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ANALYTICAL MODELING OF AN AUTONOMOUS VEHICLE STORAGE/RETRIEVAL SYSTEM

By

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A Thesis

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A Thesis Approved on

November 30th, 2007

By the following Thesis Committee:

Thesis Director

DEDICATION

This thesis is dedicated to my parents

Mr. Jiang Cai

and

Mrs. Meijuan Zhang

who have given me invaluable educational opportunities.

ACKNOWLEDGMENT

I would like to thank my major professor, Dr. Sunderesh S. Heragu, for his guidance and patience. I would also like to express my thanks to my parents, for their understanding and support during those times when there was no light at the end of anything. I would also like to thank Dr. Mahesh C. Gupta and Dr. John S. Usher who gave me many helpful suggestions. Also, many thanks to Dr. Gang Meng, who gave me many useful suggestions and guidance on the project. Finally, I would like to thank my friends here and in China.

ABSTRACT

ANALYTICAL MODELING OF AN AUTONOMOUS VEHICLE STORAGE/RETRIEVAL SYSTEM

Xiao Cai

November 30th, 2007

Automated vehicle storage/retrieval system (AVS/RS) technology is relatively new. It has been applied successfully in several European facilities in 1990s. AVS/RS is a flexible system that is a viable alternative to automated storage/retrieval systems (AS/RS), a traditional material handling technology that has been in existence for more than fifty years.

There are very few papers in the literature that focus on the use of analytical models for estimating performance measures of AVS/RS. In this thesis, queuing network theory is used to model an AVS/RS system to analyze its performance. The manufacturing system performance analyzer (MPA) is an open queuing network (OQN) analyzer based on the parametric decomposition method. This thesis models the AVS/RS and uses MPA to analyze the performance of an AVS/RS configuration. A simulation model based on discrete events is also generated by Promodel to allow comparison of MPA results with those of simulation.

A web interface for conceptualizing AVS/RS and AS/RS designs is presented in this thesis. This on-line tool provides a convenient and friendly interface between warehouse designers and the analytical model tool. Four case studies of algorithms embedded in the web interface are presented in the thesis.

An initial warehouse design is first analyzed by MPA. After this, several improvements of this initial design are evaluated. Experimental results are provided to show that the OQN methodology can be applied effectively to analyze an AVS/RS when vehicle utilization is between 60% and 85%. MPA is a better choice than simulation to quickly evaluate alternate configuration of the AVS/RS.

Additionally, two more experiments are conducted to compare MPA with another AVS/RS system performance analyzer. MPA models AVS/RS under the tier-captive configuration, whereas the other model assumes the tier-to-tier configuration.

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INTRODUCTION

1.1. Autonomous Vehicle Storage/Retrieval Systems (AVS/RS)

The AVS/RS studied in this thesis is a new material handling technology for unit load storage and retrieval (S/R) developed and implemented in Europe by Savoye Technologies.

1.1.1. Components of AVS/RS

The main components of the AVS/RS are: autonomous vehicles, lifts, and a system of rails that facilitate movement of the vehicles. These are illustrated in Figure 1.1.

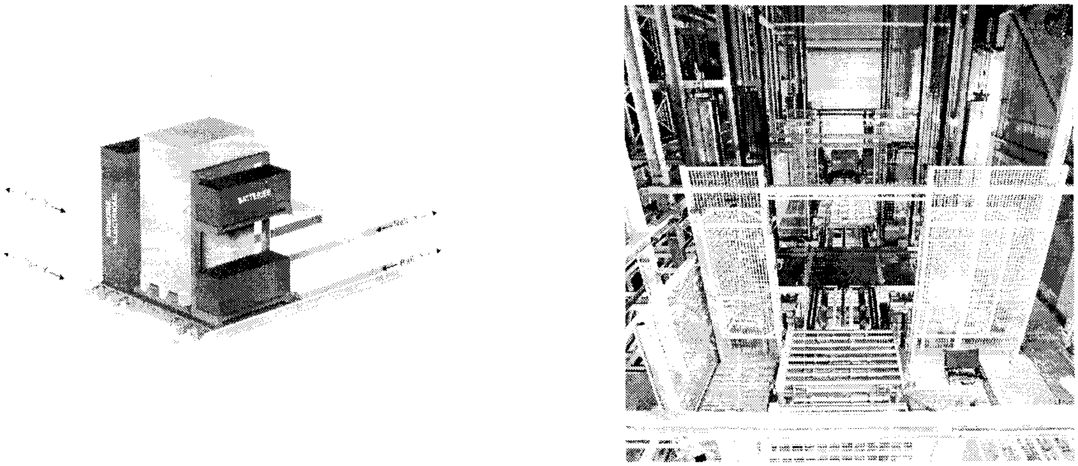


Figure 1.1. Autonomous vehicle and lift

1.1.2. AVS/RS Configurations

A typical AVS/RS is shown in Figure 1.2. Two main configurations of the AVS/RS are:

- AVS/RS with tier-to-tier vehicles
- AVS/RS with tier-captive vehicles

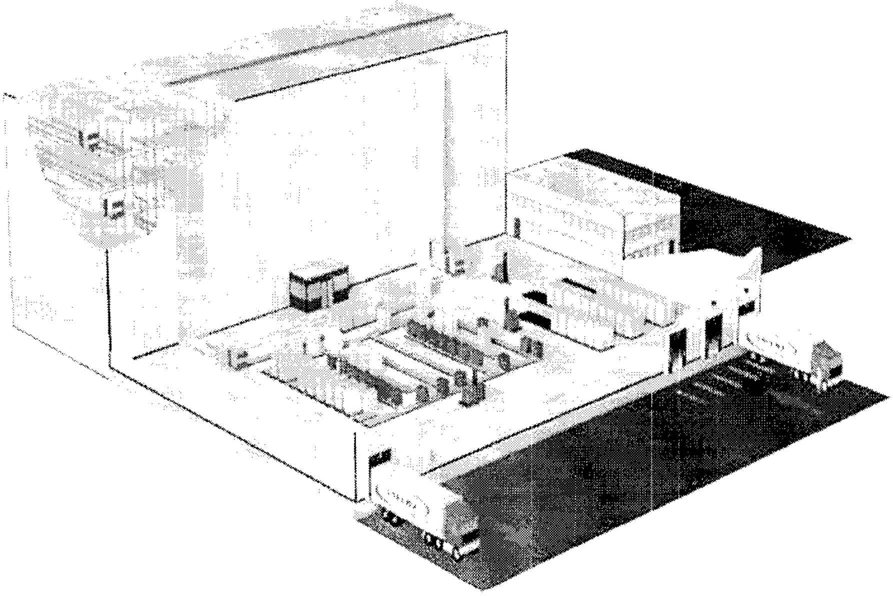


Figure 1.2. A typical AVS/RS

In the former configuration, autonomous vehicles pick up pallets from in-bound trucks and move along rails to deposit them in their designated storage racks. If the designated rack is in another tier, the vehicle interfaces with a lift to reach that tier and again uses rails within that tier to travel in the aisles to reach the designated storage space. The operations are reversed for a retrieval transaction.

AVS/RS with tier-captive vehicles operates differently when the designated rack is in another tier. The vehicle on the ground floor unloads a pallet in front of the lift, and the lift takes the pallet to the designated tier. The autonomous vehicle on that tier takes the pallet from the lift buffer and travels to the assigned storage space.

1.2. A simple AVS/RS system

1.2.1. Description of the simple system

A simple AVS/RS with tier-captive vehicles is presented in Figure 1.3. This system can be divided into four cells according to different functional areas: receiving area (Cell 1), lift bank (Cell 2), shipping area (Cell 3) and storage area (Cell 4).

Pallets containing different types of products arrive at the receiving area ready to be stored at their designated storage spaces by the AVS/RS. Pallet arrival rates usually are described by a probability distribution of the number of arrivals in an interval of time. They are taken by available autonomous vehicles in the receiving area (Cell 1) to lift bank (Cell 2). If no vehicle is available, pallets wait in a queue at the receiving buffer on the ground level. They are transported by vehicles on the ground level to the lift bank and deposited in front of the lift bank (Cell 2). If no lift is available, pallets wait in a queue. Once a lift becomes available, the waiting pallet is taken to the designated tier (Cell 4). An autonomous vehicle takes the pallet to the designated storage position determined by a storage policy. If there is no vehicle available, the pallet has to wait in the buffer area in that tier. Figure 1.4 illustrates the storage process in this system. The retrieval process is a reverse order of these events.

1.2.2. Queuing network theory

Based on the S/R process of this simple AVS/RS, it is reasonable to treat this system as a queuing network. Queuing network models are powerful tools in estimating key performance measures of discrete event, multistage service systems. Different types of customers arriving from the outside world enter the system to complete several stages of service, and then leave the system. The main components of a queuing network

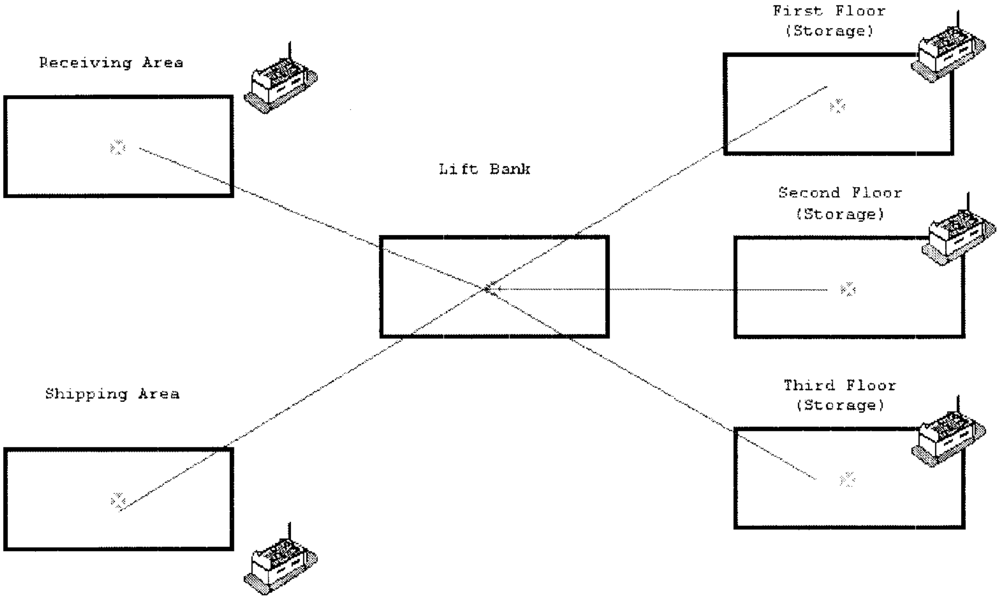


Figure 1.3. Representation of an AVS/RS with three tiers

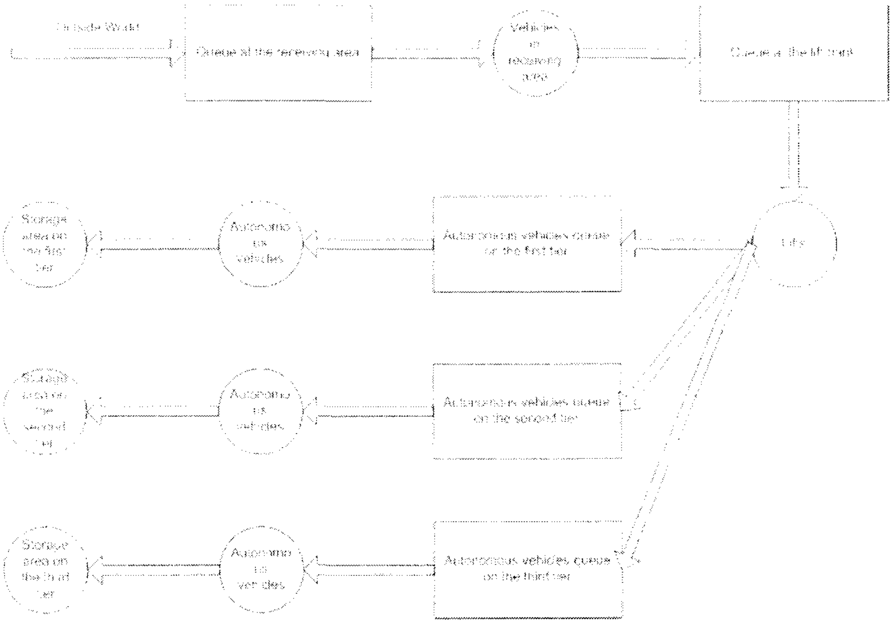


Figure 1.4. Storage Process

are servers, queues and customers. Several types of queuing networks are available in the literature - Closed Queuing Network (CQN), Open Queuing Network (OQN), and Semi-Open Queuing Network (SOQN).

The CQN has a population constraint and implicitly assumes there are infinite customers just outside the network. The population constraint is enforced by pairing each incoming customer with a limited number of another resource, such as a vehicle, which stays with the customer until the last stage of service is completed. When the customer leaves the system, the resource returns to the beginning of the network ready to be paired with a new customer. The number of resources is finite thus enforcing the population constraint in a CQN.

In OQN, customers arriving from the outside receive service at multiple stages of servers, and then depart from the system. The OQN implicitly assumes there is an infinite number of these additional resources so that an arriving customer never has to wait in the external queue.

SOQN, on the other hand, models the more realistic scenario, where a customer may have to wait for the resource or vice-versa and provides better estimates of total cycle time and work-in-process (WIP) inventory (Srinivasan and Heragu [2007]).

