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DEADLOCK AND COLLISION PREVENTION ALGORITHMS FOR MOBILE ROBOTS IN AUTOMATED WAREHOUSES

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ABSTRACT

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By the recent increase in e-commerce and rapid fulfillment necessity of customer demands, automation and effective management of warehouse operations have become crucial issues. The focus of this thesis is to develop smart deadlock and collision prevention algorithms for flexibly travel of autonomous vehicles (i.e., mobile robots) in automated warehouses so that performance of the storage and retrieval system could be improved. The developed algorithms in this work can be utilized for any system having an aisle-based layout where mobile robots travel among those aisles. It is observed that once a good deadlock and collision control policy is applied, flexible travel of mobile robots could provide better performance metrics in the system than a dedicated travel-based system design. A multi-agent modelling approach is studied where mobile robots are considered to be intelligent agents under an IoT (Internet of Things) environment so that they can communicate with each other and make autonomous decisions in transaction processing. To test the effectiveness of the developed algorithms, the experimental results are compared with their equivalent dedicated system designs, where there is a dedicated mobile robot serving for pre-defined zone so that there is no possibility of collision and deadlock of mobile robots in the system.

keywords: agent-based simulation, automated warehousing, deadlock prevention, mobile robot, storage and retrieval

ÖZ

OTOMATİK DEPOLARDAKİ MOBİL ROBOTLAR İÇİN ÇARPIŞMA VE KİLİTLENME ÖNLEME ALGORİTMALARI

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Temmuz 2021

Son zamanlarda e-ticaretin artması ve müşteri taleplerinin hızlı bir şekilde yerine getirilmesi gerekliliği ile birlikte, depo operasyonlarının otomasyonu ve etkin yönetimi çok önemli konular haline gelmiştir. Bu tezin odak noktası, araçların seyahat modellerinde daha esnek olmaları için akıllı işletim politikaları altında çalışan, kilitlenmeyen bir mobil robot seyahat tasarımı geliştirmektir. Bu çalışmada geliştirilen algoritmalar, otonom araçların bu koridorlar arasında hareket ettiği koridor tabanlı yerleşime sahip herhangi bir depo sistemi için kullanılabilir. Araçların yalnızca tahsisli yollarda hareket ettiği sistemlere kıyasla, daha az araçla daha esnek olan ve en az bu sistemler kadar iyi performans çıktıları sağlayan bir kontrol politikasının varlığı keşfedilmiştir. Modelleme için, araçların bir IoT (Nesnelerin İnterneti) ortamında aracılar olduğu, böylece birbirleriyle iletişim kurabilmeleri ve işlem işlemede özerk olarak kararlar verebilmeleri için çok aracılı bir sistem kullanılır. Geliştirilen sistem algoritmalarının etkinliğini test etmek için, deneysel sonuçlar, önceden tanımlanmış sayıda koridor için hizmet veren özel bir mobil robotun olduğu ve çarpışma ve kilitlenme önleme algoritmalarının gerekli olmadığı eşdeğer adanmış sistem tasarımlarıyla karşılaştırılır.

Anahtar Kelimeler: ajan tabanlı benzetim, otomatik depolar, çarpışma önleme, mobil robot, depolama ve çekme

ACKNOWLEDGEMENTS

First of all, I would like to thank my supervisor Banu Yetkin Ekren for her guidance and patience during this study.

I would like to express my enduring love to my parents, who are always supportive, loving and caring to me in every possible way in my life.

Ecem Eroğlu Turhanlar
İzmir, 2021

TEXT OF OATH

I declare and honestly confirm that my study, titled “DEADLOCK AND COLLISION PREVENTION ALGORITHMS FOR MOBILE ROBOTS IN AUTOMATED WAREHOUSES” and presented as a Master’s Thesis, has been written without applying to any assistance inconsistent with scientific ethics and traditions. I declare, to the best of my knowledge and belief, that all content and ideas drawn directly or indirectly from external sources are indicated in the text and listed in the list of references.

Ecem Eroğlu Turhanlar
July 26, 2021

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SYMBOLS AND ABBREVIATIONS

ABBREVIATIONS:

FSD	Flexible System Design
DSD	Dedicated System Design
SBS/RS	Shuttle-based Storage and Retrieval System
MR	Mobile Robot
AMR	Active Mobile Robot
DMR	Deadlocked Mobile Robot
AGV	Automated Guided Vehicle
AS/RS	Automated Storage and Retrieval System

CHAPTER 1
INTRODUCTION

This thesis brings a new perspective to the structure of autonomous vehicle-based storage systems by proposing deadlock and collision prevention algorithms developed on the free movement concept of mobile autonomous vehicles (i.e., mobile robots) in warehouses. To observe the performance of the proposed designs correctly, the system parameters are experimented with and compared in a sensitivity analysis manner. After that experimentation, we also determine the best parameter values providing better performance metrics.

1.1. Today' s E-commerce Structure

The revolutionary growth of e-commerce as the result of the increasing number of online shoppers, also with the effect of COVID-19, confronts the intralogistics industry with new challenges. The latest e-commerce growth has also changed the order profiles towards increased product variety, reduced delivery times, and flexible delivery requirements. In order to cope with those challenges, automated warehousing technologies developed on in-facility communication and cooperation towards Industry 4.0 advancements have become critical. Warehouse managers are eager to enforce those automation technologies for their enterprise-wide. For instance, warehouse industries tend to deploy goods with RFID tags helping efficiently implementation of robotic material handling technologies. For instance, estimation for the Global Warehouse Automation Market is at a CAGR of 14% between 2020 and 2026 which is estimated to be doubled to $30 billion by 2026 (Research and Markets, 2021).

Increased e-commerce industries have also been driving the material handling equipment market growth. Reduced labor and transportation costs support the rise of the material handling market growth. For instance, the Material Handling Market is projected to grow at a CAGR of 6.01% to reach US$ 201.057 billion by 2025, from US $141.657 billion in 2019 (Knowledge Sourcing Intelligence, 2020). Figure 1.1

shows the current and estimated material handling market growth based on their product types.

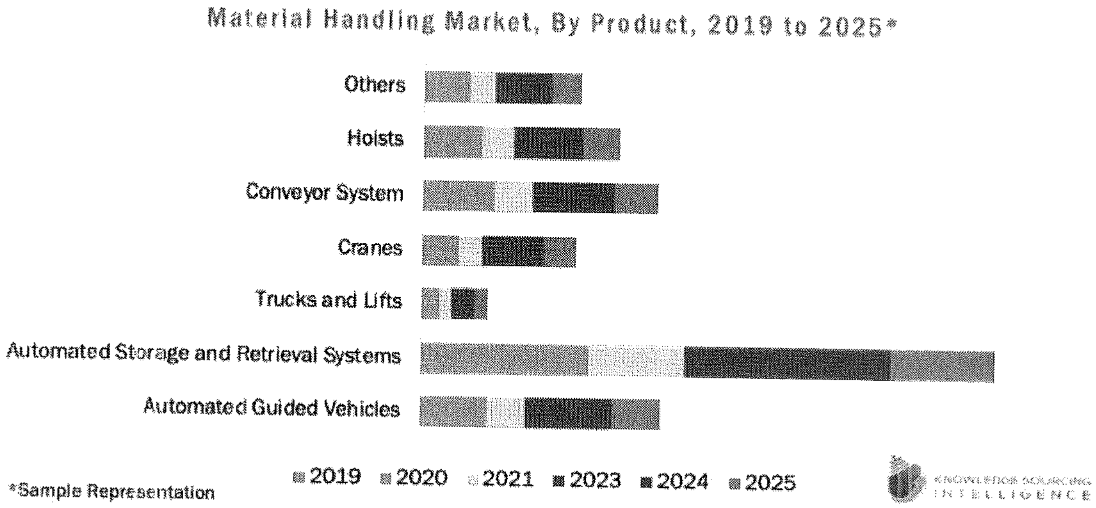

Figure 1.1. Material Handling Market Growth Forecast by Product, 2019 to 2025 (source: Knowledge Sourcing Intelligence, 2020)

Based on Figure 1.1, automated storage and retrieval systems (AS/RSs) and subsequently automated guided vehicles (AGVs) would witness the fastest growth during the forecast period. Hence, smart algorithms developed for the efficiently operation of those technologies would be emerging in warehouse operations.

The AS/RS technology providers aim to develop system designs providing reduced floor space, labor cost, and inventory levels to enhance productivity while reducing process cycle time. For instance, a mini-load AS/RS technology that is market by Dematic Group provides ultra-high-speed load handling referred to as shuttle-based storage and retrieval system (SBS/RS) mostly utilized in distribution centers and raw material stores that are specially designed for ultra-high-speed load handling (Dematic Multi-shuttle, 2021). Because there is a dedicated shuttle in each tier of an aisle, this automated warehousing technology is referred to as tier-captive SBS/RS. In this thesis, we refer to the SBS/RS as either aisle-to-aisle SBS/RS or tier-captive SBS/RS based on the shuttle's travel ability.

Mobile robots (MRs) like AGVs and automated mobile robots have growth expectations at a CAGR of 35% by 2026 according to Research and Markets (2020). It is expected that those MRs will reach more than 18% of the overall warehouse automation market share by 2026 (Research and Markets, 2021).

