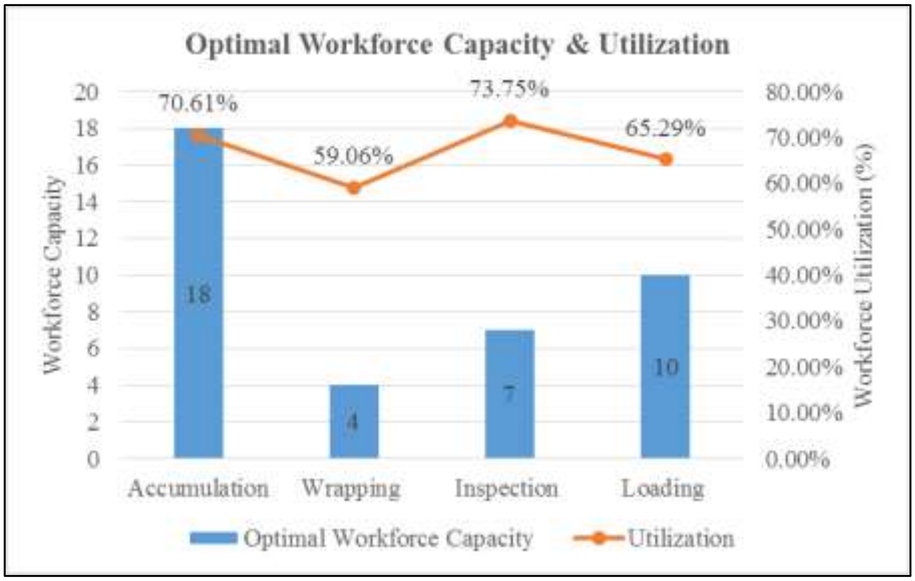


Figure 6.5: Optimal Workforce Capacity

6.2.2 Pattern Frontier Optimization

OptQuest optimizes across all responses and finds the set of scenarios that are optimal, rather than a single optimal solution based on weights. The optimal scenarios for workforce capacity that minimizes TPT and operating cost is determined by pattern frontier optimization. The optimal scenarios indicate that a 9% reduction in TPT increases the operating cost by 18% as shown in Figure 6.6 - 6.9, (see Appendix A.3), [15].