To apply queuing network theory to an AVS/RS, the pallets are treated as customers, and the autonomous vehicles and lifts are modeled as servers in the queuing network. Because vehicles and lifts are servers, and service times are travel times of these devices, pallets need no resource to "travel" between these servers. As a result, the OQN is suitable for this AVS/RS.

There are many OQN analyzers in the literature, such as the well-known Queuing Network Analyzer (QNA), and Manufacturing Performance Analyzer (MPA). MPA considers numerous real-world factors and provides reasonably accurate estimates of performance measures.

1.3. Background discussion

In the previous section, it is mentioned that AVS/RS is an alternative to AS/RS. In this section, a comparison between AVS/RS and AS/RS is presented to indicate advantages of the AVS/RS.

Crane-based AS/RS is the technology of choice for S/R in numerous applications. Although AS/RS technology has been well developed and it can achieve high throughput and fast response times in many material handling applications, it is a very rigid design and cannot easily adapt to rapid changes encountered in warehouse operations. As a result, alternative technologies, such as AVS/RS, have been developed and implemented. The AVS/RS has many advantages when compared with an AS/RS. These include flexibility and modularization, and are presented next.

1.3.1. Flexibility

The different load movement patterns make AVS/RS more flexible than AS/RS. In AS/RS, aisle captive cranes are the main S/R devices to move unit loads simultaneously in the horizontal and vertical dimensions. Because the cranes are typically aisle-captive, which mean that a crane machine can only travel on the designed aisle, we need more cranes per aisle and this could lead to low utilization of material handling devices. Unlike storage cranes in AS/RS, AVS/RS vehicles can access any aisle in any tier in the tier-to-tier configuration and any aisle in a designated tier in the tier-captive configuration. Because additional autonomous vehicles and lifts can be added or removed in the AVS/RS and vehicles are not assigned to any specific aisle, a potential advantage of AVS/RS compared AS/RS is the flexibility to satisfy different application requirements.

1.3.2. Modularization

The second advantage of AVS/RS is modularization. Because cranes complete all S/R operations in AS/RS, it is hard to modify the system configuration. A small change in AS/RS leads to costly redesign of the entire system in many applications. On the other hand, AVS/RS is highly modular. Different functional areas can be re-designed easily and have minimal impact on other areas. For example, the number of lifts can be changed to satisfy new requirements while keeping other configuration parameters constant. Similarly vehicles may be added or removed easily depending upon the throughput requirements.

1.3.3. Dispatching transactions rules

Another advantage of AVS/RS relates to the dispatching transactions rules. In AS/RS, retrieval transactions form individual queues in different storage aisles. However, storage transactions may or may not be segregated by aisles depending on the storage policy and system configuration (Malmborg [2002]). In comparison, all buffered S/R requests are in a single queue in an AVS/RS. Pooling both storage and retrieval transactions in a single queue may enable AVS/R systems to achieve higher proportion of S/R cycles using dual commands (Malmborg and Altassan [1998]). This allows the AVS/RS to be easily expanded or contracted depending upon throughput requirement. On the other hand, this feature may be a disadvantage for AVS/R systems because S/R transactions in a first come first serve (FCFS) queue may use locations on different storage tiers, which means S/R vehicles may take a longer time to complete the S/R transactions.

1.3.4. Main contributions

The main contributions of this thesis are:

- Application of an existing open queuing network analyzer to model a relatively new material handling technology.

- Development of a website embedded with previously developed analytical tools, that allow a designer to compare alternate configurations of AS/RS and AVS/RS.

1.3.5. Thesis Organization

In Chapter 2 the literature on simulation and analytical models of AS/RS is reviewed. In Chapter 3, an overview of MPA, and in Chapter 4 an overview of the Promodel simulation code generated automatically are presented. In chapter 5, the application of MPA to the AVS/RS is analyzed. A web interface developed for using analytical models to analyze AVS/RS and AS/RS designs is presented in Chapter 6. Experimental results and a comparison of MPA's performance with that of a simulation model are presented in Chapter 7 along with a comparison between MPA and another analytical model. Conclusions are drawn in Chapter 8.

CHAPTER 2

LITERATURE REVIEW

There are very few papers on AVS/RS because it is a relatively new material handling technology. Malmborg [2002] developed a conceptualization tool for AVS/RS and Fukunari et al. [2004] discussed dwell point issues of AVS/RS in detail by using a decision-tree analysis.

On the other hand, AS/RS has been in use for the past thirty years and numerous models have been developed. Various simulation models of AS/RS exist in the literature. These studies compare different storage policies for a given system configuration. Additionally, various analytical models to estimate the cost of an AS/RS have been proposed. Once an AS/RS has been installed, the performance of the entire system depends on control methods applied to the system. The control methods include storage method, order sequencing, and dwell points of S/R machines.

2.1. Simulation models

Various simulation models of AS/R systems exist in the literature. These studies evaluate alternate design choices for a given system configuration.

2.1.1. Sizing problem

The sizing problem of warehouse design is a combined problem, which is caused not only by internal layouts or storage policies but many other factors. Rosenblatt and Roll [1984] presented a combined approach of optimization techniques to determine the total cost of warehouse sizing with two decision variables: warehouse capacity and storage policy. An extension of this work has been done in Rosenblatt and Roll [1988].

A simulation model was developed to measure the relationship between warehouse size and various pertinent parameters. The stochastic nature of the demand and replenishment requires us to determine the warehouse capacity by the desired service level. The desired service level indicates the proportion of time the warehouse is able to satisfy the demand from stock. Another term in the Rosenblatt and Roll [1988] paper is the nominal capacity requirement (NCR), which refers to the average size of a warehouse calculated based on the average quantity of each item. Rosenblatt and Roll [1988] pointed out that a warehouse with an NCR capacity will provide only a 50% service level. There are various parameters that have an effect on the warehouse size for a given service level. These were studied using a simulation model. Multi-aisle S/R machine system (MASS) was studied by Hwang and KO [1988] to reduce the initial investment of installing an AS/R system. The multi-aisle system can reduce the installation cost dramatically to half the cost of single-aisle S/R machine system as long as the S/R demands are relatively low.

Choi and Shin [1997] described a paint body storage (PBS) at an automobile assembly plant as an AS/RS to re-sequence vehicles for entry into final assembly. The extension work of the application of AS/RS in automotive assembly sequences has been done by Inman [2003]. As mentioned, many automotive assembly plants use an AS/RS to adjust the assembly sequence before final assembly. Some primary drivers of the AS/RS size are the degree of sequence scrambling in body and paint shops, the number of vehicle configurations entering final assembly, and each configuration's penetration. Inman [2003] presented an analytical model for sizing this post-paint AS/RS by considering these mentioned factors.

2.1.2. Deadlock problem

A large number of studies have discussed classical operational problems such as dwell points, expected cycle-time models and optimizing transporter operations (Berg and Gademann [2000]). However, there are relatively very few papers in the literature dealing with operational controller tasks such as avoiding vehicle deadlocks in the AS/RS. Deadlock in manufacturing systems is highly unfavorable because a part's access to resources is held up by other parts. One method of deadlock resolution is to abort one or more parts involved in the deadlock and releasing resources to other parts (Fanti et al. [1997]). The approaches to address deadlocks are prevention methods, detection/recovery approaches and avoidance algorithms.

Lee et al. [1996] discussed a deadlock problem in a narrow aisle AS/RS serviced by rail-guided vehicles. They solved the deadlock problem by increasing conveyor capacity in the simulation model, which is a deadlock detection/recovery (DDR) method. However, the solution of deadlock problems had not been formally described. In order to characterize the deadlock in the AS/RS correctly, a model should be established. Dotoli and Fanti [2005] suggested a unified modeling framework for the heterogeneous AS/RS transport system by using colored timed Petri nets (CTPNs). The CTPN can describe the dynamic behavior of the system, which is modular and resource-oriented. Although the CTPN is resource-oriented and suitable to use in operational level, it is too complex for characterizing the deadlock and defining efficiency resolution policies for AS/R systems. Dotoli and Fanti [2007] presented their extended work of deadlock detection and avoidance strategies in AS/R systems. The AS/RS is modeled as a timed discrete event dynamical system (DEDS), in which the information of paths and locations of vehicles is stored in the state. The state can be changed whenever an event occurs. This characterization can be used in the analysis of deadlocks in the AS/RS.

Dotoli et al. [2004] compared two different real-time deadlock solution strategies for the AS/RS: a deadlock avoidance strategy and a deadlock detection/recovery strategy. The deadlock avoidance strategy was proposed by Fanti [2002] to guarantee an efficient system performance using a DEDS and digraph tools. The DDR strategy was proposed by Lee et al. [1996] to solve the deadlock problem by utilizing buffers to store deadlocked jobs.

2.1.3. Travel-time models

The service time for a transaction includes both S/R machine travel time and pick-up/deposit time. The pickup/deposit time is assumed to be deterministic due to the nature of the S/R machine. The travel time is variable and is thus useful in measuring important performance measures of AS/RS, for example throughput times. For single shuttle AS/RS, S/R machines can perform up to one storage and one retrieval operation as a dual command cycle (DC). However, in multi-shuttle AS/RS with two unit loads, the S/R machine can perform up to two S/R operations in a cycle as a quadruple command cycle (QC). Potrc et al. [2004] presented a simulation model of multi-shuttle AS/RS by using a new heuristic strategy instead of FCFS strategy in single-shuttle AS/RS. This simulation model indicates that multi-shuttle AS/RS has large improvements in travel time when compared with single-shuttle AS/RS. Hu et al. [2005] presented a continuous travel-time model for a new type of AS/RS, split-platform AS/RS (SP-AS/RS). By introducing a new S/R mechanism for handling extra heavy loads efficiently, the SP-AS/RS shows improved S/R machine travel-times.

2.2. Analytical models

Additionally, various analytical models to estimate the cost of an AS/RS have been proposed. Once an AS/RS is installed, the performance of the entire system depends on control methods applied on the system. The control methods include storage method, order sequencing, and dwell points of S/R machines. Research in the area of dwell points and expected travel-time models for S/R machines are reviewed in this section.

2.2.1. Dwell points models

The first area relates to dwell points. Some simple rule-of-thumb policies have been studied by Bozer and White [1984]. These strategies are easy to understand and implement, but they are static and cannot respond to changes in the S/R transactions in an AS/RS from period to period. Egbelu [1991] developed a dynamic optimal location strategy based on mathematical programming including two separated sub models to minimize the service response time. One sub model is to minimize the maximum S/R machine response time while the other solves the minimization of the expected response time. Hwang and Lim [1993] extended the Egbelu [1991] study by transferring one sub model to a single-facility location problem and developed an efficient algorithm to generate an optimal dwell point of S/R machines in AS/RS. Several dwell point specification strategies for S/R machines have been studied by Egbelu and Wu [1993] based on the simple rule-of-thumb policies by Bozer and White [1984] and dynamic strategies based on linear program developed by Egbelu [1991]. Egbelu and Wu [1993] conducted a performance comparison by using average order turnaround time as the basis for comparison. The choice of the dwell point has a significant impact on expected response time of AS/RS. Peters et al. [1996] developed an analytical model for the determination of the optimal dwell point location for an

S/R machine. This model provides a closed form solution for the dwell point location problem under a variety of system configurations. Peters et al. [1996] developed a closed form solution for square-in-time (SIT) racks. However, racks are not necessarily SIT, which means study of non-square-in-time (NSIT) and uniformly distributed racks are more valuable. Park [2001] developed a closed form solution for the optimal dwell point of NSIT racks determined by the probability of the next transaction demand type – storage or retrieval. In addition, various return paths to dwell points are also examined in this paper.

2.2.2. Expected travel-time models

Another study area is the expected travel-time of S/R machines in AS/RS. Three storage assignment rules have been compared based on expected travel-time of S/R machines by Hausman et al. [1976]. They pointed out that there is a significant reduction in crane travel time by using dedicated storage policy such as full turnover-based assignment rather than randomized storage policy. Graves et al. [1977] extended the work done by Hausman et al. [1976] to compare the operating performance of several storage assignment policies by using both continuous and discrete evaluation models. Each rule is compared on the basis of expected travel-time of S/R machines. Bozer and White [1984] developed travel-time models for single or dual command cycles. They compared the expected travel-time of an AS/RS crane for these two cycles. Travel times under different storage assignments have been investigated by Wen et al. [2001]. They considered various travel speeds with known acceleration and deceleration rates. A computerized algorithm developed by Mansuri [1997] investigated dedicated storage allocation alternatives for an AS/RS based on cycle time of the S/R crane. Ashayeri et al. [2002] presented an exact, geometry-based analytical model to compute the expected cycle travel-time for an S/R machine with single-command, dual-command, or both. The rack can be either SIT or NSIT and no fixed layout shape is assumed in this model. This approach can make the AS/RS more appealing for use in integrated supply chain systems. Sari et al. [2007] presented closed-form travel-time expressions for flow-rack AS/RS based on a continuous approach and compared them with simulation to demonstrate that this analytical model can estimate performance measures by requiring less computing time than simulation.

2.2.3. Dynamic control policies

Proper selection of dynamic control policies allows us to maximize the system throughput. Lin and Wang [1995] presented an application of stochastic Petri nets (SPNs) to describe the behavior of AS/RS and evaluate the performance of different control policies of such systems. The SPN is a graph-based tool that can build a system at different levels. This property of SPN can divide the whole system into several sub systems and model them separately, which makes it is easy to remodel changes in system configurations change. Dotoli and Fanti [2005] developed a colored Petri net (CPN) to investigate the performance of AS/RS from a control perspective. CPN is a well-known dialect of high-level SPNs that can be implemented in work flow analysis. This allows us to model a resource-oriented model suitable for real-time control. A performance analysis for multiple aisle AS/RS by using SPNs is presented by Benamar et al. [2003]. Timed Petri nets (TPNs) extended from CPNs with time concepts is applied to model the AS/RS and evaluate system performance.