1.2. Motivation and Objectives

Our motivation to present the system is to explore flexible control policies for efficient management of MRs so that even with fewer MRs in the warehouse, the system can perform well. In practice, for such systems technology solutions mostly apply dedicated roads for those autonomous vehicles not to cause any deadlock and collisions in the system. Allowing a flexible travel pattern for MRs would bring the possibility of collision and deadlock problems in the system, in which we study for a good control policy for such a system. Considering collision and deadlock prevention algorithms is significant for flexible travel of MRs, which should be developed so that while deadlock and collisions are prevented, the processing time should also be decreased.

In summary, the objective of this thesis can be summarized as two folds: First, to search for alternative novel warehouse system design for MRs in warehouses, where those MRs can be highly utilized and they can also provide a fast transaction process. Second, in that flexible travel system design, we search good collision and deadlock prevention algorithms resulting in improved system performance outputs for average flow time per transaction, average maximum flow time of transactions, throughput rate in unit time, and average vehicle utilization in the system. In other words, in this thesis work, we approach the problem from a multi-objective design perspective. We simulate the proposed algorithms for the pre-designed systems and complete a comparison study.

The flow of the thesis is as follows. First, we provide an extensive literature review related to the subject in Chapter 2. Details of the simulation study and the developed deadlock and collision prevention algorithms are presented in Chapters 3-4. The comparative analysis of simulation results and verification and validation procedure of the models are explained in Chapter 5. Last, a conclusion part summarizing this work along with future study suggestions is presented in Chapter 6.

CHAPTER 2
LITERATURE REVIEW

In this chapter, we provide related literature works containing deadlock prevention for MRs in warehouses.

Collision and deadlock prevention algorithms are mostly studied in AGV systems rather than AS/RSs (e.g., SBS/RSs). A multi-floor application for AGV systems, where AGVs can travel between aisles in a multi-tier automated storage system, can be considered as AS/RS system. Therefore, the model proposed in this thesis can also be utilized for both single- and multi-tier warehouse systems. An AGV design called EX-AGV allowing load exchange between AGVs is developed by Hsueh (2010). The results of the simulation study show the efficiency and robustness of the proposed system design in terms of the considered performance metrics. A conservative path reservation policy for collision avoidance between AGVs is presented by Cossentino et al. (2011). The proposed policy is applied on an agent-based simulation model to make autonomous decision-making in warehouses. Roy et al. (2013) develop vehicle blocking prevention protocols for three types of blocking cases for an automated warehouse with autonomous vehicles. In their numerical studies, it is concluded that delays caused by blocking give rise to transaction cycle time output of roughly 10-20%. Krnjak et al. (2015) study decentralized AGV control for deadlock prevention in an automated warehouse. Draganjac et al. (2016) propose autonomous AGV path planning and coordination of motion. They use the private zone mechanism exact method and prevent deadlock by zone control. The prevention concept includes stopping or removing the less prioritized vehicles in the conflict. Zhou et al. (2017) study a real-time and distributed algorithm to avoid collision and deadlock by stopping and resuming MRs. Lienert et al. (2020) present a deadlock avoidance approach that includes several route reservation mechanisms. So, their deadlock prevention method is time window routing. They evaluate the results by using the mean values of the simulation study. Vivaldini et al. (2010) propose a router system for an intelligent warehouse system where smart changes for priority assignment of tasks as well as robotic forklift route definitions in conflict cases are presented. They use heuristic, simulation, and dynamic programming methods for the modelling approaches. They also apply computer simulation tests for the validation of algorithms' efficiency under various working conditions.

As mentioned, an SBS/RS with aisle-changing shuttle carriers might resemble the current studied work. One of such works is presented by Lerher (2018) where analytical travel time models are presented. However, in that work, there are no deadlock and collision prevention algorithms integrated with the models. Lienert and Fottner (2017) present a model utilizing the time window routing method for safe shuttle movement in a tier-to-tier and aisle-to-aisle system configuration. Rhazzaf and Masrour (2021) divide the high dimensional warehouses into low dimensional zones and achieve good speed performance metrics. There exist some other works on autonomous vehicle-based storage and retrieval systems (AVS/RSs) considering autonomous vehicle travels between aisles (Ekren 2011; Heragu et al. 2011; Ekren and Heragu 2012; Ekren et al. 2014; Roy et al. 2015). Besides, there are some other works on AVS/RS including autonomous vehicle travel between tiers (Ekren 2020, Ekren 2021). To the best of our knowledge, those works ignore deadlock and collision cases in the systems. A collision prevention approach for a tier-to-tier SBS/RS is presented by Küçükyaşar et al. (2020) and Jerman et al. (2021) by not allowing two vehicles at the same tier simultaneously or by providing single route travel for vehicles.

The literature includes few papers examining collision and deadlock avoidance of MRs with changing aisles. Instead, the existing works mostly consider dedicated path travels for those MRs. In this thesis, we propose a flexible travel pattern for MRs, where we assume that those MRs are intelligent agents that can communicate with each other to make intelligent decisions on job (i.e., transaction) selection as well as travel routes. A multi-agent simulation modelling approach is applied to seek well-designed control policies.

CHAPTER 3

SYSTEM DESIGN

The preceding chapter provides the physical configuration of the developed flexible system design (FSD). Also, to compare the performance of the proposed FSD, we also present a dedicated system design (DSD) as an alternative to that FSD.

3.1. Physical Warehouse Design of Flexible and Dedicated Systems

In this chapter, the studied FSD and DSD are presented. Mainly, we focus on the development of FSD by aiming to reduce the travel time of MRs compared to its DSD version. By reduced travel time of MRs, the required number of MRs might be decreased in FSD compared to DSD achieving the same throughput rate performance metrics. Because MRs in FSD would have freedom in travel between warehouse aisles, there might be the possibility of collision of those MRs in FSD. Hence, the development of algorithms preventing deadlock and collision of those MRs would be significant in FSD rather than in DSD. Figure 3.1 and Figure 3.3 show the physical configurations of the studied FSD and DSD, respectively. In Figure 3.1, while the MRs may come across with each other while travelling, in Figure 3.3 due to dedicated zone travelling of MRs, they never come across.

In Figures 3.2 and 3.4, the FSD and DSD logics are applied for an SBS/RS case respectively, where each tier can be considered as if the ground level of a warehouse with MRs that can travel between aisles.

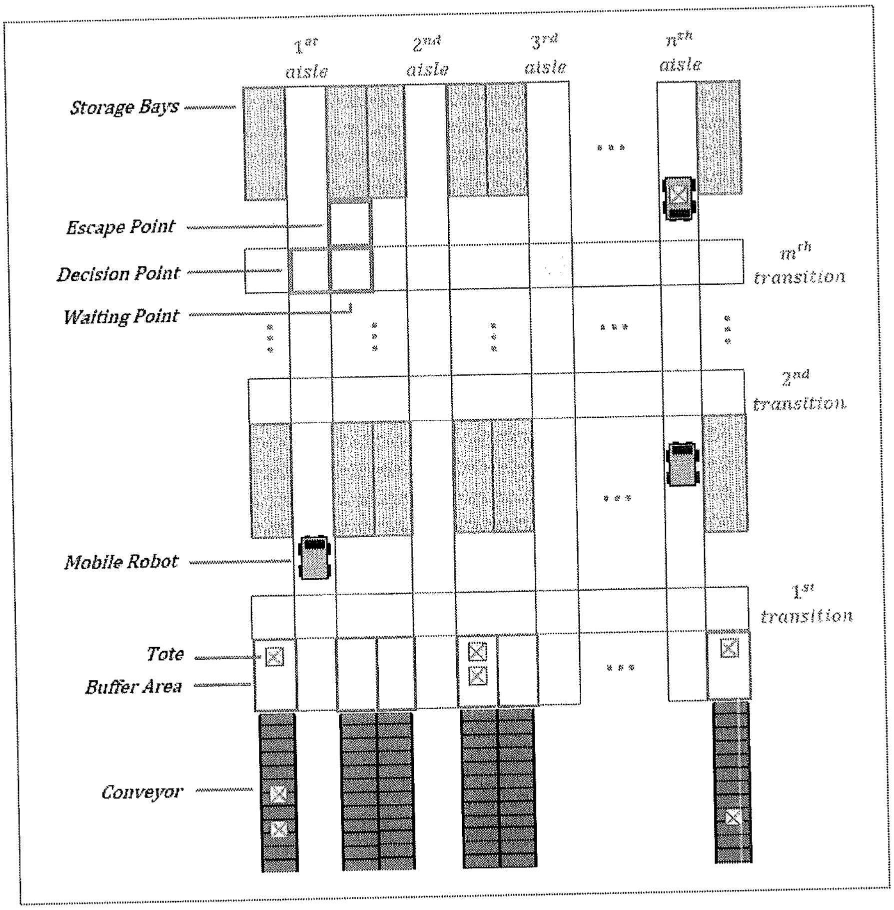

Figure 3.1. Physical Configuration of the FSD

In the FSD, the passage of MRs between aisles takes place through the passageways called "transition" where they connect aisles. The intersection of an aisle and a transition is called a "decision point" where MRs stop and make decisions on where to move. The FSD system contains as many decision points as the multiplication of the number of aisles and the number of transitions in the system. Once again, MRs stop at those points to make decisions on their next stopping point through their destination points. While deciding that, they evaluate the environmental conditions and make smart decisions resulting in not only no deadlock and collisions but also, decreased travel time of vehicles. “Waiting” and “escape” points in Figure 3.1 are significant points that are considered for preventing the deadlock of MRs. The roles of those points are explained in Chapter 4 in detail.