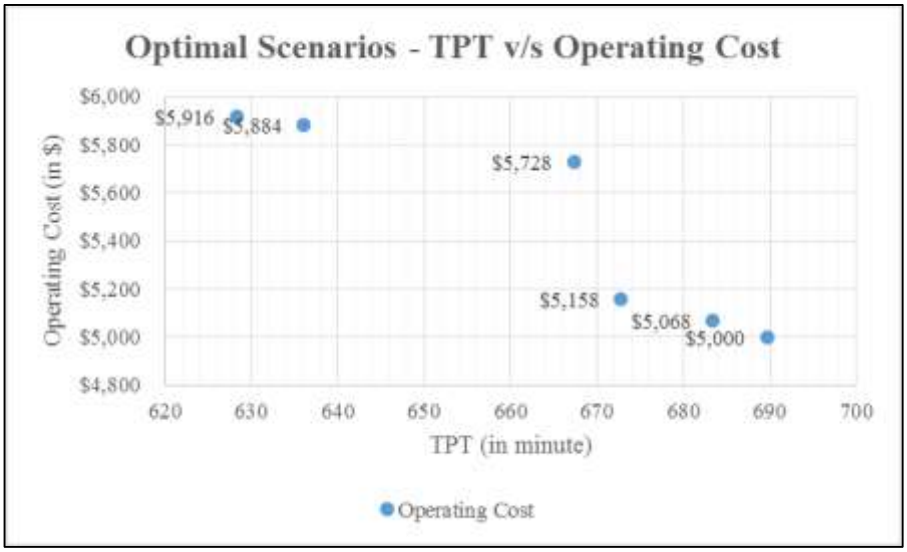


Figure 6.6: Optimal Scenarios - TPT v/s Operating Cost

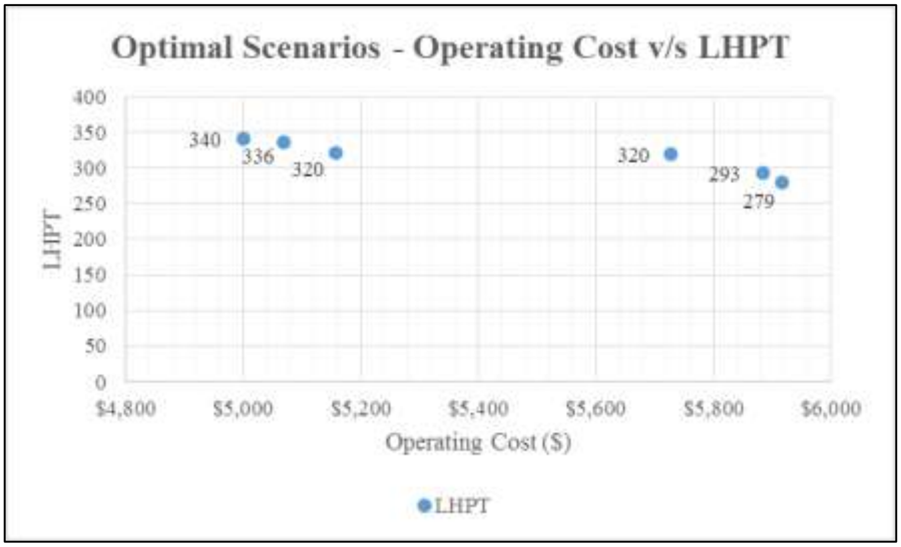


Figure 6.7: Optimal Scenarios - Operating Cost v/s LHPT

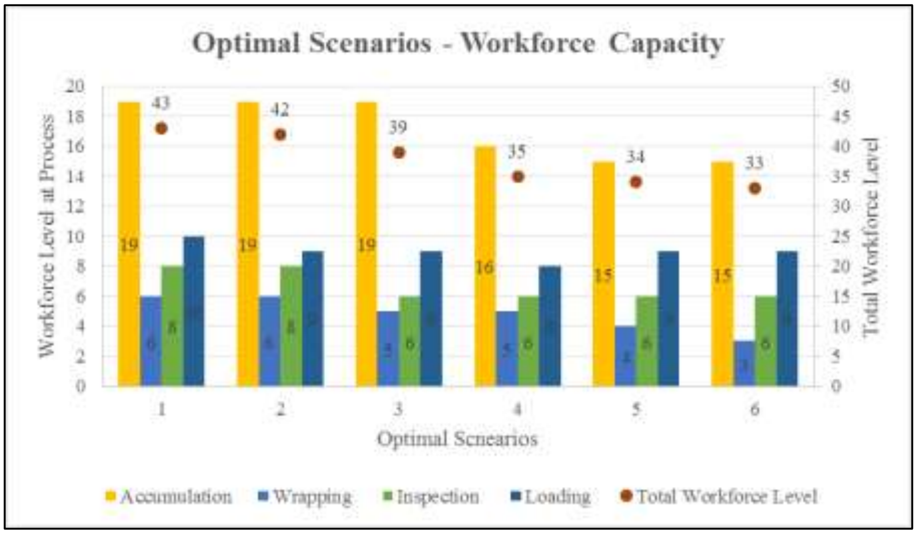


Figure 6.8: Optimal Scenarios - Workforce Capacity

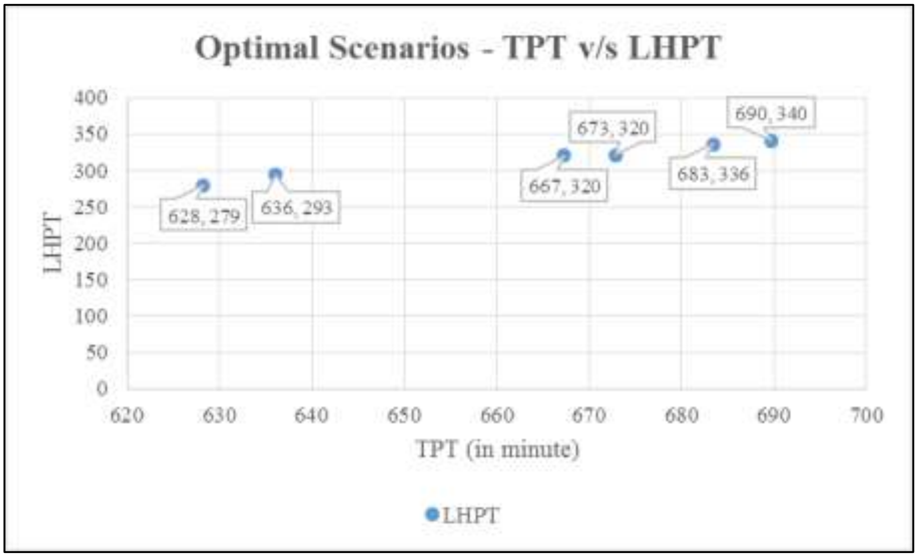


Figure 6.9: Optimal Scenarios - TPT v/s LHPT

It is observed that there are six optimal scenarios with TPT , LHPT and operating cost that range between (628.24 minutes, 340 labor hours, $5915.95) and (689.66 minutes, 279 labor hours, $5000.07) corresponding to a workforce capacity that range between 43 to 33.

6.3 Chapter Summary and Conclusions

- The analytical models are benchmarked and validated by a discrete event simulation model developed using Simio and its optimization tools. The TPT and LHPT is determined with -3.13% and -6.49% error respectively from the simulation model with reference to the analytical model.
- The optimal workforce capacity that minimizes TPT and operating cost is determined by multi-objective weighted optimization and pattern frontier optimization using the simulation model.

- It is observed that there are six optimal scenarios with TPT , LHPT and operating cost that range between (628.24 minutes, 340 labor hours, $5915.95) and (689.66 minutes, 279 labor hours, $5000.07) corresponding to a workforce capacity that range between 43 to 33.

- The optimal scenarios indicate that a 9% reduction in TPT increases the operating cost by 18%.

CHAPTER 7

SUMMARY AND CONCLUSIONS

A decision model that integrates critical operational performance measures is developed to evaluate DC performance and workforce capacity policies under varying demand scenarios. Industrial practitioners can use this model for tactical and operational decisions in DCs.