CHAPTER 3

MANUFACTURING PERFORMANCE ANALYZER

In the introduction we mentioned OQN can be used to model the AVS/RS. There are many methods developed to analyze OQN. Exact solution is possible for networks with exponential inter-arrival and service time distributions. However, external arrival processes of complex queuing networks need not be Poisson and the service time distributions need not be exponential. In order to solve more general queuing network problems, approximation methods are needed. There are several approximation methods in the literature, and the parametric decomposition (PD) method is a popular method.

The main idea of PD is to decompose a complex queuing network into several isolated queues or subsystems (Kuehn [1979]). Key points of PD include two principles. The first one is approximation of all non-renewal processes by stationary renewal processes. A renewal process means every time an event occurs, the process renews itself and starts all over again. The Poisson process is a special case of a renewal process where time between occurrences is exponentially distributed. Typically, a complex stochastic process has one or more embedded renewal processes, which allows the process to be decomposed into smaller independent systems. For example, Markovian networks can be decomposed into subsystems exactly, while general networks only can be decomposed approximately. Another important principle is consideration of the first two moments - mean value and squared coefficient of variation (SCV) of all processes. This principle rests on a number of observations in queuing networks where mean values of performance measures are mainly influenced by the mean and SCV of a random variable.

QNA developed by Whitt [1983] is a software package for OQN in communication systems, but it was modified to model discrete parts manufacturing systems. The approximation method in QNA decomposes the queuing network into several stochastically independent $GI/G/m$ queues. A $GI/G/m$ queue indicates that the arrival process of the queue with m multiple servers is a renewal process with general distribution (GI), and the distribution of service time is also general (G). QNA uses the first two moments of inter-arrival and service times to handle more generally distributed OQNs. Once the first two moments of the inter-arrival time of each customer type into the network and its routing are given, QNA calculates the first two moments of effective inter-arrival times of customers at each node. QNA also calculates the first two moments of effective service times at each node and then analyzes each node as an independent $GI/G/1$ or $GI/G/m$ queue to estimate performance measures of this node. Finally, performance measures of the entire queuing network are estimated by synthesizing performance measures of these independent $GI/G/1$ or $GI/G/m$ queues (Whitt [1983]).

MPA, an extention of QNA, and described in Meng and Heragu [2004], is an analytical model specifically designed to evaluate the performance of a manufacturing system. The analytical model of MPA in the context of a manufacturing system is introduced by briefly recapping the two systems of linear equations used to calculate the first two moments of inter-arrival and service times.

The notations used in MPA are listed here:

n = number of servers

p = number of product types

i = product type index, $i = 1, 2, ..., p$

j, k = server node index, $j, k = 1, 2, ..., n$

l = operation index, $l = 1, 2, ..., o^i$

m_j = number of machines at node j

λ_{jk} = rate at which a product leaving node j goes to node k

λ'_{jk} = rate at which a product arriving at node k comes from node j

p_{jk} = proportion of products leaving node j that go to node k

p'_{jk} = proportion of products arriving at node k that come from node j

c^2_{aj} = SCV of inter-arrival time for two consecutive arrivals into node j

τ_{sj} = mean service time on machines at node j

c^2_{sj} = SCV of service time on machines at node j

b^i_{kl} = operational batch size of lth operation of product i on machines at node k

bt^i_{jk} = transfer batch size between node j and node k

$\gamma^{i,l}_{jk}$ = relative batch size of lth operation of product i performed on machines at node j to the batch size of $(l+1)$th operation of that product on machines at node k

$$Y^i_{kl} = \begin{cases} 1 & \text{if the } l\text{th operation of product } i \text{ is done at node } k \\ 0 & \text{otherwise} \end{cases}$$

$$Y^i_{jkl} = \begin{cases} 1 & \text{if the } l\text{th and } l+1\text{th operation of product } i \text{ are done at node } j \text{ and } k \\ 0 & \text{otherwise} \end{cases}$$

3.1. Basic network operations

Whitt [1983] pointed out that an OQN combines several basic network operations no matter how complex the network is. These network operations are departure, split and superposition. Effects of these operations are discussed next.

1) Departure operation

The effective departure rate and SCV of the inter-departure times at a node are

$$\lambda_d = \lambda_a \tag{3.1}$$

$$c_d^2 = 1 + (1 - \rho^2)(c_a^2 - 1) + \frac{\rho^2}{\sqrt{m}}(c_s^2 - 1) \tag{3.2}$$

where λ_a is the arrival rate into the node, and c_a^2 is SCV of inter-arrival times. ρ is the traffic intensity or utilization at the node.

$$\rho = \lambda_a \tau_s / m$$

2) Split operation

The aggregate product is split into subaggregate products via the split operation. The effective departure rate and SCV of the arrival process of split operation are

$$\lambda_i = p_i \lambda_a \tag{3.3}$$

$$c_i^2 = p_i c_a^2 + 1 - p_i \tag{3.4}$$

3) Superposition operation

Products arriving at a node j are aggregated via the superposition operation. The first two moments of the arrival process of superposition are

$$\lambda_a = \sum_i \lambda_i \tag{3.5}$$

$$c_a^2 = \omega \sum_i \left(\frac{\lambda_i}{\sum_k \lambda_k}\right) c_i^2 + 1 - \omega \tag{3.6}$$

The weighting function is

$$\omega = [1 + 2.1(1 - \rho)^{1.8} \nu]^{-1}$$

where

$$\nu = [\sum_i (\lambda_i / \sum_k \lambda_k)^2]^{-1}$$

3.2. Estimating the first two moments of inter-arrival times

As mentioned previously, the first two moments of effective inter-arrival times are obtained by solving two sytems of linear equations, which synthesize the effects of these three basic network operations on the first and second moments of the inter-arrival times.

The first system of linear equations calculates the effective arrival rate into each node:

$$\hat{\lambda}_k = \hat{\lambda}_{0k} + \sum_{j=1}^{n} \hat{\lambda}_j p_{jk}, \quad k = 1, 2, \ldots n \tag{3.7}$$

Equation (3.7) indicates that the effective arrival rate into any node k is equal to the arrival rate from the outside world plus arrival rates from other nodes in the network.

The second system of linear equations is used to caculate the SCV of the inter-arrival time for two consecutive arrivals into any node in the network, which is the synthesis of the effects of the three basic operations:

$$c_{aj}^2 = a_j + \sum_{i=1}^{n} c_{ai}^2 b_{ij}, \quad 1 \leq j \leq n \tag{3.8}$$

In Equation (3.8), a_j and b_{ij} are constants as follows:

$$a_j = 1 + \omega_j((p'_{0j} c_{0j}^2 - 1) + \sum p'_{ij}[(1 - p_{ij}) + p_{ij} \rho_i^2 x_i])$$

$$b_{ij} = \omega_j p'_{ij} p_{ij} (1 - \rho_i^2)$$

$$x_i = 1 + m_i^{-0.5} (\max(c_{si}^2, 0.2) - 1)$$

$$\omega_j = [1 + 4(1 - \rho_j)^2 (v_j - 1)]^{-1}$$

where

$$v_j = (\sum_{i=0}^{n} pq_{ij}^2)^{-1}$$

The batching of products has an impact on the first two moments of the effective arrival rates at each node. Although Whitt [1983] considered batching, they assumed all products are batched the same way at each node. Meng and Heragu [2004] considered a more general batching model and introduced a fourth network operation. b^i_{kl} is defined as the batch size of product i at machine k for its lth operation. Define the relative batch size:

$$\gamma_{jk}^{i,l} = \frac{b^i_{jl}}{b^i_{k,l+1}}$$

as the ratio of the batch size of lth operation of product i on node j to the batch size of $(l+1)$th operation of product i on node k. If there are multiple products from node j to node k, the relative batch size is as follows:

$$\gamma_{jk} = \frac{\sum_{i=1}^{n}\sum_{l=2} o^i b^i_{j,l-1} Y^i_{jkl}}{\sum_{i=1}^{n}\sum_{l=1}^{o^i} b^i_{kl} Y_{jkl}{}^i} \tag{3.9}$$

where o^i is the number of operations of product i. The first two moments of batch operation at the node are

$$\lambda_{ak} = \gamma_{jk}\lambda_{dj} \tag{3.10}$$

$$c^2_{ak} = \gamma_{jk} c^2_{dj} \tag{3.11}$$

By considering different batch sizes in the network, the first set of linear equations can be modified as follows:

$$\hat{\lambda}_k = \hat{\lambda}_{0k} + \sum_{j=1}^{n} \hat{\lambda}_j p_{jk}\gamma_{jk}, \quad k = 1, 2, ...n \tag{3.12}$$

The only difference between Equation (3.12) and Equation (3.7) is the relative batch size that indicates the flow change due to different batch sizes for two consecutive operations (Meng and Heragu [2004]).

The second set of linear equations in MPA is as follows:

$$c^2_{ak} = a_k + \sum_{j=1}^{n} c^2_{aj} b_{jk}, \quad k = 1, 2, \ldots n \tag{3.13}$$

where

$$a_k = 1 + \omega_k\{(p'_{0k}\gamma_{0k}c^2_{0k} - 1) + \sum_{j=1}^{n} p'_{jk}\gamma_{jk}[(1 - p_{jk}) + p_{jk}\rho_j^2 x_j] + \sum_{j=0}^{n} p'_{jk}\max(\gamma_{jk} - 1, 0)\}$$

$$c_{jk} = \omega_k p'_{jk} p_{jk} \gamma_{jk}(1 - \rho_j^2)$$

$$\omega_k = \frac{1}{1 + 4(1 - \rho_k)^2(u_k - 1)}$$

$$x_j = 1 + \frac{1}{\sqrt{m_j}}[\max(c^2_{sj}, 0.2) - 1]$$

$$u_k = \frac{1}{\sum_{j=0}^{n}(p'_{jk})^2}$$

and

$$\gamma_{jk} = \frac{\sum_{i=1}^{p}\sum_{l=1}^{o^i}\hat{\lambda}^i_{jk}\gamma^{i,l}_{jk}Y^i_{jl}Y^i_{k,l+1}}{\sum_{i=1}^{p}\sum_{l=1}^{o^i}\hat{\lambda}^i_{jk}Y^i_{jl}Y^i_{k,l+1}}$$

The difference between Equation (3.13) and Equation (3.8) is also due to incorporation of the effect of batching.

3.3. Estimating the first two moments of service times

The effective mean value and SCV of service times are calculated as:

$$\tau_j = \frac{\sum_{k=1}^{r}\sum_{\ell=1}^{n_k}\lambda_k\tau_{k\ell}1\{(k,\ell) : n_{k\ell} = j\}}{\sum_{k=1}^{r}\sum_{\ell=1}^{n_k}\lambda_k 1\{(k,\ell) : n_{k\ell} = j\}} \tag{3.14}$$

$$\tau_j^2(c^2_{sj} + 1) = \frac{\sum_{k=1}^{r}\sum_{\ell=1}^{n_k}\lambda_k\tau^2_{k\ell}(c^2_{sk\ell} + 1)1\{(k,\ell) : n_{k\ell} = j\}}{\sum_{k=1}^{r}\sum_{\ell=1}^{n_k}\lambda_k 1\{(k,\ell) : n_{k\ell} = j\}} \tag{3.15}$$

3.4. Network performance measures

Now that the network has been broken up into stochastically independent nodes and their effective inter-arrival and service time parameters have been approximately calculated, we can analyze each node separately and obtain estimates of performance measures as shown next.

The average waiting time in a $GI/G/m$ queue is:

$$\mathbb{E}(WQ_k) = \frac{c_{ak}^2 + c_{sk}^2}{2}\mathbb{E}(WQ_k)^{M/M/m} \tag{3.16}$$

where $\mathbb{E}(WQ_k)^{M/M/m}$ is the average waiting time in a $M/M/m$ queue.

The basic total network performance measure is the throughput, which is same as the total external arrival rate λ_0.

$$\lambda_0 = \sum^{n} \lambda_{0i} \tag{3.17}$$

The mean and variance of the number of customers N in the entire network are

$$\mathbb{E}N = \sum_{i}^{n} \mathbb{E}N_i \tag{3.18}$$

$$Var(N) = \sum_{i}^{n} Var(N_i) \tag{3.19}$$

There are two kinds of customers: an aggregate customer and a particular customer. For an aggregate customer, p_{ij} is independent of the current state and history of the network. On the other hand, each particular customer should have a relatively negligible effect on the total network from the view of particular customers. MPA uses the view of aggregate customers.

Some important equations for estimating key performance measures are listed here

The expected number of visits to node i is

$$\mathbb{E}V_i = \lambda_i/\lambda_0 \tag{3.20}$$

The mean time a customer spends in node i is

$$\mathbb{E}T_i = (\mathbb{E}V_i)(\tau_i + \mathbb{E}W_i) \tag{3.21}$$

The expected total time in the network from arrival to departure for a customer is

$$\mathbb{E}T = \sum_{i=1}^{n} \mathbb{E}T_i = \sum_{i=1}^{n} \mathbb{E}V_i(\tau_i + \mathbb{E}W_i). \tag{3.22}$$

The variance of the time spent by a customer at node i is

$$Var(T_i) = \mathbb{E}V_i(Var(W_i) + \tau_i^2 c_{si}^2) + Var(V_i)(\mathbb{E}W_i + \tau_i)^2 \tag{3.23}$$

and

$$\mathbb{E}V_i^2 = \sum_{j=1}^{n} (\lambda_{0j}/\lambda_0)[F(2F_{dg} - 1)]_{ji} \tag{3.24}$$

where F is the matrix $(I - P)^{-1}$, and $P \equiv (p_{ij})$. F_{dg} is the $n \times n$ matrix with all off-diagonal entries 0 and diagonal entries the same as F.