As mentioned, if the FSD shown in Figure 3.1 is applied for a tier of a multi-tier warehouse, then, the physical configuration of such a warehouse could be shown by Figure 3.2. In that design, MRs are called shuttles.

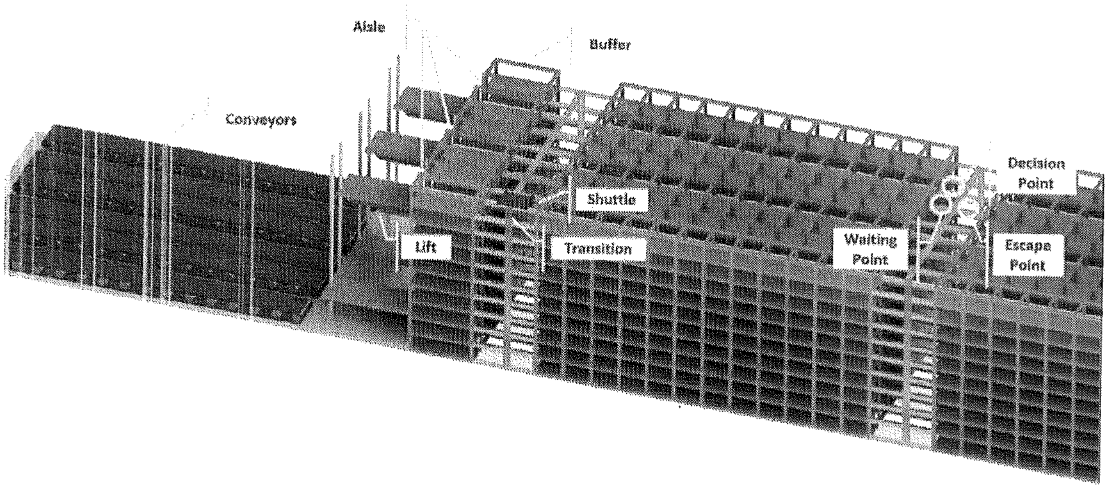

Figure 3.2. Physical Configuration of the FSD in an SBS/RS

Basically, the developed FSD includes multiple transitions allowing MRs move between aisles freely and decision/waiting/escape points where they stop at and/or move there to prevent any deadlock and collision.

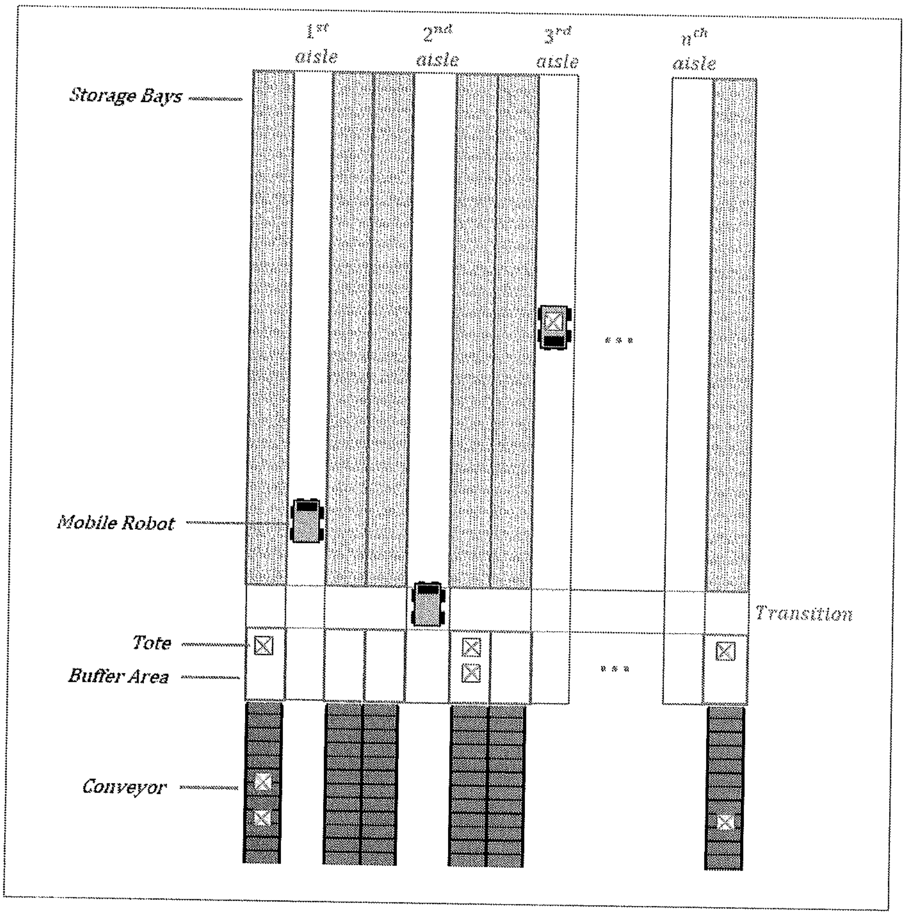

Figure 3.3. Physical Configuration of the DSD

In DSD, a single MR is dedicated for travel between a certain number of adjacent aisles and, it cannot move to others rather than those dedicated ones. Namely, in DSD, an

MR can travel between the pre-assigned aisles. DSD includes only a single "transition" as seen in Figure 3.3 providing passage between aisles. That transition is located in front of the "buffer area" where the loads are picked up and dropped off at that area.

As mentioned previously for FSD, if the DSD shown in Figure 3.3 is applied for a tier of multi-tier warehouse, then, the physical configuration of such a warehouse could be shown in Figure 3.4.

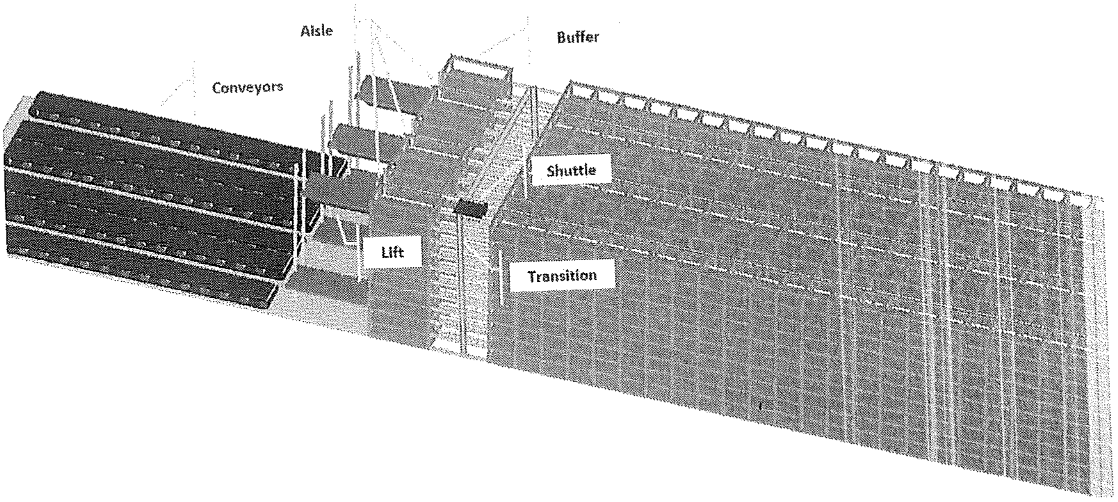

Figure 3.4. Physical Configuration of the DSD in an SBS/RS

Here, our aim is to compare the performance of those two designs: FSD and DSD, under developed deadlock and collision prevention policies as well as different warehouse configurations.

3.2. Agent-based simulation modelling

In an effort to model the developed algorithms, we utilize an agent-based simulation modelling approach. Here, agents are actors simulated in the simulation models. Agents can also be described as continuously and autonomously functioning entities in an environment with other agents and processes (Shoham, 1997). The decision procedures of the simulated actors in an agent-based simulation model are clearly defined at the micro level. The macro-level system structure arises as a result of agent actions, agent-agent and agent-environment interactions (Siebers and Aickelin, 2008).

We apply a multi-agent simulation model to test the developed algorithms' performance. Due to the complexity of the system and desired real-time information tracking purpose from the environment, multi-agent simulation modelling is found to be advantageous and appropriate. MRs and arriving transaction demands are defined to be agents in the system. They are treated as intelligent agents so that they become dynamic objects in the system which can sense their environment and make autonomous decisions. Those multi-agents have the ability to communicate with each other and tracking real-time information from their environment. MR agents act as decision-makers in the system. The main smart decisions that they can take in the system are: a proper transaction (i.e., storage or retrieval) selection waiting in queue and, travel route decision to the destination point. Figure 3.5 shows how agents interact with each other.