- The existing literature is heavily focused on warehouse design & control using travel time models and performance analysis in terms of throughput, resource utilization and storage strategy for order picking systems. As labor cost can be a significant component of variable cost in DCs, it is evident that there is a need for research to explore the impact of workforce capacity on DC performance by considering cost and service level trade-off for varying demand scenarios.

- A generic computational model, with length (L), width (W), aisle-width (A) and number of docks (N) as parameters, is developed to estimate forklift travel times in DCs, which is capable to evaluate DCs with a size between 60,000 sq.ft. (small scale) and 500,000 sq.ft. (large scale) and up to 45 docks. The travel times are modelled as random variables and the moments of travel time distribution is used as input to analytical queueing model and discrete event simulation model of DC.

- The analytical queueing model facilitate development and evaluation of workforce capacity policies for the DC for several demand scenarios by providing performance estimates, particularly in terms of TPT and LHPT, for each policy-scenario combination.

- DC workforce capacity is estimated by adapting SRS rule used for call center staffing. The workforce capacity estimated using the analytical queueing model and SRS rule are comparable only for a low demand scenario.

- The analytical models are benchmarked and validated by a discrete event simulation model developed using Simio and its optimization tools. The TPT and LHPT is determined with -3.13% and -6.49% error respectively from the simulation model with reference to the analytical model.

- The optimal workforce capacity that minimizes TPT and operating cost is determined by multi-objective weighted optimization and pattern frontier optimization using the simulation model. The optimal scenarios indicate that a 9% reduction in TPT increases the operating cost by 18%.

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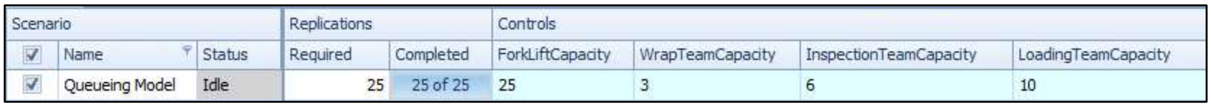
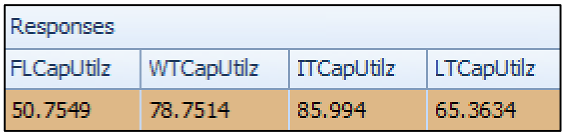
APPENDIX