By assuming that T_is at the different nodes are conditionally independent,

$$T = (\sum_{j=1}^{n} \sum_{k=1}^{V_j} T_{kj}) \tag{3.25}$$

where T_{kj} is the time for the kth visit to node j.

Finally,

$$\mathbb{E}(T^2) = \sum_{i=1}^{n} \mathbb{E}(\sum_{k=1}^{V_i} T_{ki})^2 + 2\sum_{i=1}^{n} \sum_{j=i+1}^{n} \mathbb{E}(\sum_{k=1}^{V_i} T_{ki} \sum_{\ell=1}^{V_j} T_{\ell j}) \tag{3.26}$$

and

$$Var(T) = \mathbb{E}(T^2) - (\mathbb{E}(T))^2 \tag{3.27}$$

Hence,

$$Var(T) = \sum_{i=1} nVar(T_i) + 2\sum_{i=1}^{n} \sum_{j=i+1}^{n} \mathbb{E}(T_{1i}\mathbb{E}(T_{1j})Cov(V_i, V_j)) \tag{3.28}$$

To summarize, MPA analyzes the network system in following four steps (Meng et al. [2004]):

- Calculate the first two moments of the inter-arrival times of the aggregated product into each node.

- Calculate the first two moments of the effective service time of the aggregate product at each node.

- Calculate the performance measures of each node as a $GI/G/m$ queue.

- Calculate product-specific metrics and overall system performance.

CHAPTER 4

SIMULATION MODEL

4.1. Overview

The simulation model has been developed by using the Promodel software tool. Promodel is a powerful simulation tool for simulating and analyzing all types of production systems. Promodel focuses on system performances such as resource utilization, production capacity, and inventory levels. As a discrete event simulator, Promodel is excellent for using in assembly lines, transfer lines, flexible manufacturing systems and so on.

A Promodel simulation model consists several modules to model a real system. Main modules of a Promodel model are entities, locations, resources and processes. The entities present the tasks in the system, while the locations define places where these tasks occur. The resources are the items required to process tasks and the processes define logic relationships among entities, locations and resources (Macro and Salmi [2002]).

4.2. Model generation

MPA can generate a Promodel simulation model according to input data sheets automatically. The mechanism of model generation is Visual Basic for Applications (VBA) for Mircrosoft Access. VBA is a macro language when Visual Basic (VB) is used within another application. VBA has the similar integrated development environment (IDE) as VB and is easy to be developed.

Because Promodel is an object linking and embedding (OLE) server, VBA can control it similar as control an Access object (Cameron [1999]). A program written by VBA generates the simulation model by setting properties of every module from input data sheets.

Tables 4.1 - 4.3 show a typical set of properties of main modules in the Promodel simulation model generated by MPA. All properties can be changed dynamically in different scenarios.

Table 4.1. Location Properties

Locations	Properties				
	Capacity	Units	Down Times	Stats	Rules
Batch Area (B)	Inf	1	None	Time Series	Oldest
Queue Area (Q)	Inf	1	None	Time Series	Oldest
Servers (M)	1	1	Usage	Time Series	Oldest

Table 4.2. Entities Properties

Entities	Properties	
	Speed	Stats
Product (I)	1500 fpm	Time Series

Table 4.3. Processes Properties

Processes	Properties			
	Location	Output	Destination	Rule
Product(I)	Batch Area (B)	Next Product Type	Next Location	Oldest
Product(I)	Queue Area (Q)	Next Product Type	Next Location	Oldest
Product(I)	Server (M)	Next Product Type	Next Location	Oldest

The locations module presents servers, batch areas and queues in the system. The first property of this module is capacity, which indicates the capacity of servers as well as batch areas and queues. The capacity of servers is one, which means a server can process only one entity in one transaction. For example, the capacity of lifts is one, which means a lift can only take one pallet per time. The capacity of batch areas and queues are infinity as default values, which is a reasonable assumption in AVS/RS. This property is usually kept constant.

The second property is unit, which indicates the number of each type of server, batch area and queue. For batch areas and queues, the default unit value is 1, which is reasonable to assume there is only one batch area and waiting queue in front of each type of server.

The down times and stats properties are same if there is no particular requirement. The rules property defines how a location selects the next incoming entity from several entities that are waiting to enter this location, how multiple entities at a location queue for output, and which unit of a multi-unit location is selected by an incoming entity. There are many rules that can be selected, such as oldest by priority, random and least available capacity. The oldest by priority is chosen as the default value.

The entities module presents pallets in AVS/RS. Two properties need to be set in this module: speed and stats. The speed applies to self-moving entities. In AVS/RS, pallets are transported by vehicles and lifts. However, because vehicles and lifts are treated as servers by queuing network theory, pallets "move" between servers. As a result, the speed can be set to be the same for all types of pallets. The default value of stats is time series.

The processes module defines the routing of entities through the system and the operations at each location in the route. Location, output, destination and rules properties need to be set in this module.

The location property defines the location where the entity is. The output property is the type of entity after leaving the location. Because split and superposition operations are not considered in this case study system, the output property can be set as the same product type. The destination is the next location the entity will enter. For example, the autonomous vehicle takes a pallet to the lift bank, then the destination of this pallet is the batch area of the lift bank. The rules property is same in the location module, and the default value is oldest by priority.

CHAPTER 5

APPLICATION OF MPA IN AVS/RS

MPA was designed for a discrete parts manufacturing system. It needs to be modified to be applied to the AVS/RS. Main changes of MPA are listed in Tables 5.1 - 5.3.

Table 5.1. Server parameters

Parameter	Meaning
m	Unique vehicle or lift index number in the system
c	Cell number
loc	Locations of vehicles or lifts
$capacity$	Number of the vehicle or lift type in the cell
$type$	Server type
$MTTF$	Mean time to failure of the server
$MTTR$	Mean time to repair the server
N_s	The server needs to be setup after Ns loads
T_s	Setup time of the server
$c_{T_s}^2$	SCV of Ts

Table 5.2. Product parameters

Parameter	Meaning
p	Product index
λ_p	Arrival rate of product p from the outside world
$c_{\lambda_p}^2$	SCV of λ_p
t_p	Mean setup time of product p on the material handling device
$c_{t_p}^2$	SCV of t_p

We assume each storage space on each tier to be a server, where loads are stored for a random time period. However, performance of storage areas are not considered in this paper, because they are not meaningful in measuring the performance of an AVS/RS.

Table 5.3. Parameters for operations

Parameter	Meaning
p	Product index
o	Operation index of product p
m	Absolute server index
b	Batch size of each server
t_o	Natural service time of each operation for product p
$c_{t_o}^2$	SCV of t_o
t_s	Mean setup time of every server for each operation
$c_{t_s}^2$	SCV of t_s

MPA is a complex network analyzer with many functions. In order to apply MPA to estimate performance of an AVS/RS, some parameters in MPA are simplified with some default values. For example, although it can be relaxed, the assumption has been made that the MTTFs and the MTTRs are equal in the system studied in this thesis. Additionally, T_ss are assumed to be 0 for all servers in the system. All SCVs are assumed to be 1, which indicates only exponential distribution is considered.

CHAPTER 6

WEB INTERFACE FOR THE CONCEPTUALIZATION OF AVS/RS AND AS/RS

6.1. Introduction of the web interface

Analytical modeling of warehouse design is an alternative to simulation. The analytical model can significantly reduce the time to establish the warehouse design. However, if the analytical models reside on a local computer , and use specific software, for example, Matlab, it is difficult for warehouse designers who do not have the background or access to the analytical models or the software to use them. The web based tool presented in the thesis provides a user-friendly interface between the analytical models and warehouse designers. Users need not know details of the algorithm used to solve the analytical models. The main function of the on-line interface is to help warehouse designers to quickly evaluate alternate designs by using the conceptualization tools developed to analyze AS/RS and AVS/RS. Four different algorithms for AVS/RS and AS/RS are embedded in the website, and can be used for different system design requirements.

6.1.1. Basic technologies to develop the web interface

The web interface is based on a browser/server (B/S) system configuration. Applications based on B/S frame have many advantages. There can be nearly unlimited client access if the application is running on a super computer. Another advantage is that the application only needs to be changed on the sever side, instead of changing thousands of client-installed applications. The drawback of B/S configuration compared to another configuration, for example the client/server (C/S) is that all calculations need to be computed on the server computer, which may lead to data blocking. In our application, analytical models do not require much computation time, and thus the B/S configuration is suitable in developing this interface.

Many webpage languages existed in the market, and we chose the Java Server Pages (JSP). JSP is a dynamic webpage language, which can display dynamic generated content. This language has several advantages including ability to function on any web server, separating the realization logic from the appearance of pages, and allowing real-time development.

The website has a real-time database to store user information and design data. We chose MySQL technology to develop this database. MySQL has many advantages. The first one is flexibility. MySQL only needs one mega byte of data storage to run the database itself. As a result, MySQL provides much flexibility. MySQL is an open-source application allowing developers to add unique requirements to the database server. The second advantage is high performance and reliability. A database on the server computer should be static and able to handle some data error. MySQL provides strong data protection and exceptional security features to ensure the website runs as intended.

6.1.2. Details of the web interface

The process by which the user enters data can be divided into three steps:

- Provide user information
- Select an algorithm and enter required parameters
- Run the algorithm and compare results.

Figure 6.1 shows the data entry process of the web interface.

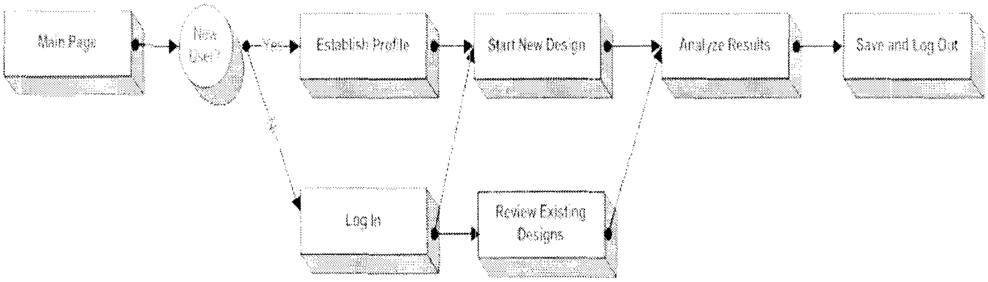


Figure 6.1. Data entry steps

6.2. Case studies

There are four algorithms embedded in our website. Four case studies are presented in this section.

1) AS/RS_m algorithm:

This algorithm calculates the expected system cycle time, system throughput, crane utilization and total system cost for an AS/RS when the total storage space requirement is given.

Tables 6.1 and 6.2 show the list of input and output parameters of AS/RS_m algorithm.

Table 6.1. Input parameters of AS/RS_m algorithm

Parameter	Meaning
Rs	Arrival rate of storage request (arrivals per minute)
Rr	Arrival rate of retrieval request (arrivals per minute)
T	Total number of tiers in the warehouse
A	Total number of aisles in the warehouse
n	Total storage space requirement
LBC	Lower bound on the total number of rack columns
UBC	Upper bound on the total number of rack columns
uH	The height of each storage space
uL	The width of each storage space
Vv	Vehicle horizontal speed
Vl	Vehicle/lift vertical speed
Cost_Crane	Cost per crane in thousands of dollars
Cost_Cell	Cost per rack cell in thousands of dollars

Table 6.2. Output parameters of AS/RS_m algorithm

Parameter	Meaning
C	Total number of columns of the rack
U	Crane utilization
ECT	Expected system cycle time
Cost	The total estimated cost of the system

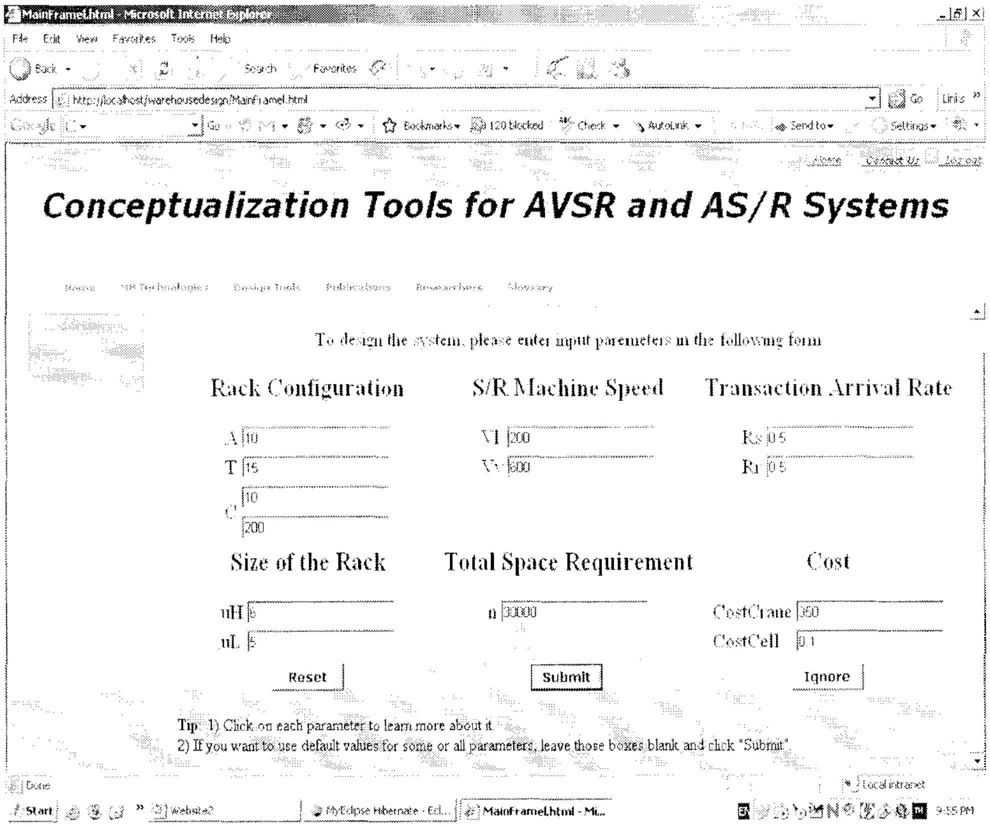
Table 6.3 shows a study case using the AS/RS_m algorithm. These parameters are divided into six parts. The rack configuration denotes the basic design parameters of the warehouse, such as the number of aisles and number of tiers. The S/R machine speed defines the horizontal and vertical speeds of the S/R crane. The transaction arrival rate involves two types of arrival rate: storage and retrieval requests. The total space requirement is required in this algorithm. The cost consists of two parts: the cost of a crane and the cost of a storage cell. The algorithm can calculate the optimal system cost using these data.