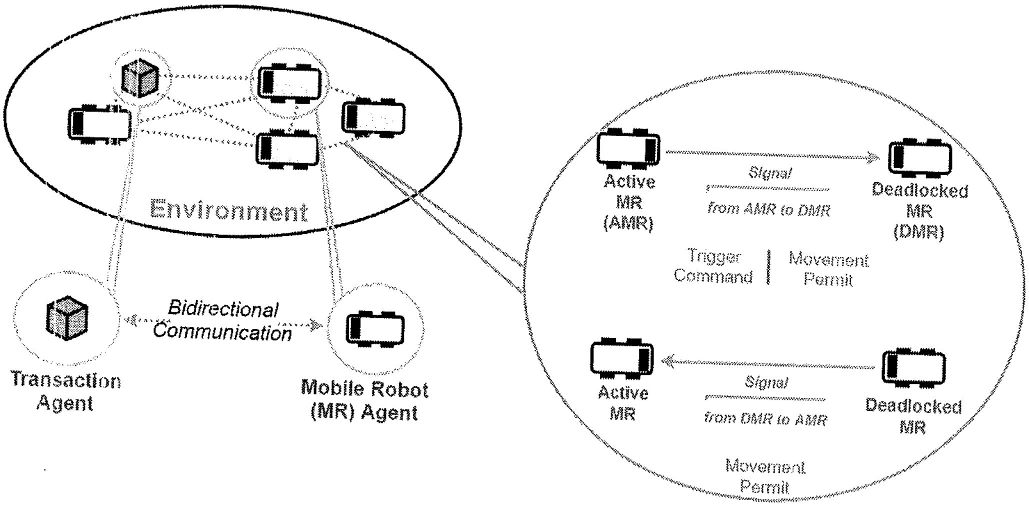

Figure 3.5. Agent Interactions

According to Figure 3.5, MR agents and a transaction agent representing all demands are defined. The information from the current system status is provided to all agents in the environment. The MR agents take action by evaluating those pieces of information. Here, the mentioned evaluation procedure between agents (i.e., the decision-making strategy) is referred to as bidding strategy, which is the foundation of agent-based modelling. Bidirectional communications between all agents are seen as red dashed lines in Figure 3.5. Since all agents are in bidirectional communication, the decisions are taken as a result of this communication procedure. Communication between MR agents is somewhat more complicated due to the multitude of situation possibilities. In order to clearly explain the communication procedure between MR agents, the two agents in communication are named active MR (AMR) and deadlocked

MR (DMR). The right side of Figure 3.5 shows the communication between MR agents which are in a case having the possibility of deadlock. In such a case, the AMR agent having priority in decision-making sends a signal to the DMR agent that is likely to cause a deadlock (Trigger Command-TC or Movement Permit-MP). Here, AMR is an MR triggering the other MR having the potential of causing a deadlock in the system. That triggered MR is called DMR. The movement of the triggered MR always starts after a signal transmission, by the AMR. Details of those procedures are presented in Chapter 4.

3.2.1. Simulation Model Parameters and Assumptions

In the simulation models, we utilize the below notations:

Λ: Monthly transaction arrival rate (transactions/month)
TR: Monthly throughput rate (transactions/month)
V_{max}: The maximum speed that an MR can reach in long travel distance (*m*/*sec*)
a_s, d_s: Acceleration and deceleration value of an MR (*m*/sec^2)
B: Number of bays at one side of an aisle
C: Total capacity of the warehouse (i.e., in terms of number of bays)
T: The number of bays between two sequential transitions
N: Total number of MRs in the system

Also, notations for system performance measures are as follows:

U_{avg}: Average utilization of MRs (%)
T_{avg}: Average flow time of a transaction (*sec*/transaction)
T_{max}: Maximum flow time of transactions (*sec*)
SD: Standard deviation of transaction flow times

The assumptions that are considered in the simulation model are summarized as follows:

- Mean arrival rate (Λ) for storage and retrieval transactions follows the Poisson process with an equal rate (Roy et al. 2013, Marchet et al. 2013, Ning et al. 2016, Ha and Chae 2019, Eder 2019, Wu et al. 2020). Here, the mean values are adjusted such that we obtain 95% average utilization for MRs (U_{avg}).
- Storage or retrieval requests are created randomly for their bay addresses.

- The maximum velocity (V_{max}) is assumed to be 2 *m*/sec - 3 *m*/sec based on the pre-defined experiments (Lerher 2018).
- The acceleration and deceleration values for velocities (a_s, d_s) are same and equal to 2 m/sec^2 or 3 m/sec^2 based on the considered experiments.
- The distance between all adjacent storage bays and points (i.e. buffers, decision, waiting, escape points) is assumed to be 0.5 m. (Ning et al. 2016, Eder 2019, Ha and Chae 2019).
- The simulation run length is one month with a one-week warm-up period that is decided by the eye-ball technique.
- The model is run for five independent replications.
- MRs do not break down during the simulation runs.

Verification and validation of the simulation models are done by debugging the model by animating the system as well as with the help of an expert working on the design and analyses of those systems practically.

CHAPTER 4

DEADLOCK AND COLLISION PREVENTION PROCEDURES

The first decision to be made in the agent-based system is on which transaction would be selected by the AMR. The pseudo-code of that selection procedure is given in Figure 4.1. According to that, the MR selects a transaction by considering the smallest estimated travel distance to the transaction, the transaction's current waiting time, and aisle congestion conditions, etc. Specifically, according to Figure 4.1, the transaction selection procedure works as follows: This procedure is performed when there is at least one transaction waiting in the queue ($n(T) \geq 1$) and at least one available MR ($n(A) \geq 1$) in the system. If there is only one transaction waiting to be processed in the queue ($n(T) = 1$), the MR (m) closest to the location of that transaction (t) among the available MRs ($\boldsymbol{min}_{D(t,m)}$) selects that transaction. Otherwise, the current waiting times of pending transactions ($W(t)$) are checked. If there is a transaction waiting longer than the current average waiting time of so far transactions ($W(t)> W^{avg}$), that transaction and the closest available MR to that transaction are paired without seeking any other conditions. Otherwise, the match is done based on the aisle's congestion ($AD(t)$) value through the route of the waiting transaction. Here, $AD(t)$ represents the number of transactions that are being processed in the aisle of the waiting transaction (t) location. As a result, the transaction with the lowest aisle congestion value ($\boldsymbol{min}_{AD(t)}$) and the closest location to an available MR ($\boldsymbol{min}_{D(t,m)}$) is selected.

```
Algorithm 1: The algorithm for transaction assignment to mobile robots
  Data: $M$: Set of Mobile Robots (MRs), $A$: Set of Available MRs,
        $T$: Set of Waiting Transactions, $A \subseteq M$, $m \in A$, $t \in T$.
  Result: $m$ and $t$ ;
  $D(t,m)$: Distance between address of $t$ and current location of $m$,
  $W(t)$: Waiting time of t, $W^{avg}$: Average waiting time of all $t$ s,
  $AD(t)$: Aisle density of address of $t$.
  while $n(A) \geq 1$ and $n(T) \geq 1$ do
      if $n(T) = 1$ then
          Match: $m$ and $t$ having $min_{D(t,m)}$
      else
          if $W(t) > W^{avg}$  $\exists t \in T$ then
              Match: $m$ and $t$ having $min_{D(t,m)}$ where $W(t) > W^{avg}$ for
                $t$
          else
              Match: $m$ and $t$ having $min_{D(t,m)}$ where $AD(t)= min_{AD(t)}$
                for $t$
          end
      end
  end
```

Figure 4.1. Transaction Assignment Procedure

The movement procedure of an MR is such that it travels from one decision point to another until it reaches the destination address. However, in some cases, the MR can travel through two decision points without stopping. This condition takes place if the following two decision points are available when the MR is to decide at a decision point where to travel. Hence, the MR travels to that second decision point without stopping. When the MR arrives at the destination address (i.e., bay), it stores the load at the bay if the transaction type is storage; otherwise, it retrieves the load.

If the MR has completed a storage transaction and there is no other job assigned to that MR, this MR waits at the closes available decision point until it selects a new transaction to process. If the MR has completed a retrieval process, then the MR travels to the closest decision point to the buffer area where the load is dropped off.

An MR travels to its destination address by prioritizing the aisle change by considering its shortest route option. In case of encountering a DMR during this movement, it follows the following policy:

If there is an alternative decision point in the direction of AMR's destination address, then AMR continues its travel from that alternative route.

However, if it requires to proceed on the same route with the DMR (i.e., no alternative route exists), then it follows the actions depending on the status of the DMR. Namely, if the DMR's route is not through the AMR's direction, then the AMR waits for the DMR to travel. However, if two are to collide due to opposed travel requirements, then the AMR triggers the DMR to travel to a decision, waiting or escape point. How that triggering policy works as well as how the triggered MR travels accordingly are shown in the flowcharts of Figure 4.2 and Figure 4.3, respectively.

Actions taken by MRs are referred to as procedures (*P*) in Figures 4.2 and 4.3. To explain how those procedures work, we show some critical deadlock and collision cases in Figure 4.4. Note that the regarding procedures numbered in Figures 4.2 and 4.3 can be seen in Figure 4.4 visually.