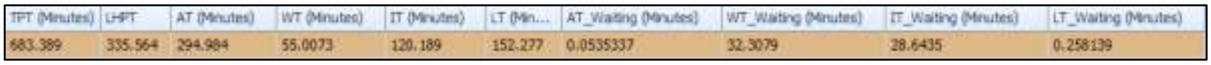
A.1 Simio Simulation Output



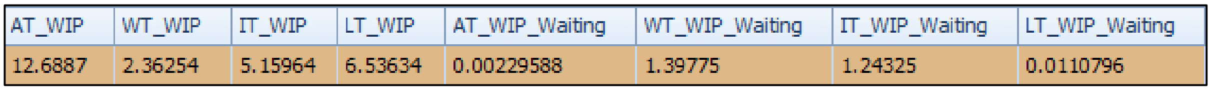
Scenario			Replications		Controls			
☑	Name	Status	Required	Completed	ForkLiftCapacity	WrapTeamCapacity	InspectionTeamCapacity	LoadingTeamCapacity
☑	Queueing Model	Idle	25	25 of 25	25	3	6	10



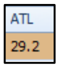
Responses			
FLCapUtilz	WTCapUtilz	ITCapUtilz	LTCapUtilz
50.7549	78.7514	85.994	65.3634



TPT (Minutes)	LHPT	AT (Minutes)	WT (Minutes)	IT (Minutes)	LT (Min...	AT_Waiting (Minutes)	WT_Waiting (Minutes)	IT_Waiting (Minutes)	LT_Waiting (Minutes)
683.389	335.564	294.984	55.0073	120.189	152.277	0.0535337	32.3079	28.6435	0.258139

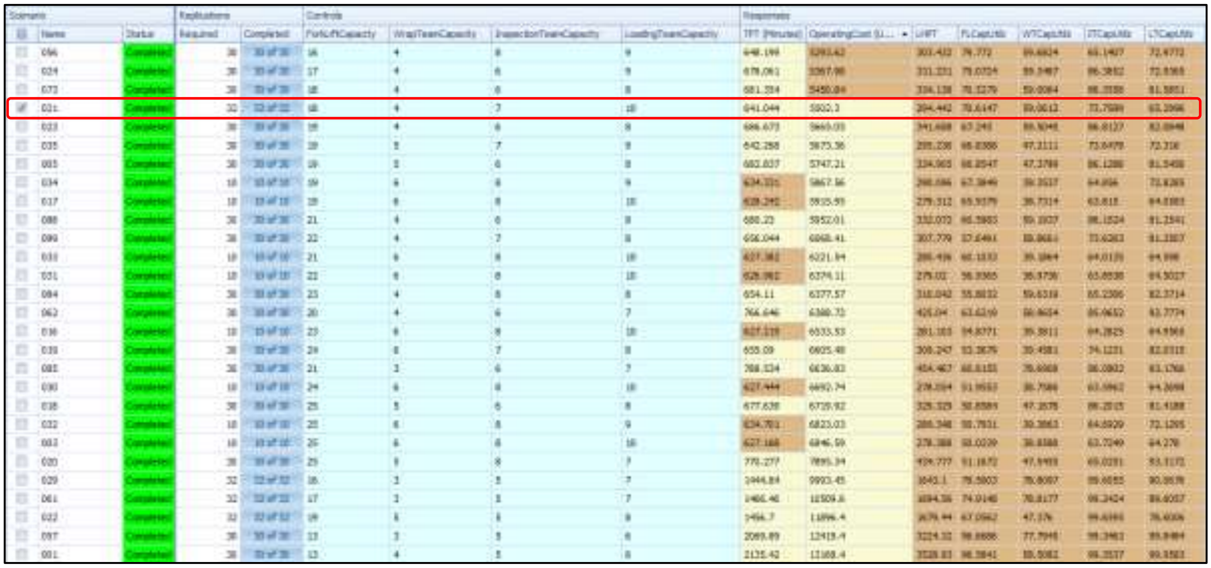


AT_WIP	WT_WIP	IT_WIP	LT_WIP	AT_WIP_Waiting	WT_WIP_Waiting	IT_WIP_Waiting	LT_WIP_Waiting
12.6887	2.36254	5.15964	6.53634	0.00229588	1.39775	1.24325	0.0110796



