DOKUZ EYLÜL UNIVERSITY
GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES

SIMULTANEOUS AND DYNAMIC OPTIMIZATION OF OPERATIONAL PLANNING PROBLEMS IN FULLY AUTOMATED PARKING SYSTEMS

by
Nurhan DUDAKLI

November, 2022
İZMİR

SIMULTANEOUS AND DYNAMIC OPTIMIZATION OF OPERATIONAL PLANNING PROBLEMS IN FULLY AUTOMATED PARKING SYSTEMS

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Nurhan DUDAKLI

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Ph.D. THESIS EXAMINATION RESULT FORM

We have read the thesis entitled **"SIMULTANEOUS AND DYNAMIC OPTIMIZATION OF OPERATIONAL PLANNING PROBLEMS IN FULLY AUTOMATED PARKING SYSTEMS,"** completed by **NURHAN DUDAKLI** under the supervision of **PROF. DR. ADİL BAYKASOĞLU** and we certify that, in our opinion, it is fully adequate, in scope and in quality, as a thesis for the degree of Doctor of Philosophy.

Prof. Dr. Adil BAYKASOĞLU

Supervisor

Prof. Dr. Okan TUNA

Thesis Committee Member

Assoc. Prof. A. Serdar TAŞAN

Examining Committee Member

Prof. Dr. Gözde ULUTAGAY

Examining Committee Member

Assoc. Prof. Zeynel Abidin ÇİL

Examining Committee Member

Prof. Dr. Okan FISTIKOĞLU

Director

Graduate School of Natural and Applied Sciences

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SIMULTANEOUS AND DYNAMIC OPTIMIZATION OF OPERATIONAL PLANNING PROBLEMS IN FULLY AUTOMATED PARKING SYSTEMS

ABSTRACT

Fully Automated Parking Systems (FAPSs) are new generation car parking systems where the sensor technology is used, and the parking process is carried out with the help of automated carriers (lifts, conveyors, robots). Since they offer effective, economical, and environmentally friendly solutions, FAPSs are seen as the future of parking systems and becoming more prevalent daily. However, although there are many studies on the design and technological equipment of FAPSs, the number of studies on the operational planning and control problems is very limited.

The software for planning and executing operations in FAPSs generally utilizes simple dispatching/heuristic rules like “first-come-first-served” and “nearest available slot.” However, solving these problems as an optimization problem instead of using certain rules will significantly improve system performance, especially service time. In this thesis, dynamic and proactive methods were developed to handle and solve operational planning and control problems of FAPSs.

A computational intelligence system using a new allocation procedure was developed to improve the operational efficiency of FAPSs. Finally, the performance of the proposed (simulation-based optimization) approach was compared with the classical (rule-based) approach via a simulation study. The results showed that the proposed approach could provide an improvement between 3%-10%. These results prove that the simultaneous use of technology, data, and knowledge will increase the operational efficiency of FAPSs, especially in the era of Industry 4.0.

Keywords: Fully automated parking systems, operational planning and control problems, rule-based planning, optimization-based planning, simulation.

TAM OTOMATİK OTOPARK SİSTEMLERİNDE OPERASYONEL PLANLAMA PROBLEMLERİNİN EŞ ZAMANLI VE DİNAMİK OPTİMİZASYONU

ÖZ

Tam Otomatik Otopark Sistemleri (FAPS), sensör teknolojisinin kullanıldığı, otomatik taşıyıcılar (asansör, konveyör, robot) yardımıyla park işleminin gerçekleştirildiği yeni nesil otopark sistemleridir. FAPS'ler etkin, ekonomik ve çevre dostu çözümler sundukları için otopark sistemlerinin geleceği olarak görülmekte ve her geçen gün daha da yaygınlaşmaktadır. Ancak FAPS'lerin tasarımı ve teknolojik donanımı ile ilgili çok sayıda çalışma olmasına rağmen, operasyonel planlama ve kontrol problemlerine yönelik çalışmaların sayısı oldukça sınırlıdır.

FAPS'lerde operasyonları planlamak ve yürütmek için kullanılan yazılımlarda, genellikle "ilk gelen ilk işlem görür", "en yakın yere yerleştir" gibi basit kurallar kullanılmaktadır. Ancak belirli kuralları kullanmak yerine, problemler bir optimizasyon problemi olarak ele alıp ve çözülürse, sistem performansı ve özellikle servis süresi önemli ölçüde iyileştirecektir. Bu tezde, FAPS'lerin operasyonel planlama ve kontrol problemlerini çözmek için dinamik ve proaktif yöntemler geliştirilmiştir.

Bu amaçla, FAPS'lerin operasyonel verimliliğini artırmak için yeni bir yerleştirme prosedürü kullanan bir sistem geliştirilmiştir. Son olarak, önerilen (simülasyon tabanlı optimizasyon) yaklaşımın performansı, bir simülasyon çalışması aracılığıyla klasik (kural tabanlı) yaklaşımla karşılaştırılmıştır. Sonuçlar, önerilen yaklaşımın %3-10 arasında bir iyileştirme sağlayabileceğini göstermiştir. Bu sonuçlar, teknoloji, veri ve bilginin aynı anda kullanılmasının, özellikle Endüstri 4.0 çağında FAPS'lerin operasyonel ve toplam verimliliğini artıracağını kanıtlıyor.