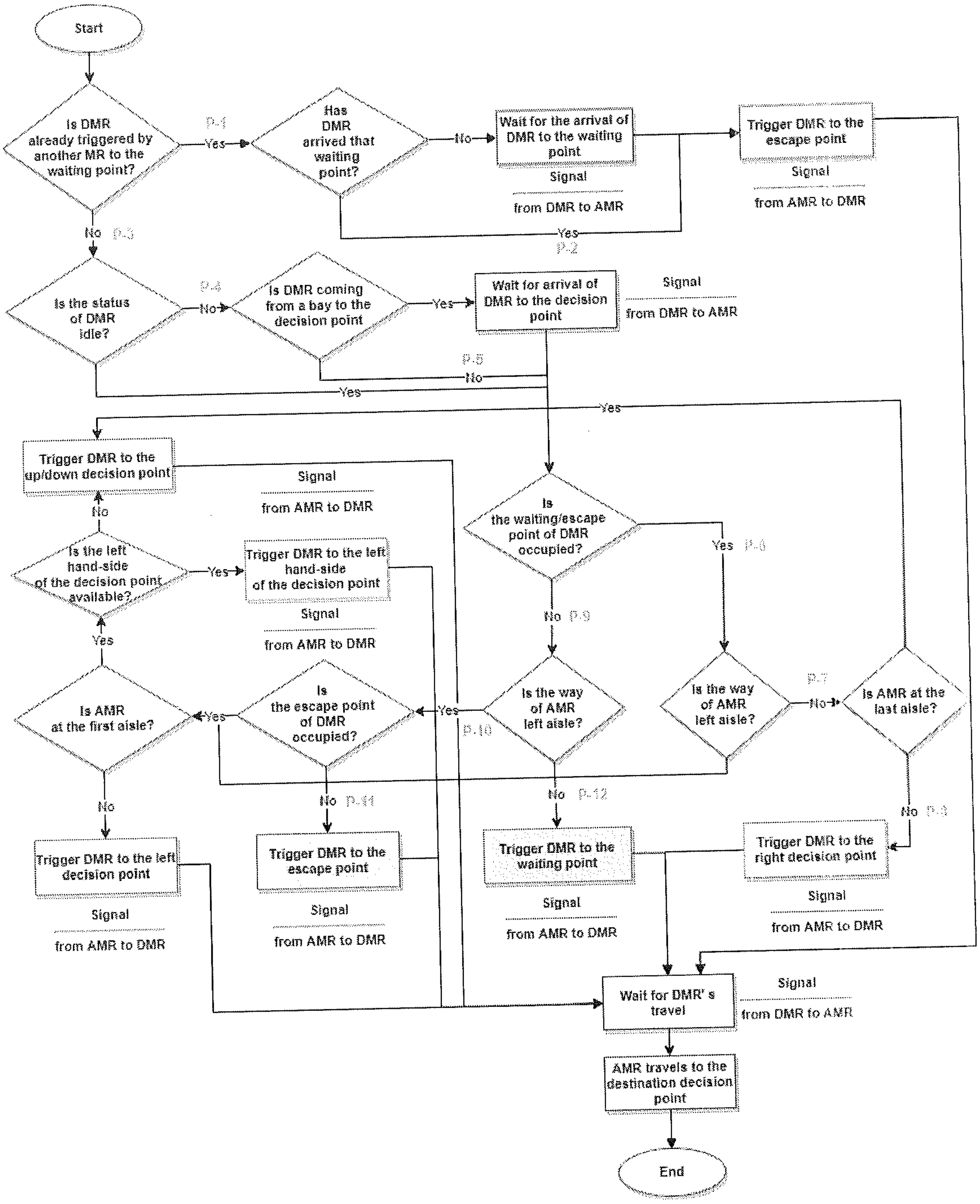

Figure 4.2. Flowchart of the MR Trigger Procedure

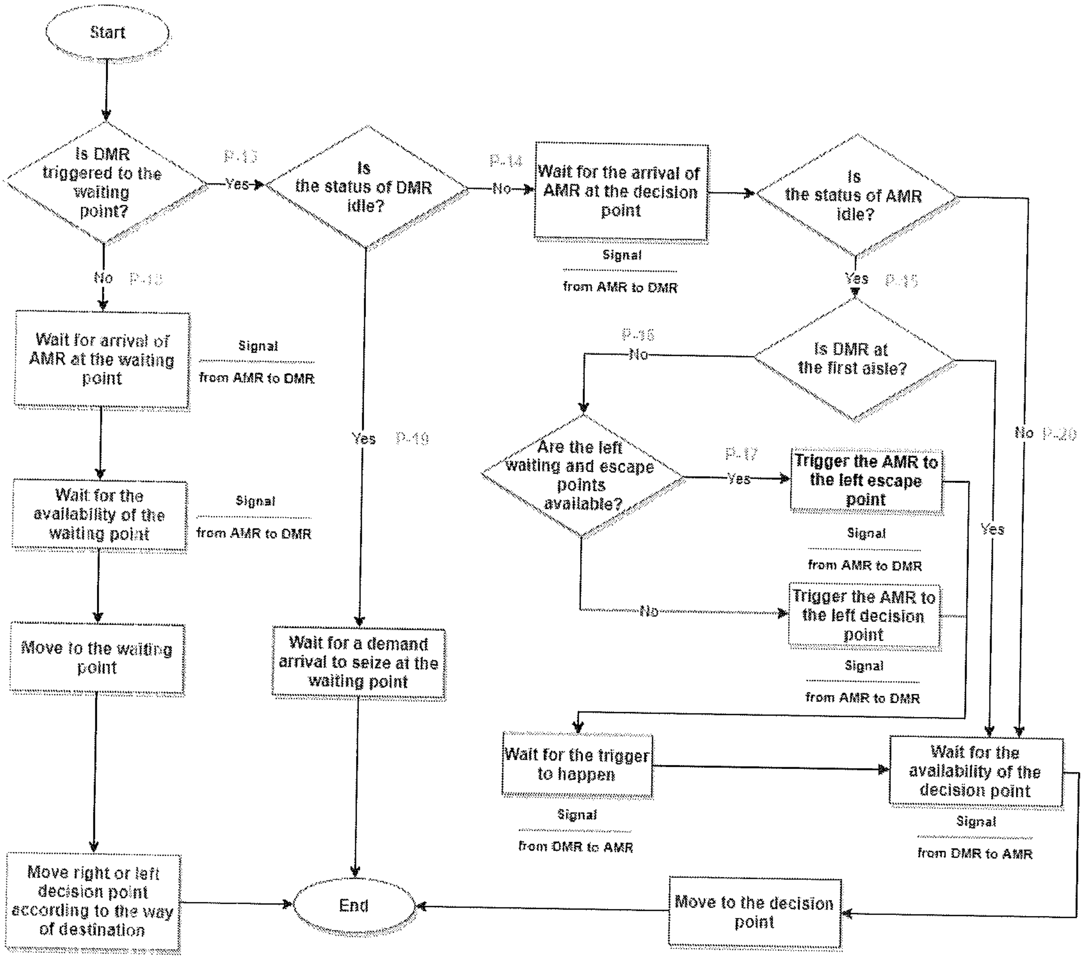

Figure 4.3. Flowchart of the Triggered MR Movement Procedure

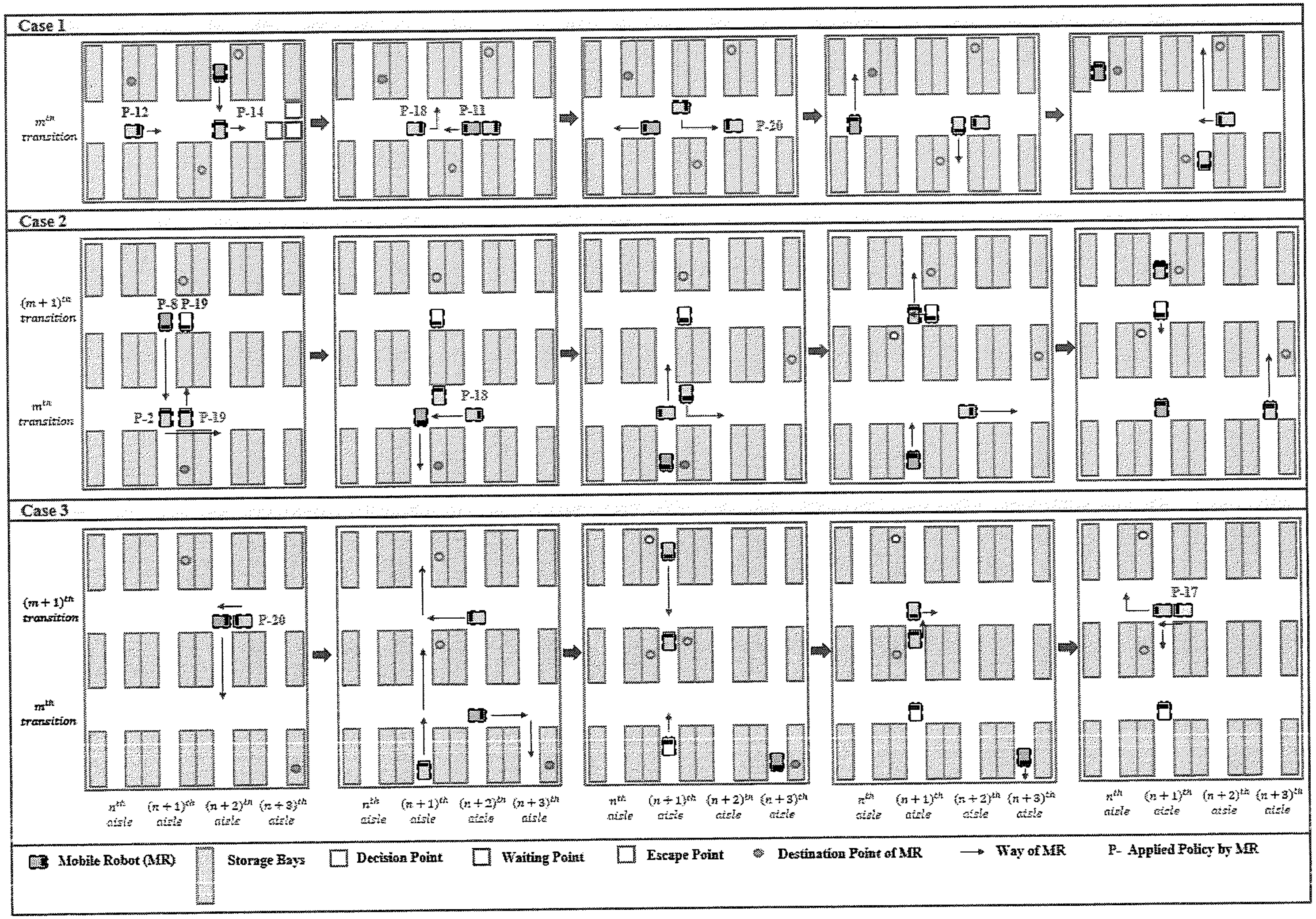

Figure 4.4. Example for Deadlock and Collision Case

In Figure 4.4, the balls and the MRs with the same color represent where those MRs aim to arrive as storage or retrieval addresses. Red, blue, and green lined squares represent decision, waiting, and escape points, respectively. The red arrows show the direction of the MR as the result of an action taken by the MR. Remember that, some of the policies shown in Figures 4.2-4.3 also appear in Figure 4.4. Three significant collision and deadlock cases are explained in Figure 4.4.

In Case 1, the blue and green MRs tend to come across during their travels. Since the MR tending to exit an aisle has priority in movement, the blue MR triggers the green MR to travel to the closest available waiting point. This operation corresponds to P-3, P-4, P-5, P-9, and P-12. When the blue MR reaches the decision point, it tends to encounter the orange MR on its way. In this case, the blue MR (AMR) travels to the next decision point where the orange MR (DMR) is currently located. Before that, it triggers the orange MR (DMR) to the escape point (P-3, P-4, P-5, P-9, P-10, and P-11). Meanwhile, the triggered orange MR waits for the blue MR to leave its waiting point. At that time, it leaves the escape point and travels to the waiting point (P-18). On the other hand, the green MR triggered to the waiting point by the blue MR waits for both blue and orange MRs to arrive at target decision points (P-13 and P-14). It waits there until that closest decision point becomes completely available. Once that decision point becomes available, it travels to that decision point and then to its target location (P-13, P-14, and P-20).

In Case 2, again the blue and green MRs tend to travel in opposite directions of each other. This time, the blue MR triggers the green MR to the right decision point (P-3, P-4, P-5, P-6, P-7, and P-8), since one of the waiting and escape points of the green MR is occupied. The green MR triggers the orange MR to the escape point (P-1 and P-2) to travel to the right decision point in the next step. As observed, this time the green MR becomes both a triggering (AMR) and a triggered (DMR) MR at the same time. When the blue MR reaches the target decision point and continues on its way, the green MR travels towards that decision point. At this time, the orange MR is idle, so it will wait for a demand selection (P-19). When a transaction is selected by the orange MR, then it waits for the green MR to transit the decision point (P-18). waits at a waiting point (P-19) until the green MR leaves the decision point after selecting a transaction to process. Then it moves to the decision point in the direction of its target and from there to its target address.