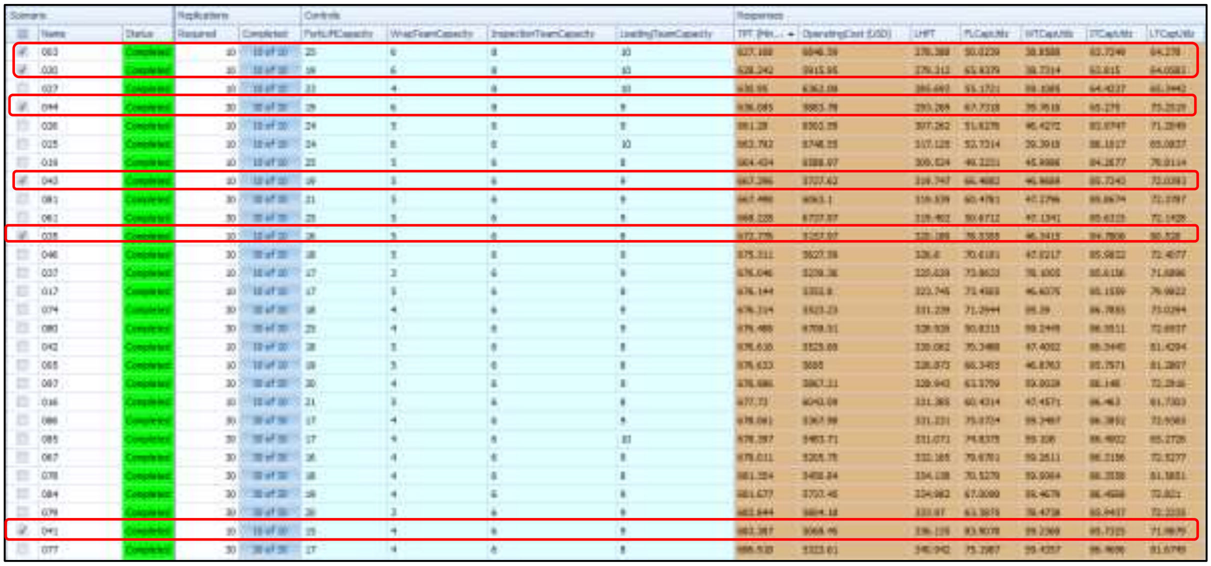
ATL
29.2

A.2 Multi-Objective Optimization Simulation Output

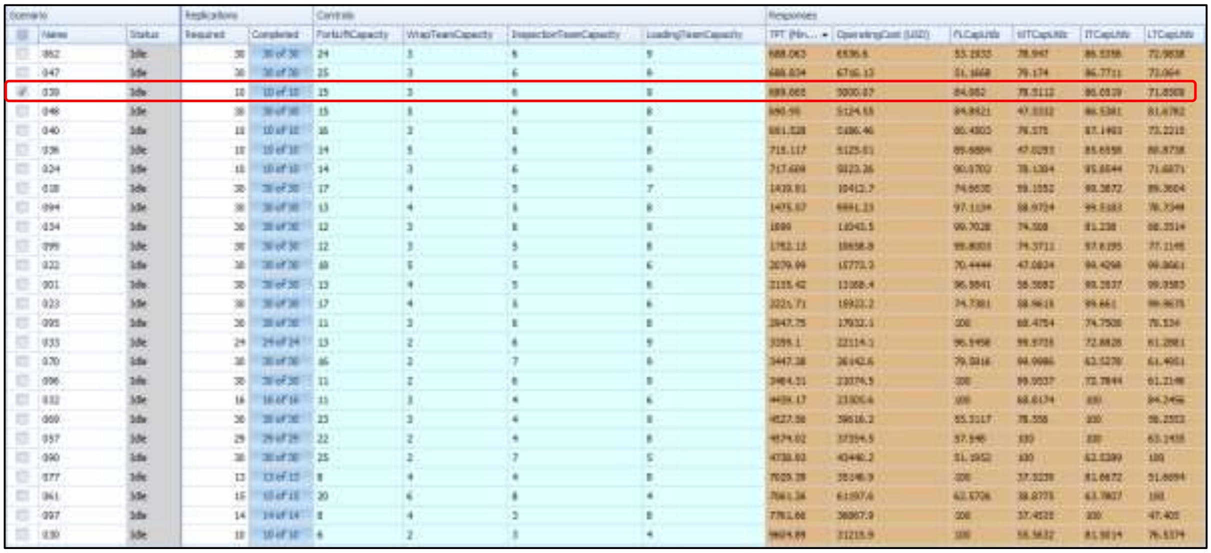


Scenario			Replications		Controls				Responses						
☐	Name	Status	Required	Completed	ForkLiftCapacity	WrapTeamCapacity	InspectionTeamCapacity	LoadingTeamCapacity	TPT (Minutes)	OperatingCost (U... ▲	LHPT	FLCapUtilz	WTCapUtilz	ITCapUtilz	LTCapUtilz
☐	056	Completed	30	30 of 30	16	4	8	9	648.199	5283.42	303.432	79.772	89.6824	68.1407	72.4772
☐	024	Completed	30	30 of 30	17	4	6	9	678.061	5367.98	331.231	79.0724	89.3487	86.3852	72.8368
☐	073	Completed	30	30 of 30	18	4	6	8	681.354	5450.84	334.138	78.3279	89.0084	88.3358	81.5851
☑	021	Completed	32	32 of 32	18	4	7	10	641.044	5502.3	294.442	78.6147	89.0612	73.7589	65.2066
☐	023	Completed	30	30 of 30	19	4	6	8	686.673	5669.03	341.688	67.245	89.3046	86.8127	82.0848
☐	035	Completed	30	30 of 30	19	5	7	9	642.288	5673.36	295.236	68.0386	47.2111	73.6479	72.316
☐	005	Completed	30	30 of 30	19	5	6	8	682.837	5747.21	334.965	68.2547	47.3788	86.1288	81.5408
☐	034	Completed	10	10 of 10	19	6	8	9	634.331	5867.56	288.086	67.3849	39.3517	64.856	72.8283
☐	017	Completed	10	10 of 10	19	6	8	10	628.292	5935.99	279.312	65.9379	38.7314	63.818	64.8383
☐	088	Completed	30	30 of 30	21	4	6	8	680.23	5952.01	332.072	60.5983	59.1927	88.1524	81.2541
☐	099	Completed	30	30 of 30	22	4	7	8	656.044	6068.41	307.779	57.6461	58.8661	73.6263	81.3307
☐	033	Completed	10	10 of 10	21	6	8	10	627.382	6221.84	286.436	60.1832	39.1844	64.0135	64.898