Table 6.3. A study case using the AS/RS_m algorithm

Parameter	Value
Rs	0.5
Rr	0.5
T	15
A	10
n	30000
LBC	10
UBC	200
uH	6
uL	5
Vv	600
Vl	200
Cost_Crane	350
Cost_Cell	0.1

Figure 6.2 shows the input page of AS/RS_m algorithm. Figure 6.3 shows the output page of AS/RS_m algorithm.

2) AS/RS_mc algorithm:



Conceptualization Tools for AVSR and AS/R Systems

To design the system, please enter input paremeters in the following form

Rack Configuration

A 10
T 15
C 10
200

S/R Machine Speed

Vl 200
Vv 600

Transaction Arrival Rate

Rs 0.5
Rr 0.5

Size of the Rack

nH 6
nL 5

Total Space Requirement

n 30000

Cost

CostCrane 350
CostCell 0.1

Tip: 1) Click on each parameter to learn more about it.
2) If you want to use default values for some or all parameters, leave those boxes blank and click "Submit".

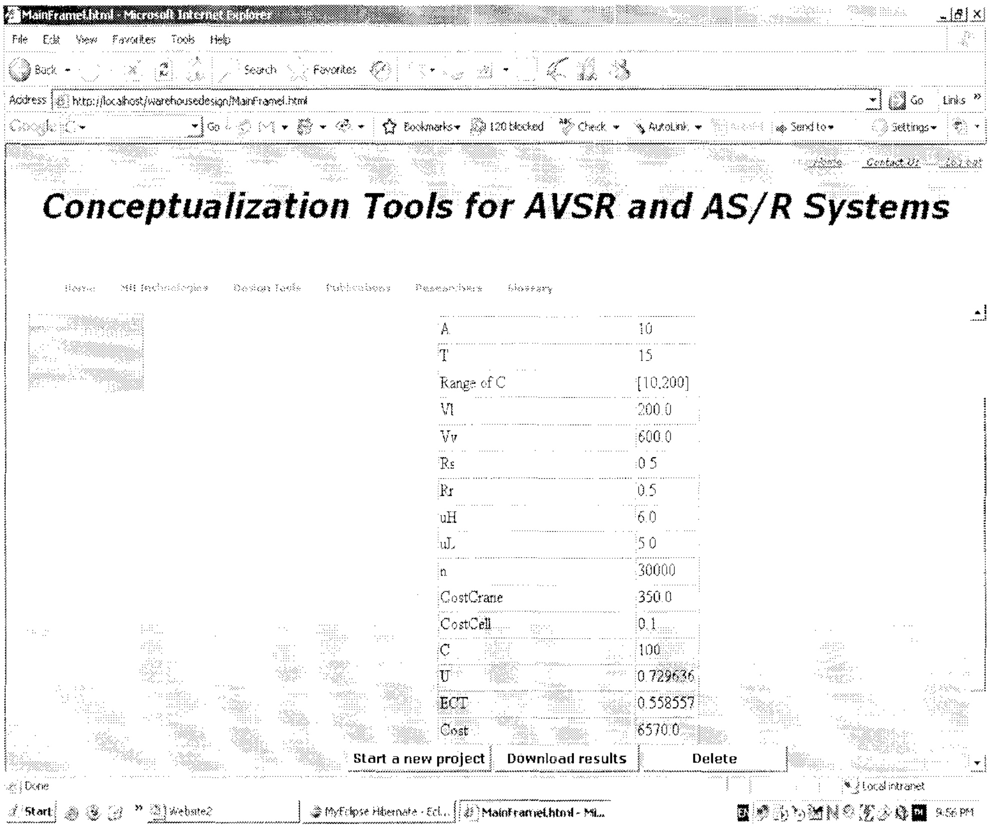
Figure 6.2. Input parameters page of AS/RS_m algorithm

This algorithm also calculates the expected system cycle time, system throughput, crane utilization and total system cost for an AS/RS. The only difference between this algorithm and AS/RS_m algorithm is that the number of columns is required instead of the total storage space requirement.

Tables 6.4 and 6.5 show the list of input and output parameters of AS/RS_mc algorithm. Table 6.6 shows a study case of AS/RS_mc algorithm. Figure 6.4 shows the input page of AS/RS_mc algorithm and Figure 6.5 shows the output page of AS/RS_mc algorithm.

3) AVS/RS_m algorithm:

This algorithm calculates the expected system cycle time, system throughput, lift utilization, vehicle utilization and total system cost for an AVS/RS.



Conceptualization Tools for AVSR and AS/R Systems

A	10
T	15
Range of C	[10,200]
Vl	200.0
Vv	600.0
Rs	0.5
Rr	0.5
uH	6.0
uL	5.0
n	30000
CostCrane	350.0
CostCell	0.1
C	100
U	0.729636
ECT	0.558557
Cost	6570.0

Figure 6.3. Output parameters page of AS/RS_m algorithm

Table 6.4. Input parameters of AS/RS_mc algorithm

Parameter	Meaning
Rs	Arrival rate of storage request (arrivals per minute)
Rr	Arrival rate of retrieval request (arrivals per minute)
T	Total number of tiers in the warehouse
A	Total number of aisles in the warehouse
C	Total number of columns in the warehouse
uH	The height of each storage space
uL	The width of each storage space
Vv	Vehicle horizontal speed
Vl	Vehicle/lift vertical speed
Cost_Crane	Cost per crane in thousands of dollars
Cost_Cell	Cost per rack cell in thousands of dollars

Tables 6.7 and 6.8 show the list of input and output parameters of AVS/RS_m algorithm. Table 6.9 shows a case study using the AVS/RS_m algorithm. The horizontal speed is the autonomous vehicle speed, and the vertical speed is the lift speed.

Table 6.5. Output parameters of AS/RS_mc algorithm

Parameter	Meaning
U	Crane utilization
ECT	Expected system cycle time
Cost	The total estimated cost of the system

Table 6.6. A study case of using the AS/RS_mc algorithm

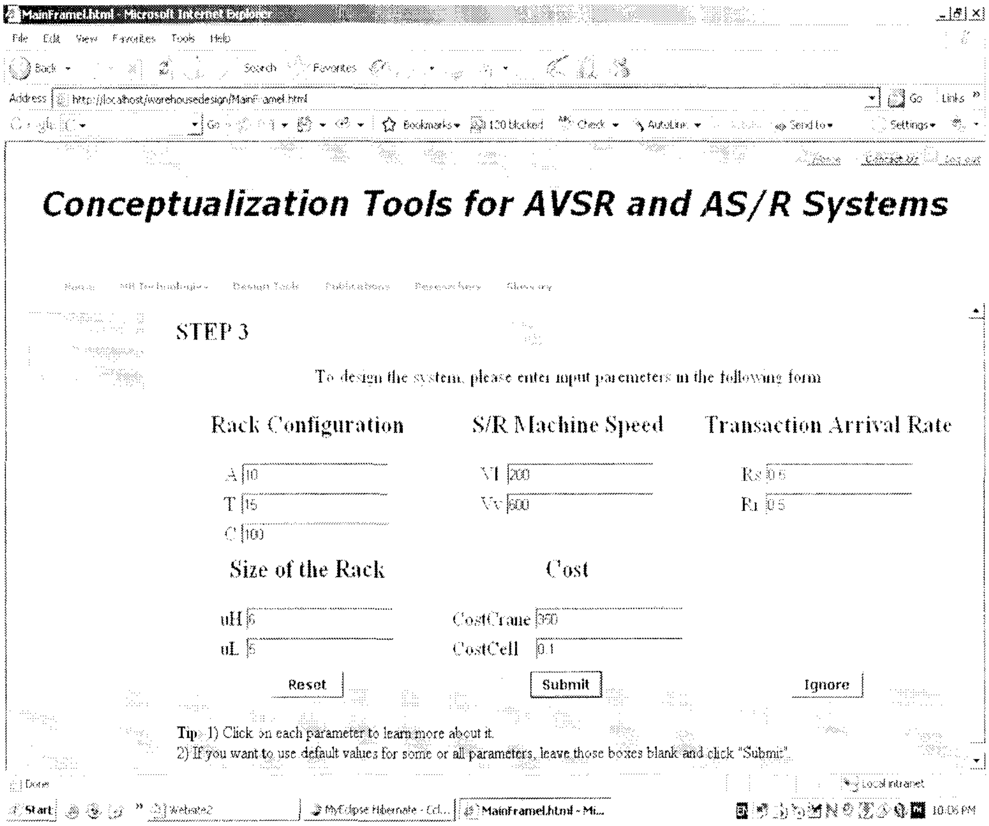
Parameters	Value
Rs	0.5
Rr	0.5
T	15
A	10
C	100
uH	6
uL	5
Vv	600
Vl	200
Cost_Crane	350
Cost_Cell	0.1

Figure 6.6 shows the input page of AVS/RS_m algorithm. Figure 6.7 shows the output page of AVS/RS_m algorithm.

4) AVS/RS_mc algorithm

This algorithm also calculates the expected system cycle time, system throughput, lift utilization, vehicle utilization and total system cost for an AVS/RS. The only difference between this algorithm and AVS/RS_m algorithm is that the number of columns is required instead of the total storage space requirement.

Tables 6.10 and 6.11 show the list of input and output parameters of AVS/RS_mc algorithm. Table 6.12 shows a case study of using the AVS/RS_mc algorithm. Figure 6.8 shows the input page of AVS/RS_mc algorithm. Figure 6.9 shows the output page of AVS/RS_mc algorithm.



Conceptualization Tools for AVSR and AS/R Systems

STEP 3

To design the system, please enter input paremeters in the following form

Rack Configuration

A 10
T 15
C 100

S/R Machine Speed

Vl 200
Vv 600

Transaction Arrival Rate

Rs 0.5
Rr 0.5

Size of the Rack

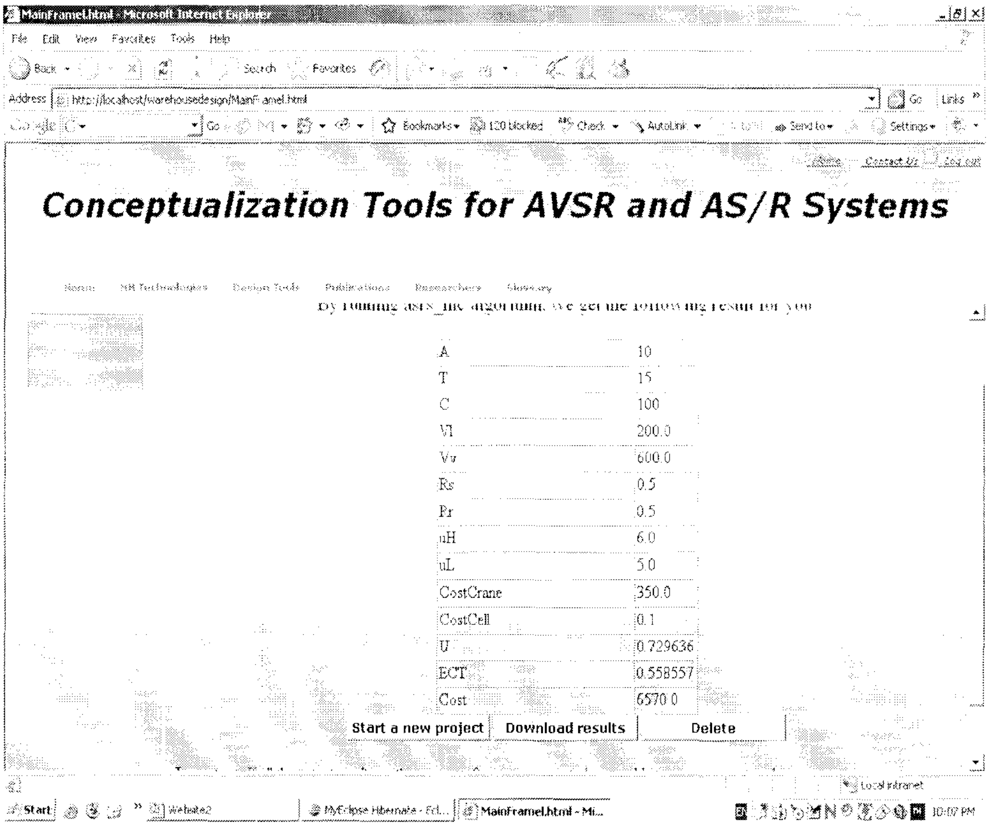
uH 6
uL 5

Cost

CostCrane 350
CostCell 0.1

Tip: 1) Click on each parameter to learn more about it.
2) If you want to use default values for some or all parameters, leave those boxes blank and click "Submit".