Case 3 shows the example for alternative route assignment and triggering an idle MR through the out of the way of an AMR. Normally, MRs which tend to change their aisles have priority in travel. However, if there is an alternative available direction towards the target aisle then, that new direction can be preferred. Namely, instead of making an aisle change, the blue MR travels to the down decision point (i.e., transition change) to open the way of the green MR. After the green MR reaches its target location and tends to return to the closest decision point and an idle orange MR also tends to travel to that decision point, then the orange MR triggers the green MR to the waiting point after it reaches to that decision point. Then, the green MR at the waiting point triggers the orange MR to the left side (opposite) escape point and it travels in the direction of its target (P-13, P-14, P-15, P-16, and P-17).

CHAPTER 5
RESULTS

5.1. Comparative Analysis of Flexible and Dedicated Systems

To summarize, the main purpose of this thesis is to develop intelligent collision and deadlock prevention algorithms for flexible travel of MRs among multiple aisles in an automated warehouse. In the developed intelligent algorithm in FSD, MR agents are able to make their own decisions towards their goals to obtain improved performance measures as well as no collision and deadlock in the system. To test the effectiveness of the developed algorithms, the simulation results are compared with their dedicated system designs, DSD, under different warehouse configurations. The warehouse designs are considered to be: warehouse capacity (C) in terms of number of bays, number of aisles (A), and number of bays (T) between two adjacent decision points/transitions within the same aisle. Note that there are no multiple transitions in DSD. We also consider, the MR-related design parameters such as velocity scenario (V_{max}; a_s, d_s) and the number of MRs (N). The design parameters along with their specific values are summarized in Table 5.1.

Table 5.1. Experimental Design

Layout Design			Vehicle Scenario	
C	A	T	V_{max}; a_s, d_s	N
1200	6	10	2; 3, 3	3
3600	12	12-13	3; 3, 3	4
		16-17		
		25		

In system designs under equal warehouse capacity (C), an increase in the number of aisles means a decrease in the number of bays in an aisle. Warehouse capacity is equal to the number of aisles multiplied by the number of bays on either side of an aisle ($C = A*2*B$). Figure 5.1 shows the warehouse layouts with 6 and 12 aisles, respectively.

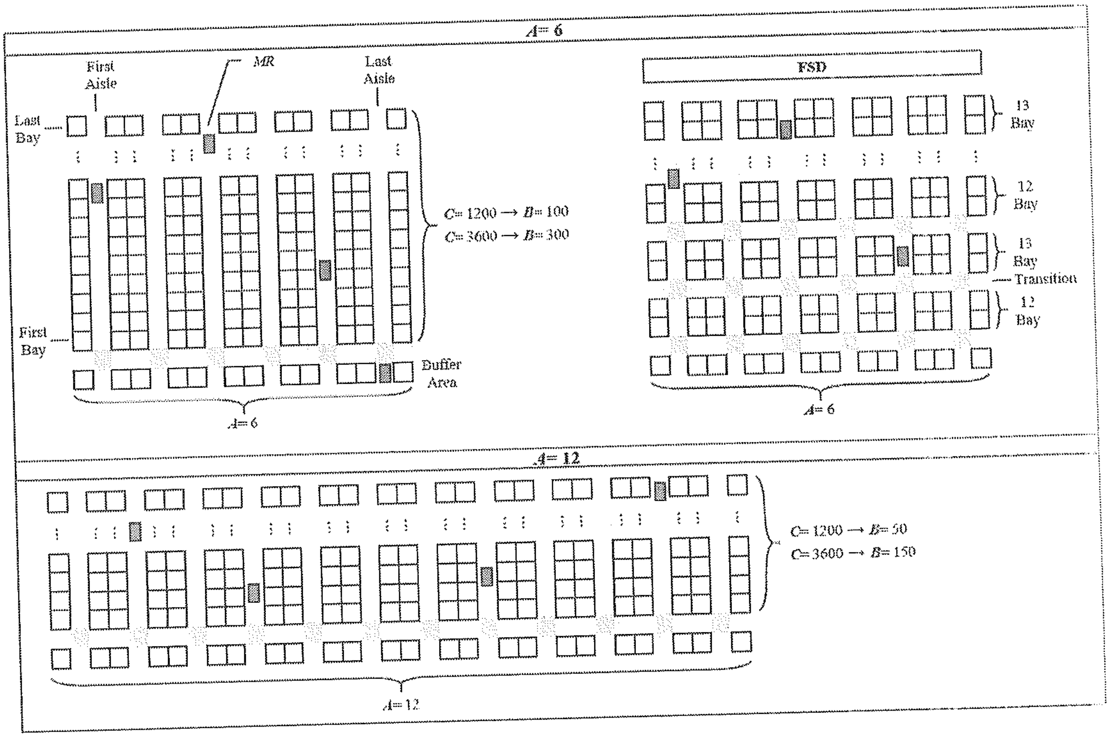

Figure 5.1. Example for Aisle Designs

The system designs are run at arrival rates producing high average MR utilization U_{avg} (i.e., 95%). The pre-defined performance measures observed in the analysis are monthly throughput rate, *TR*, average flow time of transactions, T_{avg}, which is the time between the creation and disposal of a transaction request in the system, average maximum flow time of transactions T_{max}, and standard deviation of flow time values, *SD*. The performance of the designs is evaluated based on those performance measures. Results of five simulation replications under 95% confidence intervals are presented in Table 5.2. Also, the graphs summarizing the results of FSD and DSD are given in Figure 5.2 and Figure 5.3, respectively. Note that, experimentation results of FSD are given under the input parameter T value, which gives the best results for all design combinations.