☐	031	Completed	10	10 of 10	22	6	8	10	628.982	6374.11	279.02	56.3365	38.3736	63.8538	64.5027
☐	084	Completed	30	30 of 30	23	4	5	8	654.11	6377.57	310.042	55.8832	59.6318	88.2386	82.2714
☐	062	Completed	30	30 of 30	20	4	6	7	766.646	6388.72	425.04	63.6216	58.8634	86.0652	83.7774
☐	036	Completed	10	10 of 10	23	6	8	10	627.119	6533.53	281.183	54.8771	39.3811	64.2825	64.9368
☐	039	Completed	30	30 of 30	24	5	7	8	655.09	6605.48	308.247	53.2676	39.4581	74.1231	82.0318
☐	085	Completed	30	30 of 30	21	3	6	7	768.324	6636.83	404.467	60.8155	78.6968	88.0802	83.1768
☐	030	Completed	10	10 of 10	24	6	8	10	627.444	6692.74	278.284	51.9653	38.7588	63.5962	64.2698
☐	038	Completed	30	30 of 30	25	5	6	8	677.638	6739.92	329.329	50.8589	47.2678	88.2015	81.4188
☐	032	Completed	10	10 of 10	25	6	8	9	634.701	6823.03	288.348	50.7931	39.3863	64.8929	72.1265
☐	003	Completed	10	10 of 10	26	6	8	10	627.168	6846.59	278.388	50.0239	38.8388	63.7249	64.278
☐	020	Completed	30	30 of 30	25	5	8	7	770.277	7895.34	424.777	51.1672	47.9493	69.0281	83.7172
☐	029	Completed	32	32 of 32	16	3	5	7	1444.84	9993.45	1040.1	78.5803	78.8097	89.6655	90.3578
☐	061	Completed	32	32 of 32	17	3	5	7	1466.46	10509.6	1094.36	74.0146	78.8177	98.2424	89.6037
☐	022	Completed	32	32 of 32	19	5	5	8	1456.7	11896.4	1079.44	67.0562	47.376	89.6395	78.6006
☐	097	Completed	30	30 of 30	13	3	5	6	2089.89	12419.4	1224.32	98.8686	77.7946	99.3463	89.8484
☐	001	Completed	30	30 of 30	13	4	5	6	2125.42	13168.4	1328.83	98.3841	88.5082	99.3537	99.3583