Figure 6.4. Input parameters page of AS/RS_mc algorithm



Conceptualization Tools for AVSR and AS/R Systems

By running asrs_mc algorithm, we get the following result for you

A	10
T	15
C	100
Vl	200.0
Vv	600.0
Rs	0.5
Pr	0.5
uH	6.0
uL	5.0
CostCrane	350.0
CostCell	0.1
U	0.729636
ECT	0.558557
Cost	6570.0

Figure 6.5. Output parameters page of AS/RS_mc algorithm

]

Table 6.7. Input parameters of AVS/RS_m algorithm

Parameter	Meaning
Rs	Arrival rate of storage request (arrivals per minute)
Rr	Arrival rate of retrieval request (arrivals per minute)
T	Total number of tiers in the warehouse
A	Total number of aisles in the warehouse
V	Total number of vehicles
L	Total number of lifts
n	Total storage space requirement
LBC	Lower bound on the total number of rack columns
UBC	Upper bound on the total number of rack columns
uH	The height of each storage space
uD	The depth of each storage space
uW	The width of each storage space
uA	The width of each aisle
Vv	Vehicle horizontal speed
Vl	Vehicle/lift vertical speed
Cost_V	Cost per vehicle in thousands of dollars
Cost_L	Cost per lift in thousands of dollars
Cost_Cell	Cost per rack cell in thousands of dollars

Table 6.8. Output parameters of AVS/RS_m algorithm

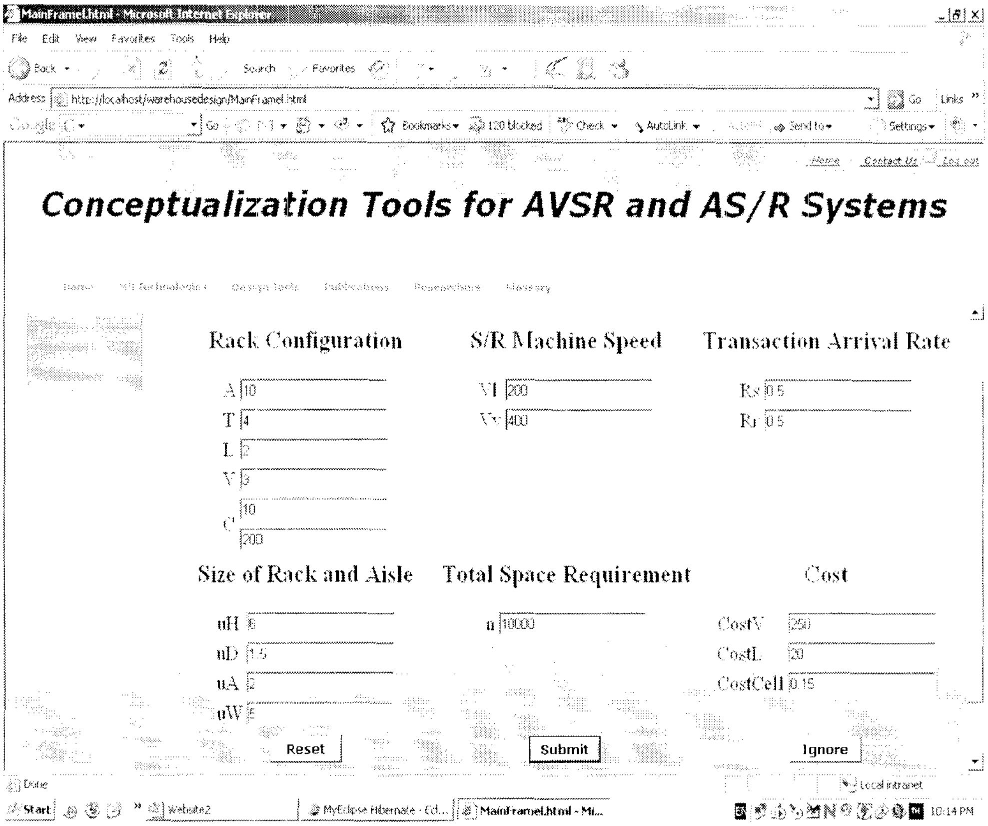
Parameter	Meaning
C	Total number of columns of the rack
UL	Lift utilization
WQL	Average waiting time for an available lift
UV	Vehicle utilization
ECT	Expected system cycle time
CostAll	The total estimated cost of the system

Table 6.9. A study case of using the AVS/RS_m algorithm

Parameter	Value
Rs	0.5
Rr	0.5
T	4
A	10
V	3
L	2
n	10000
LBC	10
UBC	200
uH	6
uD	1.5
uW	5
uA	2
Vv	400
Vl	200
Cost_V	250
Cost_L	50
Cost_Cell	0.5

Table 6.10. Input parameters of AVS/RS_mc algorithm

Parameter	Meaning
Rs	Arrival rate of storage request (arrivals per minute)
Rr	Arrival rate of retrieval request (arrivals per minute)
T	Total number of tiers in the warehouse
A	Total number of aisles in the warehouse
V	Total number of vehicles
L	Total number of lifts
C	Total number of rack columns
uH	The height of each storage space
uD	The depth of each storage space
uW	The width of each storage space
uA	The width per aisle
Vv	Vehicle horizontal speed
Vl	Vehicle/lift vertical speed
Cost_V	Cost per vehicle in thousands of dollars
Cost_L	Cost per lift in thousands of dollars
Cost_Cell	Cost per rack cell in thousands of dollars



Conceptualization Tools for AVSR and AS/R Systems

Rack Configuration

A 10
T 4
L 2
V 3
C 10
200

S/R Machine Speed

Vl 200
Vv 400

Transaction Arrival Rate

Rs 0.5
Rr 0.5

Size of Rack and Aisle

uH 6
uD 1.5
uA 2
uW 5

Total Space Requirement

n 10000

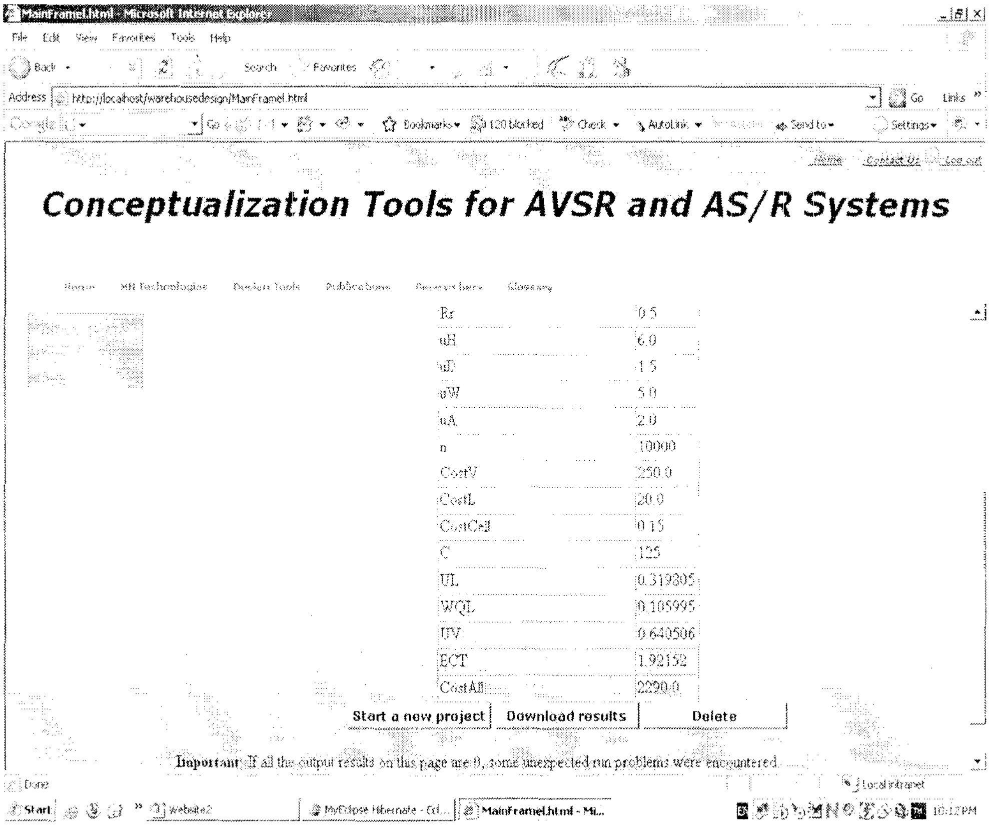
Cost

CostV 250
CostL 20
CostCell 0.15

Figure 6.6. Input parameters page of AVS/RS_m algorithm

Table 6.11. Output parameters of AVS/RS_mc algorithm

Parameter	Meaning
UL	Lift utilization
WQL	Average waiting time for an available lift
UV	Vehicle utilization
ECT	Expected system cycle time
CostAll	The total estimated cost of the system



Conceptualization Tools for AVSR and AS/R Systems

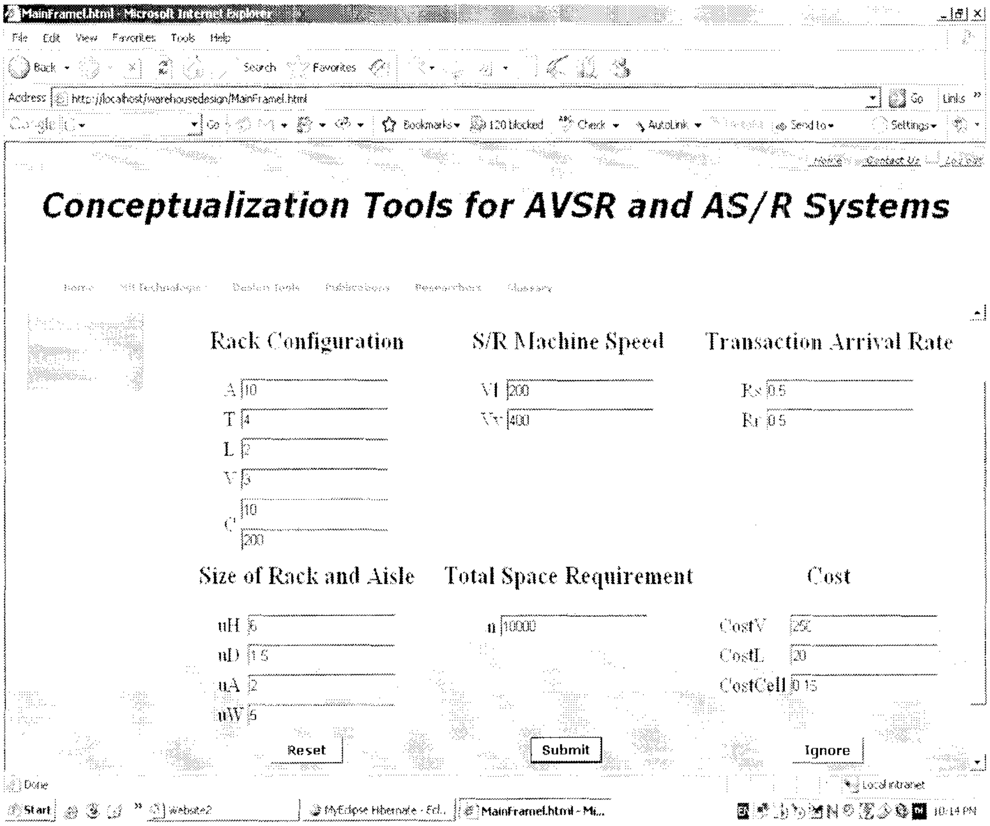
Rr	0.5
uH	6.0
uD	1.5
uW	5.0
uA	2.0
n	10000
CostV	250.0
CostL	20.0
CostCell	0.15
C	125
UL	0.319305
WQL	0.105995
UV	0.640506
ECT	1.92152
CostAll	2290.0

Important: If all the output results on this page are 0, some unexpected run problems were encountered.