Table 5.2. Simulation Results for FSD

Layout design		**MR parameters**		**Performance measures**				
C	A	V_{max}; a_s, d_s	N	*TR*	U_{avg}	T_{avg}	T_{max}	*SD*
1200	6	2; 3, 3	3	225,590 ± 278	94.9 ± 0.1	77.4 ± 0.3	1,155	71.5 ± 1.0
1200	6	2; 3, 3	4	297,860 ± 312	94.9 ± 0.3	68.3 ± 0.5	772	38.5 ± 0.5
1200	6	3; 3, 3	3	264,820 ± 424	94.6 ± 0.1	63.1 ± 0.2	940	57.4 ± 0.5
1200	6	3; 3, 3	4	345,940 ± 542	95.2 ± 0.1	59.0 ± 0.3	991	52.6 ± 0.8

Table 5.2 (cont'd). Simulation Results for FSD

Layout design		MR parameters		Performance measures				
C	A	V_{max}; a_s, d_s	N	TR	U_{avg}	T_{avg}	T_{max}	SD
1200	12	2; 3, 3	3	328,420 ± 472	95.2 ± 0.1	53.7 ± 0.3	876	48.8 ± 0.8
1200	12	2; 3, 3	4	428,820 ± 524	95.0 ± 0.4	46.0 ± 0.4	691	36.3 ± 0.4
1200	12	3; 3, 3	3	365,370 ± 530	94.9 ± 0.1	47.1 ± 0.2	780	42.6 ± 0.5
1200	12	3; 3, 3	4	480,170 ± 565	95.0 ± 0.4	40.9 ± 0.4	609	32.2 ± 0.4
3600	6	2; 3, 3	3	97,896 ± 248	94.8 ± 0.1	183.9 ± 2.0	2,508	175.5 ± 4.8
3600	6	2; 3, 3	4	128,370 ± 219	95.2 ± 0.2	174.6 ± 1.4	2,320	167.3 ± 3.1
3600	6	3; 3, 3	3	124,690 ± 289	95.3 ± 0.1	149.5 ± 1.2	2,057	144.7 ± 2.4
3600	6	3; 3, 3	4	161,560 ± 355	95.4 ± 0.4	136.0 ± 1.0	2,127	135.2 ± 2.1

Table 5.2 (cont'd). Simulation Results for FSD

Layout design		**MR parameters**		**Performance measures**				
C	A	V_{max}; a_s, d_s	N	TR	U_{avg}	T_{avg}	T_{max}	SD
3600	12	2; 3, 3	3	173,040 ± 428	95.2 ± 0.1	103.1 ± 0.4	1,511	96.2 ± 0.7
3600	12	2; 3, 3	4	222,720 ± 375	94.5 ± 0.1	85.2 ± 0.4	1,145	68.1 ± 0.8
3600	12	3; 3, 3	3	207,520 ± 372	95.0 ± 0.1	85.4 ± 0.3	1,318	79.3 ± 1.0
3600	12	3; 3, 3	4	270,350 ± 441	94.6 ± 0.1	72.4 ± 0.3	972	58.9 ± 0.9

Table 5.3. Simulation Results for DSD

Layout design		**MR parameters**		**Performance measures**				
C	A	V_{max}; a_s, d_s	N	TR	U_{avg}	T_{avg}	T_{max}	SD
1200	6	2; 3, 3	3	225,590 ± 278	82.8 ± 0.1	80.0 ± 0.2	2,385	81.5 ± 0.7

Table 5.3 (cont'd). Simulation Results for DSD

Layout design		**MR parameters**		**Performance measures**				
C	***A***	V_{max}; a_s, d_s	***N***	***TR***	U_{avg}	T_{avg}	T_{max}	***SD***
1200	6	2; 3, 3	4	298,260 ± 578	74.8 ± 0.1	123.7 ± 1.4	7,016	201.0 ± 5.7
1200	6	3; 3, 3	3	264,820 ± 424	78.1 ± 0.1	55.9 ± 0.2	1,468	53.0 ± 0.2
1200	6	3; 3, 3	4	345,940 ± 543	70.9 ± 0.1	76.5 ± 0.5	4,303	111.3 ± 2.3
1200	12	2; 3, 3	3	328,290 ± 279	84.1 ± 0.2	58.0 ± 0.6	1,852	68.2 ± 0.8
1200	12	2; 3, 3	4	428,640 ± 279	80.5 ± 0.2	50.4 ± 0.6	1,354	52.5 ± 1.2
1200	12	3; 3, 3	3	365,280 ± 199	80.7 ± 0.1	45.1 ± 0.3	1,398	50.3 ± 0.4
1200	12	3; 3, 3	4	480,040 ± 219	77.6 ± 0.1	40.2 ± 0.3	1,007	40.0 ± 0.7
3600	6	2; 3, 3	3	97,897 ± 247	88.6 ± 0.1	241.3 ± 1.3	7,902	365.6 ± 4.6

Table 5.3 (cont'd). Simulation Results for DSD

Layout design		**MR parameters**		**Performance measures**				
C	A	V_{max}; a_s, d_s	N	TR	U_{avg}	T_{avg}	T_{max}	SD
3600	6	2; 3, 3	4	128,380 ± 217	77.8 ± 0.1	385.8 ± 6.1	12,442	475.6 ± 35.9
3600	6	3; 3, 3	3	124,690 ± 287	83.3 ± 0.2	146.5 ± 0.5	4,147	147.9 ± 2.1
3600	6	3; 3, 3	4	162,130 ± 451	73.8 ± 0.1	197.7 ± 1.5	8,598	295.6 ± 5.3
3600	12	2; 3, 3	3	172,833 ± 345	86.9 ± 0.4	128.2 ± 2.2	3,839	156.6 ± 6.5
3600	12	2; 3, 3	4	222,514 ± 375	86.4 ± 0.4	126.9 ± 2.4	3,451	145.6 ± 4.3
3600	12	3; 3, 3	3	207,777 ± 403	81.6 ± 0.4	82.9 ± 1.2	2,289	91.9 ± 3.0
3600	12	3; 3, 3	4	270,560 ± 351	81.2 ± 0.3	83.2 ± 1.0	2,271	89.4 ± 2.0

From the results, it is observed that although the U_{avg} values are mostly low in DSD compared to FSD, the T_{avg} values are higher in DSD than the FSD. This is probably because that there are increased accumulated transaction requests in certain aisles in DSD waiting for MR to be available.

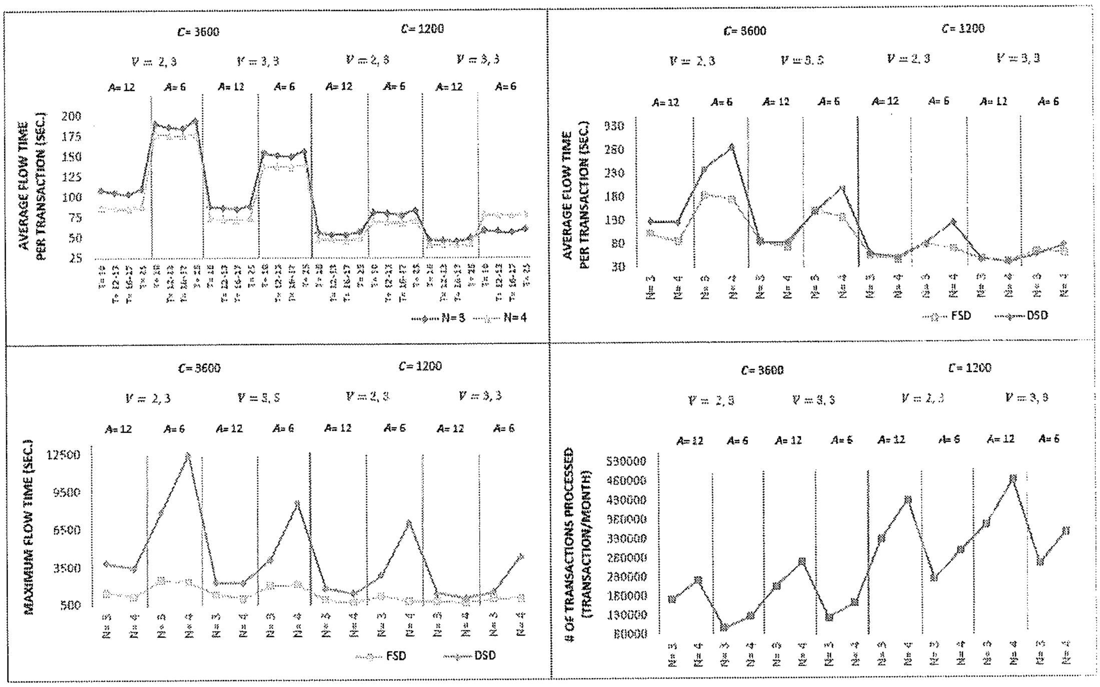

Figure 5.2. Graphical Representations of Simulated Experiments

In the experimentation work, first, the number of transitions where the flexible system works best for all warehouse scenarios is decided. The experimental results graph for the number of transitions is shown at the top left corner in Figure 5.2 graphs. From that figure, it is observed that FSD performs best under design 16-17 bays transition. Therefore, we proceed with a 16-17 bays layout design for the FSD system. The observations from Figure 5.2 are summarized as below:

- According to the results, it is observed that when the number of aisles (A) increases in the system, T_{avg} tends to decrease. Remember that, in a fixed capacity, a layout having a large number of aisles results in a low number of bays in each aisle.
- Increased A also provides increased TR and decreased T_{avg}, T_{max}, and SD. The probable reason for that can be that there would be less congestion in front of the buffer areas because that each aisle has its own buffer area. This condition is also traced by the aisle congestion value ($AD(t)$), where this value is low under the high number of aisles designs.