A.3 Pattern Frontier Optimization Simulation Output



Scenario			Replications		Controls				Responses						
☐	Name	Status	Required	Completed	FortLiftCapacity	WrapTeamCapacity	InspectionTeamCapacity	LoadingTeamCapacity	TPT (Min... ▲	OperatingCost (USD)	LHFT	FLCapUtils	WTCapUtils	ITCapUtils	LTCapUtils
☑	003	Completed	10	10 of 10	25	6	8	10	627.188	6846.39	278.388	50.0239	38.8588	63.7249	64.278
☑	030	Completed	10	10 of 10	19	6	8	10	628.242	5915.95	279.312	65.6379	38.7314	63.815	64.0583
☐	027	Completed	10	10 of 10	22	4	8	10	630.95	6362.08	285.697	55.1721	59.3385	64.4237	65.3442
☑	044	Completed	30	30 of 30	19	6	9	9	636.085	5983.78	293.269	67.7318	39.7618	65.278	73.2529
☐	036	Completed	10	10 of 10	24	5	8	9	661.28	8302.59	307.262	51.6278	46.4272	83.0747	71.2049
☐	025	Completed	10	10 of 10	24	8	8	10	663.792	8748.55	317.128	52.7314	39.3918	88.1817	65.0837
☐	016	Completed	10	10 of 10	25	5	6	8	664.434	6388.97	309.024	49.2231	45.9986	84.2677	78.0114
☑	043	Completed	10	10 of 10	19	5	6	9	667.286	3727.62	316.747	66.4682	46.9684	85.7243	72.0383
☐	081	Completed	30	30 of 30	21	5	6	9	667.498	6063.1	316.539	60.4781	47.2796	89.8674	71.3787
☐	061	Completed	30	30 of 30	25	5	6	8	668.228	6727.87	319.402	50.6712	47.1341	85.6323	71.1428
☑	035	Completed	10	10 of 10	26	5	6	8	672.776	5252.97	320.188	76.5388	46.3419	84.7808	80.528
☐	046	Completed	30	30 of 30	18	5	8	8	675.311	5627.38	326.6	70.6181	47.0217	85.9822	72.4077
☐	037	Completed	10	10 of 10	17	2	6	9	676.046	5209.36	320.639	73.8633	78.1005	85.6136	71.6896
☐	017	Completed	10	10 of 10	17	5	6	8	676.144	5355.8	323.746	73.4583	46.6076	85.1559	79.0822
☐	074	Completed	30	30 of 30	18	4	6	9	676.314	5923.23	331.239	71.2944	89.39	86.7885	73.0294
☐	080	Completed	30	30 of 30	25	4	8	9	679.488	6709.31	328.928	50.8315	59.2449	86.3511	72.6977
☐	042	Completed	10	10 of 10	28	5	8	8	676.636	5523.69	330.082	75.3488	47.4092	88.2445	81.4294
☐	065	Completed	10	10 of 10	19	5	6	8	676.633	5685	328.873	66.3493	46.8763	85.7571	81.2807
☐	087	Completed	30	30 of 30	20	4	8	8	676.686	3867.11	328.943	63.3709	59.0028	88.148	72.2916
☐	018	Completed	10	10 of 10	21	3	6	8	677.73	6040.09	331.365	60.4314	47.4571	86.463	61.7303
☐	086	Completed	30	30 of 30	17	4	8	9	678.061	5367.99	331.231	75.0724	59.2487	86.3851	72.9583
☐	085	Completed	30	30 of 30	17	4	8	10	678.287	5463.71	331.073	74.8375	59.306	86.4602	65.2726
☐	067	Completed	30	30 of 30	16	4	6	8	679.011	5205.78	332.165	79.6761	59.2611	86.2156	72.5277
☐	078	Completed	30	30 of 30	18	4	8	8	681.354	5458.84	334.138	70.5279	59.9064	86.2538	81.3851
☐	084	Completed	30	30 of 30	16	4	6	8	681.677	3703.46	334.982	67.0099	59.4676	86.4568	72.821
☐	079	Completed	30	30 of 30	20	2	6	9	682.644	5604.18	333.97	63.3875	78.4738	65.9437	72.2233
☑	041	Completed	10	10 of 10	15	4	6	9	683.387	5068.46	336.135	83.9078	59.2369	65.7325	71.9875
☐	077	Completed	30	30 of 30	17	4	6	8	686.538	5323.61	345.942	75.2987	59.4357	86.9606	81.6749