Figure 6.7. Output parameters page of AVS/RS_m algorithm

Table 6.12. A study case of using the AVS/RS_mc algorithm

Parameters	Value
Rs	0.5
Rr	0.5
T	4
A	10
V	3
L	2
C	100
uH	6
uD	1.5
uW	5
uA	2
Vv	400
Vl	200
Cost_V	250
Cost_L	50
Cost_Cell	0.15



Conceptualization Tools for AVSR and AS/R Systems

Rack Configuration

A 10
T 4
L 2
V 5
C 10
200

S/R Machine Speed

Vl 200
Vv 400

Transaction Arrival Rate

Rs 0.5
Rr 0.5

Size of Rack and Aisle

uH 6
uD 1.5
uA 2
uW 5

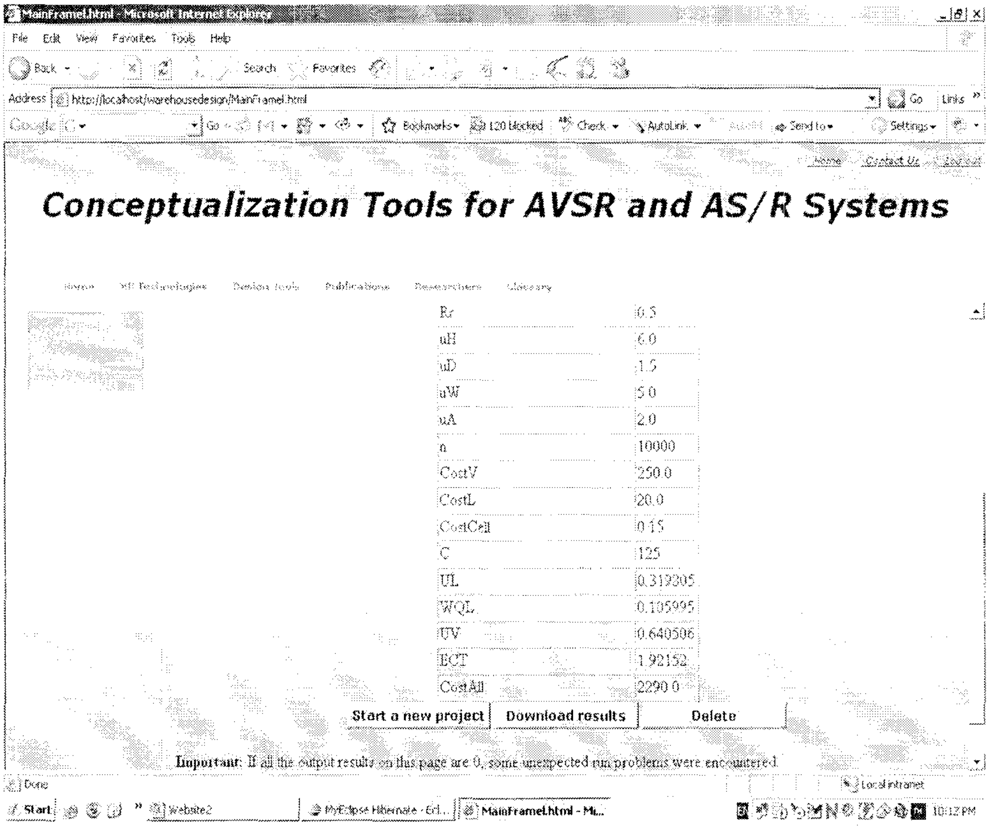
Total Space Requirement

n 10000

Cost

CostV 250
CostL 20
CostCell 0.15

Figure 6.8. Input parameters page of AVS/RS_mc algorithm



Rr	0.5
uH	6.0
uD	1.5
uW	5.0
uA	2.0
n	10000
CostV	250.0
CostL	20.0
CostCell	0.15
C	125
UL	0.319305
WQL	0.105995
UV	0.640506
ECT	1.92152
CostAll	2290.0

Important: If all the output results on this page are 0, some unexpected run problems were encountered.

Figure 6.9. Output parameters page of AVS/RS_mc algorithm

CHAPTER 7

EXPERIMENTS AND DISCUSSION

7.1. Comparison between MPA and simulation

7.1.1. Experimental design

In this section, an initial design is analyzed first, and several design improvements are proposed. Results of MPA are compared with those of simulation.

Table 7.1 shows the operation sequences and external arrival rates for nine products. S_1 refers to the autonomous vehicle in the receiving area, and S_2 is the autonomous vehicle in the shipping area. S_3 is the lift in lift bank that can transport pallets between different tiers. S_4, S_5 and S_6 are autonomous vehicles on the three storage tiers, and S_7, S_8 and S_9 are storage areas on the three tiers. The number of vehicles and lifts can be modified to meet the throughput and other performance requirements. There are three storage tiers in this system, but more tiers can be added easily.

Table 7.1. Operation sequences and external arrival rates for nine products

Product	Storage Sequence	Retrieval Sequence	Arrival rate (per min)
P_1	$S_1 \rightarrow S_3 \rightarrow S_4 \rightarrow S_7$	$S_7 \rightarrow S_4 \rightarrow S_3 \rightarrow S_1$	0.4
P_2	$S_1 \rightarrow S_3 \rightarrow S_5 \rightarrow S_8$	$S_8 \rightarrow S_5 \rightarrow S_3 \rightarrow S_3$	0.4
P_3	$S_1 \rightarrow S_3 \rightarrow S_6 \rightarrow S_9$	$S_9 \rightarrow S_6 \rightarrow S_3 \rightarrow S_1$	0.4
P_4	$S_1 \rightarrow S_3 \rightarrow S_4 \rightarrow S_7$	$S_7 \rightarrow S_4 \rightarrow S_3 \rightarrow S_1$	0.4
P_5	$S_1 \rightarrow S_3 \rightarrow S_5 \rightarrow S_8$	$S_8 \rightarrow S_5 \rightarrow S_3 \rightarrow S_3$	0.4
P_6	$S_1 \rightarrow S_3 \rightarrow S_6 \rightarrow S_9$	$S_9 \rightarrow S_6 \rightarrow S_3 \rightarrow S_1$	0.4
P_7	$S_1 \rightarrow S_3 \rightarrow S_4 \rightarrow S_7$	$S_7 \rightarrow S_4 \rightarrow S_3 \rightarrow S_1$	0.4
P_8	$S_1 \rightarrow S_3 \rightarrow S_5 \rightarrow S_8$	$S_8 \rightarrow S_5 \rightarrow S_3 \rightarrow S_3$	0.4
P_9	$S_1 \rightarrow S_3 \rightarrow S_6 \rightarrow S_9$	$S_9 \rightarrow S_6 \rightarrow S_3 \rightarrow S_1$	0.4

Table 7.2 presents the operation time (t_o) for each operation, and the time unit is minute. Because S_3, S_4 and S_5 are autonomous vehicles on the three tiers, the S/R times are different. However, assuming storage operation time is equal to retrieval operation time for every server is reasonable for the AVS/RS.

Table 7.2. Product operation times

P/S	S_1	S_2	S_3	S_4	S_5	S_6	S_7	S_8	S_9
P_1	0.2	0.3	0.1/0.1	0.3/0.3			2		
P_2	0.2	0.2	0.1/0.1		0.3/0.3			3	
P_3	0.2	0.2	0.1/0.1			0.3/0.3			6
P_4	0.2	0.2	0.1/0.1	0.3/0.3			2		
P_5	0.2	0.2	0.1/0.1		0.3/0.3			3	
P_6	0.2	0.2	0.1/0.1			0.3/0.3			6
P_7	0.2	0.2	0.1/0.1	0.3/0.3			2		
P_8	0.2	0.2	0.1/0.1		0.3/0.3			3	
P_9	0.2	0.2	0.1/0.1			0.3/0.3			6

7.1.2. Experimental results and discussion

Different designs and results are presented next.

Scenario 1 (Initial Design):

Three types of products are stored in three different tiers with arrival rate 0.2 transactions per minute. The number of each type of server is one. Table 7.3 shows results of queue lengths in front of the servers, number of customers waiting and being processed at the servers, and the utilization of servers for scenario 1.

Table 7.3. Results for scenario 1

S	L_q			L			Utilization		
	MPA	Simu	Diff	MPA	Simu	Diff	MPA	Simu	Diff
S_1	0.040	0.078	0.486	0.280	0.316	0.113	0.240	0.239	0.004
S_2	0.015	0.031	0.495	0.175	0.188	0.066	0.160	0.157	0.004
S_3	0.025	0.694	0.964	0.545	0.563	0.033	0.520	0.515	0.008
S_4	0.038	0.088	0.567	0.278	0.333	0.164	0.240	0.244	0.017
S_5	0.362	0.674	0.463	0.922	1.234	0.252	0.559	0.559	0.001
S_6	0.009	0.018	0.488	0.129	0.134	0.038	0.120	0.116	0.003

Scenario 2:

The utilization of servers in the initial design is low, which means the material handling system capacity is not utilized adequately. In scenario 2, the arrival rates is increased to test if the utilization can be improved. The number of product types is still kept at three and the number of each type of server remains at one, while the arrival rates of products are higher (0.5 transactions per minute). Table 7.4 shows results for scenario 2.

Table 7.4. Results for scenario 2

S	L_q			L			Utilization		
	MPA	Simu	Diff	MPA	Simu	Diff	MPA	Simu	Diff
S_1	0.395	0.394	0.005	0.845	0.841	0.006	0.450	0.447	0.007
S_2	0.130	0.153	0.151	0.430	0.451	0.046	0.300	0.298	0.008
S_3	10.36	9.465	0.095	11.26	10.36	0.087	0.900	0.895	0.006
S_4	0.906	0.977	0.072	1.506	1.572	0.042	0.600	0.595	0.008
S_5	1.644	1.373	0.197	2.344	2.066	0.134	0.700	0.693	0.010
S_6	0.144	0.158	0.090	0.444	0.456	0.028	0.300	0.298	0.005

Scenario 3:

By checking results of scenario 2, it is found that the utilization of lift is 90%, which may impact the robustness of the system. One solution is to increase the number of lifts to decrease the chance of blocking in the lift bank and improve system performance. The number of lifts increases from one to two. Table 7.5 shows results of scenario 3.

Table 7.5. Results for scenario 3

S	L_q			L			Utilization		
	MPA	Simu	Diff	MPA	Simu	Diff	MPA	Simu	Diff
S_1	0.395	0.386	0.025	0.845	0.835	0.012	0.450	0.449	0.001
S_2	0.130	0.136	0.043	0.430	0.435	0.012	0.300	0.299	0.002
S_3	0.292	0.292	0.000	1.192	1.193	0.000	0.450	0.450	0.000
S_4	0.906	0.893	0.014	1.506	1.491	0.010	0.600	0.597	0.004
S_5	1.644	1.554	0.058	2.344	2.245	0.042	0.700	0.695	0.006
S_6	0.144	0.142	0.078	0.444	0.443	0.002	0.300	0.300	0.000

Scenario 4:

Results of scenario 3 indicate that this system can handle more products with higher arrival rates by increasing the number of servers. In this improved design, product types are increased to nine, and other parameters are the same as scenario 3. Table 7.6 shows results of scenario 4.

Table 7.6. Results for scenario 4

S	L_q			L			Utilization		
	MPA	Simu	Diff	MPA	Simu	Diff	MPA	Simu	Diff
S_1	8.100	7.986	0.014	9.000	8.885	0.013	0.900	0.899	0.001
S_2	18.62	14.70	0.266	19.57	15.64	0.251	0.950	0.940	0.010
S_3	0.233	0.228	0.020	1.133	1.125	0.007	0.450	0.448	0.003
S_4	8.150	8.614	0.054	9.050	9.513	0.049	0.900	0.899	0.001
S_5	8.150	9.011	0.095	9.050	9.915	0.087	0.900	0.904	0.004
S_6	8.150	7.392	0.102	9.050	8.283	0.093	0.900	0.890	0.001

Scenario 5:

From the results of scenario 4, it is easy to find that the arrival rates are too high, which leads to a high utilization of servers. The arrival rates of products can be decreased to 0.4 transactions per minute, and then a reasonable utilization of all servers is found under this new system configuration. Table 7.7 shows results of scenario 5.

Table 7.7. Results for scenario 5

S	L_q			L			Utilization		
	MPA	Simu	Diff	MPA	Simu	Diff	MPA	Simu	Diff
S_1	1.851	1.842	0.005	2.571	2.562	0.003	0.720	0.720	0.000
S_2	2.482	2.403	0.033	3.242	3.162	0.026	0.760	0.757	0.003
S_3	1.886	1.834	0.028	2.606	2.551	0.021	0.720	0.718	0.003
S_4	1.863	1.840	0.013	2.583	2.560	0.009	0.720	0.720	0.000
S_5	1.863	1.823	0.022	2.583	2.540	0.017	0.720	0.720	0.004
S_6	1.863	1.889	0.014	2.583	2.612	0.011	0.720	0.723	0.004

Scenario 6:

Often, the external product arrival rates can not be controlled. In order to explore the optimal configuration of a system with higher arrival rates, this experiment increases the arrival rates of products and changes the number of servers. The arrival rates of products are set to 0.9 transactions per minute, which are relatively high compared to the initial design. Keeping the number of each type of server to two is an ideal configuration under this situation. Table 7.8 shows results of scenario 6.

Table 7.8. Results for scenario 6

S	L_q			L			Utilization		
	MPA	Simu	Diff	MPA	Simu	Diff	MPA	Simu	Diff
S_1	2.844	2.861	0.006	4.444	4.464	0.004	0.800	0.802	0.002
S_2	4.351	4.364	0.003	6.041	6.057	0.003	0.845	0.846	0.001
S_3	2.895	2.874	0.007	4.495	4.478	0.004	0.800	0.802	0.002
S_4	3.109	2.971	0.046	4.729	4.592	0.030	0.810	0.810	0.000
S_5	3.109	3.287	0.054	4.729	4.915	0.038	0.810	0.814	0.005
S_6	2.438	2.460	0.009	4.000	4.025	0.007	0.780	0.783	0.004

Figures 7.1 to 7.6 present the comparison of queue length and utilization between MPA and the simulation model.