Note that in a multi-tier warehouse system, having a large number of aisles may cause the increased number of lift installations and increased operating costs in front of the buffer area. However, more experiments including the number of tier designs can be completed to find a good design for a multi-tier warehouse case.

- In the system designs with low capacity, C, the difference of T_{avg}'s in FSD and DSD are relatively low compared to the high capacity case. Namely, in high capacity system designs (i.e., C= 3600) the performance difference between the two systems become more explicit.

- When the velocity of MR increases T_{max}, and SD tend to decrease in FSD. When both, the number of MRs and velocity profiles increase, FSD becomes more advantageous in terms of T_{max}, and SD.

- It is observed that the reason for the increase in T_{avg} in DSD is due to the long waiting times of transactions in MR queues. Even in FSD, an MR stops several times for making decisions on route directions, it processes transactions faster than FSD. This is probably because that in FSD, any MR can be assigned to any waiting transaction decreasing waiting time of those transactions.

- For example, in the C= 3600 capacity design when A= 12, V_{max}; a_s, d_s= 2; 3, 3, and N = 3, T_{avg} is 103 seconds in FSD and it is 128 seconds in DSD. Looking at the average travel time of an MR in this scenario (i.e., it is not provided as a performance metric in this study) it is observed that it is 44 seconds for FSD and 41 seconds for DSD. Here, the average travel time does not include the waiting time of transactions in the queue. It solely includes travel time as well as loading and unloading times. Hence, it is computed that the average waiting time of a transaction in the queue in FSD is 49% of the flow time and it is 68% in DSD.

In the light of decreased T_{avg} in FSD, we also complete extra experiments to test whether or not FSD can work with less number of MRs under better performance metrics than DSD. For that, five and six numbers of shuttles are considered for FSD and DSD, respectively. The simulation results are provided in Table 5.4. In that design, A= 12, B= 150, C= 3600, V_{max}; a_s, d_s= 2; 3, 3. To make a fair comparison, we consider the same transaction arrivals in two system designs. Table 5.4 summarizes the results.

Table 5.4. The Simulation Results under Different Number of MRs Scenarios

System	N	TR	U_{avg}	T_{avg}	T_{max}	SD
FSD	5	278,640 ± 365	94.9 ± 0.3	82.0 ± 0.3	978	62.9 ± 0.8
DSD	6	278,694 ± 327	75.0 ± 0.5	96.8 ± 1.8	2,095	94.8 ± 5.2

From Table 5.4, it is observed that even under decreased numbers of MRs, FSD produces better results (roughly, 15% better results for T_{avg}, and 53% better results for T_{max}). Hence, it might be worth exploring more racking design scenarios for the decreased number of MRs in FSD. Besides, the decreased number of MRs, we also study how the reduction of the number of buffer areas would affect the system performance. A decrease in the number of buffers may also cause the decreased number of lifts in multi-tier systems. Decreased number of lifts would also result in decreased initial investment cost in the system. Therefore, it may be meaningful to analyze the effect of buffer areas on FSD performance as well.

It is assumed that there is a buffer area at each aisle. Hence, the number of buffers is equal to the number of aisles. In designs with less buffer case, it is assumed that there are eight numbers of buffers having two buffers in each zone and four buffers having a single buffer located at the middle of each zone. Again the results are obtained at the arrival rates providing roughly 95% U_{avg} value in FSD. The other design parameters are the same as in Table 5.1. The results are summarized in Table 5.5.

Table 5.5. The Simulation Results under Different Number of Buffers Scenarios

System	# of Buffer	*TR*	U_{avg}	T_{avg}	T_{max}	*SD*
FSD	12	225,590± 281	94.8± 0.1	88.4± 0.6	1,195	72.2± 0.9
FSD	6	217,600± 554	94.7± 0.1	91.8± 0.6	1,241	76.2± 1.1
FSD	4	207,520± 372	94.6± 0.1	105.3± 0.5	2,456	125.9± 2.6
DSD	12	225,340± 345	86.9± 0.4	130.1± 2.1	3,322	154.0± 4.9
DSD	6	218,320± 284	85.9± 0.3	127.2± 1.8	3,602	146.0± 4.7
DSD	4	207,368± 316	83.0± 0.4	117.9± 2.0	2,877	128.0± 6.5

From Table 5.5, it is observed that even under the reduced number of buffers, the FSD is still advantageous over DSD. For instance, eight numbers of buffers might be a good design option for FSD producing reasonable T_{avg} and T_{max} compared to twelve numbers of buffers case. Note that, in this case, the number of lifts might be considered to be decreased due to the decreased numbers of buffers.

5.2. Validation

As a result of model debugging and tracing by animation, the models are verified and validated by observing that the system designs function as desired. A snapshot from the animation of the simulated model is shown in Figure 5.3.

Comparison of the models of FSD and DSD shows that the performance metric values are consistent. Since there is no real FSD design, comparison with a known result could not be completed. In addition, degenerate tests are applied to test the correctness of the developed models. For example, when the arrival rate of the transactions is increased in the system, the MR utilization levels tend to increase. Also, when the velocity of MRs is decreased the average flow time of transactions value tends to increase. Experimented models are run after all those tests.

Internal validity was tested by observing variability between replications, which makes the system questionable if they are high. To see this, the half-width values of the simulation results are checked.

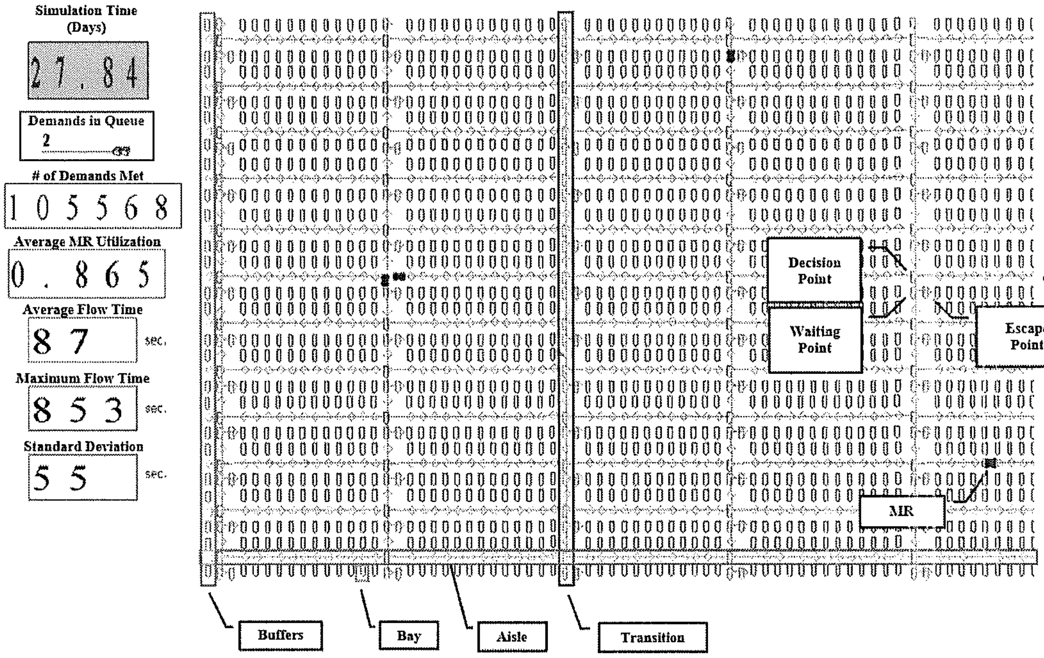

Figure 5.3. A Snapshot from the Simulation Animation

CHAPTER 6

CONCLUSIONS AND FUTURE RESEARCH

The revolutionary e-commerce growth as the result of the increasing online shopping trend with the COVID-19 effect challenges the intralogistics industry. The change in the order profile with that growth requires increased product variety, reduced delivery times, and flexible delivery options. Automated technologies based on in-facility communication and cooperation brought by Industry 4.0 have become critical in terms of coping with those challenges.

This thesis tackles the coordination of MRs in confined spaces while avoiding deadlocks which is a challenging problem. Smart collision and deadlock prevention algorithms are proposed for a flexible system design working under an IoT environment and real-time information tracking of intelligent agents in the system. A multi-agent simulation modelling is used to imitate the considered design in a computer environment so that the effectiveness of the developed algorithms can be tested. The developed algorithms' results are compared with the equivalent dedicated systems designs. The main motivation of the proposed work is to obtain better performance metrics by the flexible travel pattern of mobile robots. The developed algorithms studied can be utilized for any system having mobile robots (i.e., AGV; AS/RS) travelling on ground level between aisles.

The experiments are designed under different layout designs and vehicle scenarios. It is observed that up to 55% improvement in the average flow time value and 80% in the maximum flow time value can be achieved by the developed flexible design. The results also show that there may be more scenarios with the potential to reduce costs by working with fewer shuttles and lifts in the flexible system.

As future works, more experiments on those two designs, by also including warehouse rack designs could be considered. Besides, different layouts and smart decision-making rules could also be developed and tested.

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