Scenario			Replications		Controls				Responses					
☐	Name	Status	Required	Completed	FortLiftCapacity	WrapTeamCapacity	InspectionTeamCapacity	LoadingTeamCapacity	TPT (Min... ▲	OperatingCost (USD)	FLCapUtils	WTCapUtils	ITCapUtils	LTCapUtils
☐	062	Idle	30	30 of 30	24	3	8	9	688.063	6536.6	53.1933	78.947	86.5358	72.9838
☐	047	Idle	30	30 of 30	25	3	6	9	688.834	6716.13	51.1668	79.174	86.7711	73.064
☑	039	Idle	10	10 of 10	15	3	8	9	689.665	5000.07	84.082	78.5112	86.0519	71.8568
☐	048	Idle	30	30 of 30	15	5	6	8	690.58	5124.65	84.8921	47.3332	86.5381	81.6782
☐	040	Idle	10	10 of 10	16	3	8	8	691.528	5486.46	80.4303	76.575	87.1463	73.2215
☐	026	Idle	10	10 of 10	14	5	8	8	715.117	5125.61	89.6884	47.0283	85.6558	80.8738
☐	024	Idle	10	10 of 10	14	3	6	8	717.609	5023.26	90.3702	78.1304	85.8044	71.6871
☐	018	Idle	30	30 of 30	17	4	5	7	1439.81	10412.7	74.8630	99.1552	99.3872	89.3604
☐	094	Idle	30	30 of 30	13	4	5	8	1475.97	6891.23	97.1134	58.9724	99.5183	78.7349
☐	034	Idle	30	30 of 30	12	3	8	8	1699	14043.5	99.7028	74.308	81.238	68.3514
☐	099	Idle	30	30 of 30	12	3	5	8	1752.13	10658.9	99.8003	74.3711	97.6395	77.2148
☐	022	Idle	30	30 of 30	10	5	5	6	2079.99	15773.2	70.4444	47.0824	99.4298	99.8661
☐	001	Idle	30	30 of 30	13	4	5	8	2135.42	13368.4	96.5841	58.3682	99.2837	99.9583
☐	023	Idle	30	30 of 30	17	4	5	6	2221.71	18922.2	74.7381	58.9618	99.661	99.9675
☐	095	Idle	30	30 of 30	11	3	8	8	2947.75	17932.1	100	68.4754	74.7508	78.534
☐	033	Idle	24	24 of 24	13	2	8	9	3359.1	22114.1	96.5458	99.9735	72.8828	61.2881
☐	070	Idle	30	30 of 30	16	2	7	8	3447.28	26142.6	79.5816	99.9986	62.5278	61.4951
☐	096	Idle	30	30 of 30	11	2	8	8	3484.31	23079.5	100	99.9537	72.7844	61.2148
☐	032	Idle	16	16 of 16	11	3	4	6	4439.17	23305.6	100	68.6174	100	94.2456
☐	069	Idle	30	30 of 30	23	3	4	8	4527.58	39616.2	55.3117	78.558	100	58.2353
☐	057	Idle	29	29 of 29	22	2	4	8	4574.02	37354.5	57.548	100	100	63.1435
☐	090	Idle	30	30 of 30	25	2	7	5	4738.63	43440.2	51.1952	100	62.5289	100
☐	077	Idle	13	13 of 13	8	4	4	8	7029.38	35146.9	100	37.3228	81.6672	51.6694
☐	061	Idle	15	15 of 15	20	6	8	4	7061.36	61597.6	62.5726	38.8775	63.7807	100
☐	097	Idle	14	14 of 14	8	4	3	8	7761.66	36867.9	100	37.4535	100	47.405
☐	030	Idle	10	10 of 10	6	2	3	4	9604.89	31215.9	100	56.5632	81.5014	76.5374