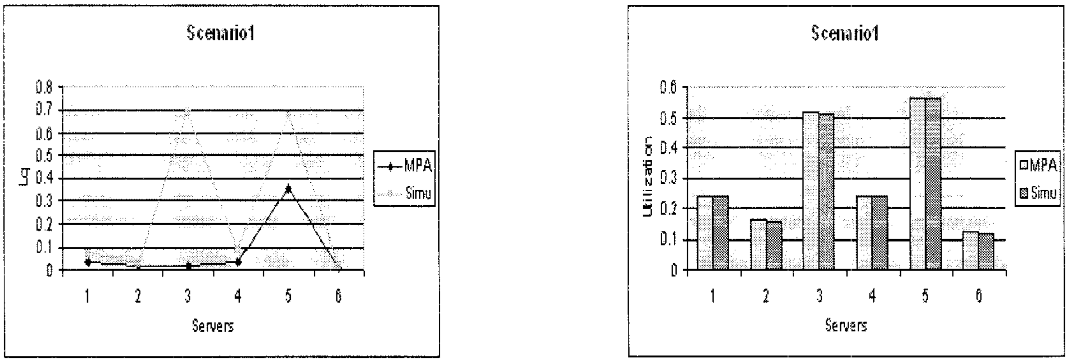


Figure 7.1. L_q and utilization of servers in scenario 1

Experimental results indicate that the accuracy of MPA decreases when resource utilization is very low (e.g., less than 60%) or very high (> 90%). Because system designers do not design systems in these utilization ranges, MPA is a very valuable tool in estimating system performance for normal utilization ranges of 60-90%.

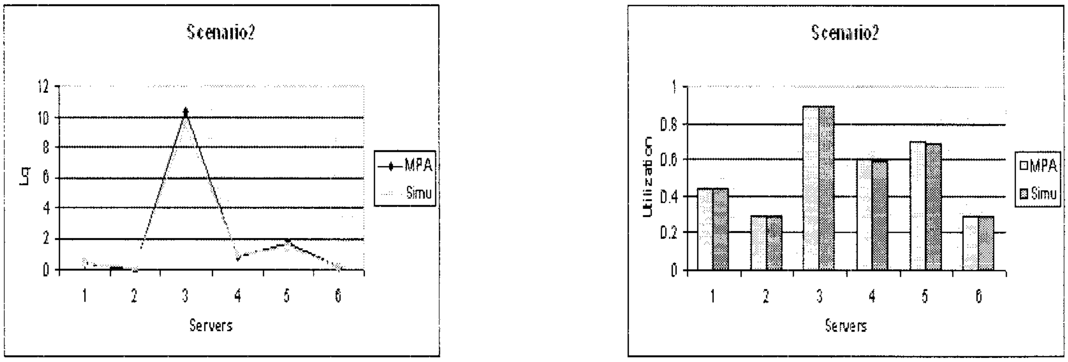


Figure 7.2. L_q and utilization of servers in scenario 2

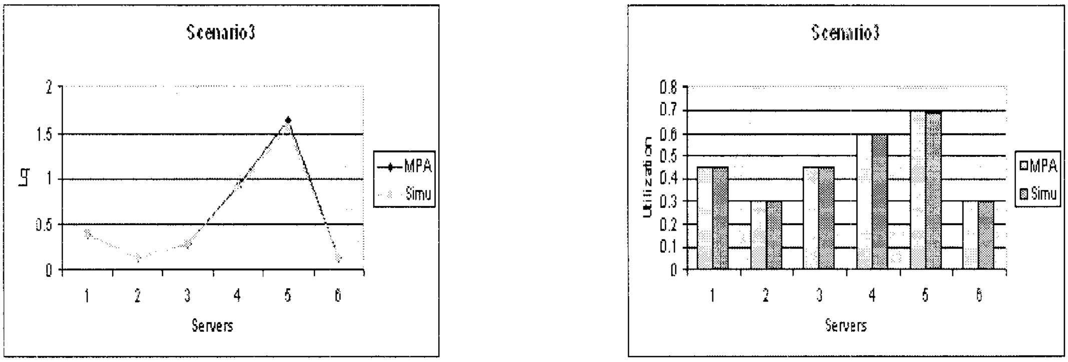


Figure 7.3. L_q and utilization of servers in scenario 3

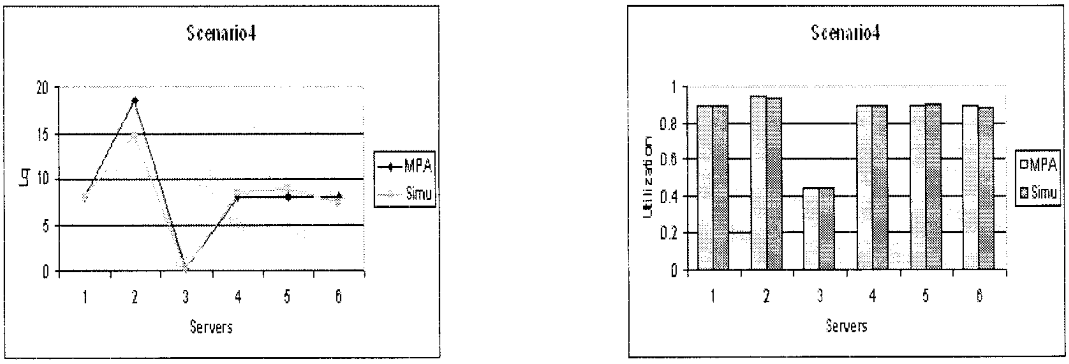


Figure 7.4. L_q and utilization of servers in scenario 4

7.2. Comparison between MPA and the conceptualization tools

7.2.1. Experimental design

Malmborg [2002] presented a conceptualization tool for AVS/RS. This tool establishes a function of some key system attributes including storage capacity, rack configuration

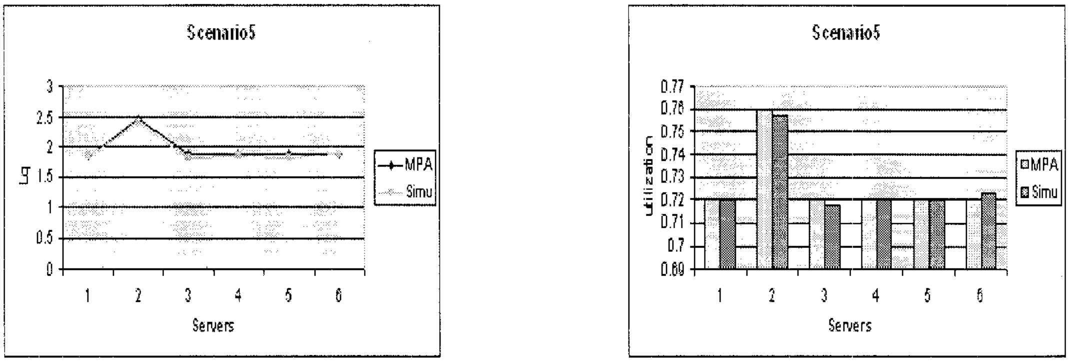


Figure 7.5. L_q and utilization of servers in scenario 5

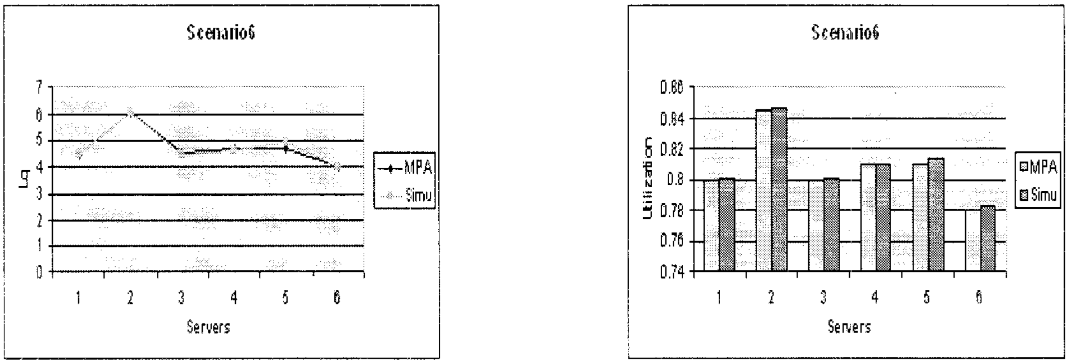


Figure 7.6. L_q and utilization of servers in scenario 6

and fleet size to estimate system performances. The default system configuration of this tool is tier-to-tier. It is valuable to make a comparison between this configuration and the tier-captive configuration by MPA.

Two kinds of comparison have been conducted. The first one is using the same set of input parameters for MPA and the analytical model of Malmborg [2002] to make a comparison. Another comparison is based on a different line of thought: what designs under the two configurations would produce the same system performance.

As mentioned, the analytical model of Malmborg [2002] uses some system attributes such as rack configuration and fleet size to model the AVS/RS. However, MPA uses process times to establish the model of AVS/RS. Before the comparison, the connection between these two tools needs to be established. Table 7.9 lists all input parameters of the analytical model of Malmborg [2002].

Table 7.9. Parameters of the analytical model of Malmborg [2002]

Parameters	Meaning
λ_s	Arrival rate of storage request with unit of minute
λ_R	Arrival rate of retrieval request with unit of minute
T	Total number of tiers of the warehouse rack
A	Total number of aisles of the warehouse rack
V	Total number of vehicles
L	Total number of lifts
n	Total space requirement
C	Total number of rack columns
u_h	The height per unit cell of the rack
u_d	The depth per unit cell of the rack
u_w	The width per unit cell of the rack
u_a	The width per aisle
V_v	Vehicle horizontal speed
V_l	Vehicle/lift vertical speed
$Cost\_V$	Cost per vehicle with unit of \$1000
$Cost\_L$	Cost per lift with unit of \$1000
$Cost\_Cell$	Cost per rack cell with unit of \$1000

The warehouse size can be calculated as follows:

- Total width of the warehouse

$$u_w \cdot C = u_w \cdot \frac{n}{2 \cdot T \cdot A} \tag{7.1}$$

- Total height of the warehouse

$$u_h \cdot T \tag{7.2}$$

- Total depth of the warehouse

$$(2 \cdot u_d + u_a) \cdot (A - 1) \tag{7.3}$$

The lift process time for the tth tier can be calculated as:

$$t_o = \frac{(t-1) \cdot u_h}{V_l} \tag{7.4}$$

The vehicle process time can be estimated as:

$$t_o = \frac{3 \cdot u_w \cdot C + (2 \cdot u_d + u_a) \cdot (A-1)}{V_v} \tag{7.5}$$

The storage time in storage area is:

$$t_o = \frac{1}{\lambda_r} \tag{7.6}$$

7.2.2. Experimental results and discussion

A study case has been designed to make the comparison. The input parameters are listed in Tables 7.10 and 7.11.

Table 7.10. Input parameters for the analytical model of Malmborg [2002]

Parameter	Value
λ_s	0.5
λ_r	0.5
T	4
A	10
V	3
L	2
C	125
u_h	6
u_d	1.5
u_w	5
u_a	2
V_v	400
V_l	200

In the tier-to-tier configuration, four vehicles can visit any tier. Malmborg [2002] analytical model can be used to model this system configuration. However, in the tier-captive configuration, every vehicle can travel only on one tier. This system

Table 7.11. Equivalent input parameters for MPA

Parameter	Value
λ_p	0.5
t_o (Lift tier 1)	0.01
t_o (Lift tier 2)	0.06
t_o (Lift tier 3)	0.12
t_o (Lift tier 4)	0.18
t_o (Vehicle)	0.9
t_o (Storage area)	2

configuration is modeled by MPA. This difference of system configuration leads to different utilization. Four different inputs and outputs under two system configurations are presented in Table 7.12.

Table 7.12. Comparison of outputs

Tool	Utilization	L = 1	L = 1	L = 2	L = 2
		V = 4	V = 8	V = 4	V = 8
Conceptualization tools	U_l	0.64	0.64	0.33	0.33
	U_v	0.81	0.49	0.51	0.27
MPA	U_l	0.37	0.37	0.19	0.185
	U_v	0.90	0.45	0.90	0.45

From experimental results shown in Table 7.12, one common feature of tier-to-tier and tier-captive system configurations can be seen. The utilization of lifts is dependent upon the vehicle utilization and other system attributes when vehicles performance is maintained to be the same. The utilization of lifts depends on the lift performance such as the speed, and other factors including fleet size, arrival rates of S/R requests.

The difference in the utilization of vehicles is listed in Table 7.12. The utilization of vehicles depends on the utilization of lifts in the tier-to-tier system.

The opposite experiment is to determine what designs under two configurations lead to the same system performance. Table 7.13 presents the experimental results.

Table 7.13. Comparison of inputs

	MPA	Conceptualization tools	Conceptualization tools
L	1	2	3
V	8	5	4
U_l	0.37	0.33	0.33
U_v	0.45	0.41	0.47

From Table 7.13, tier-to-tier AVS/RS uses more lifts to achieve the same utilization as tier-captive AVS/RS. This suggests that tier-captive AVS/RS can utilize lifts better. On the other hand, tier-captive AVS/RS needs more vehicles to achieve the same system performance as the tier-to-tier AVS/RS. One possible reason is vehicles can only travel on designed tiers, which may increase the idle time of vehicles. This is a potential disadvantage of tier-captive AVS/RS.

CHAPTER 8

CONCLUSION

AVS/RS, as a relatively new autonomous warehouse S/R technology is presented in this thesis. Two configurations of AVS/RS are possible: tier-to-tier and tier-captive. The configuration with tier captive vehicles is studied in this thesis. It is compared with the traditional crane-based AS/RS technology, and some advantages of AVS/RS are presented. There are many ways to analyze the AVS/RS. We used the OQN method. MPA, a tool for evaluating OQNs, was chosen to estimate performance measures of AVS/RS. Several scenarios were designed to verify the accuracy of MPA in evaluating AVS/RS. Comparison with a simulation model shows that MPA is adequate to model the AVS/RS when utilization is between 60 and 85 percent. However, the AVS/RS with tier-to-tier vehicles is not suitable to use OQN to analyze system performance, which may be solved by another type of queuing network, SOQN. There is a broad scope for improvement in this area. The comparison between MPA and another performance analyzer of AVS/RS, indicates the common and different features of tier-captive and tier-to-tier AVS/RS.

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