Anahtar kelimeler: Tam Otomatik Otopark Sistemleri, operasyonel planlama ve kontrol problemleri, kural-tabanlı planlama, optimizasyon-tabanlı planlama, simülasyon.

CONTENTS

Page

THESIS EXAMINATION RESULT FORM ii
ACKNOWLEDGMENT iii
ABSTRACT iv
ÖZ v
LIST OF FIGURES ix
LIST OF TABLES xii

CHAPTER 1-INTRODUCTION 1

1.1 Motivation 2
1.2 Importance of the Study 7
1.3 Outline of the Thesis 11

CHAPTER 2-FULLY AUTOMATED PARKING SYSTEMS 17

2.1 Types of Fully Automated Parking Systems 20
2.2 The Design Features of FAPSs 25
2.3 Planning Problems of FAPSs 29
2.3.1 The Design Problems of FAPS 29
2.3.2 The Operational Problems of FAPS 31

CHAPTER 3-OPERATIONAL PLANNING AND CONTROL PROBLEMS . 33

3.1 General Structure of Operational Problems in FAPSs 35
3.1.1 Fundamental Planning and Control Problems 37
3.1.2 Parameters and Constraints of the System 38
3.1.3 Solution Approaches to Operational Planning & Control Problems 40
3.2 The Review and Analysis of Related Literature 41
3.2.1 The Studies Closely Related to Our Study 45
3.2.2 The Gap in Literature and Contribution of this Study 48
3.3 Conclusion and Remarks 49

CHAPTER 4-RESEARCH METHODOLOGY AND MODELLING ASSUMPTIONS 52

4.1 Performance Criteria 53
4.2. The Objective Function 55
4.3 System Parameters of the Experimental Study 61
4.3.1 Deterministic System Parameters 61
4.3.2 Stochastic System Parameters 63
4.3.2.1 Analysis of Customer Number 64
4.3.2.2 Analysis of Arrival and Departure Pattern of Customers 67
4.3.2.3 Analysis of Parking Durations 70
4.4 The General Structure of the Simulation Model 72
4.5 Verification and Validation of the Simulation Model 73

CHAPTER 5-THE CLASSIC RULE-BASED PLANNING AND CONTROL APPROACH 76

5.1 Candidate Dispatching Rules and Heuristics for FAPS's Operations 78
5.2 The Simulation Study 83
5.3 Results and Discussions of the Simulation Study 89
5.3.1 Comparison of Allocation and Sequencing Rules' Performances 89
5.3.2 Analysis of Dispatching Rules under Different Conditions 92
5.3.2.1 Performance Analysis Based on Mean Arrivals 92
3.6.2.2 Performance Analysis based on Mean Duration 94
5.3.2.3 Performance Analysis based on Duration Pattern 95
5.3.2.4 Performance Analysis Based on Arrival Pattern 98
5.4 Conclusion and Remarks 100

CHAPTER 6-THE NOVEL OPTIMIZATION-BASED PLANNING AND CONTROL APPROACH 102

6.1 Characteristics of the Operational Planning and Control in FAPS 105
6.1.1 The Decision Variables 108
6.1.2 The Objective Function 110
6.2 The Proposed Intelligent System 111
6.2.1 The Proposed GRASP-Based Algorithm 115
6.2.2 The Proposed Allocation Procedure 116
6.2.3 The Main Vectors and Matrices of the Algorithm 121
6.3 The Simulation Study 123
6.4 Results and Discussion 125
6.4.1 Efficiency of the Proposed Approach 125
6.4.2 Efficiency of the Proposed Algorithm 132
6.4.3 Impact of Additional Information 134
6.5 Conclusion and Remarks 136

CHAPTER 7-CONCLUSION 138

7.1 Summary 138
7.2 Contribution of the Study 142
7.3 Future Works 144

REFERENCES 146

APPENDICES 158

Appendix-A.1 158
Appendix A.2 167
Appendix A.3 175

LIST OF FIGURES

Page

Figure 1.1 The trend in motorization in OECD countries, 1970-2012 3
Figure 1.2 Different FASPs that have different designs and slot layouts 6
Figure 1.3 The general frame and components of the Ph.D. thesis 12
Figure 1.4 The general structure and flow of the Ph.D. thesis 13
Figure 2.1 An example of FAPS structure 19
Figure 2.2 Tower type FAPS with different designs 21
Figure 2.3 Silo Type FAPS with different designs 22
Figure 2.4 Crane type FAPS with different designs 23
Figure 2.5 Shuttle type FAPS with different designs 23
Figure 2.6 Puzzle type FAPS 24
Figure 2.7 AGV parking system 25
Figure 2.8 Horizontal space utilization of different FAPS designs 27
Figure 2.9 The fundamental operational processes in FAPSs 32
Figure 3.1 The general process flow diagram of FAPSs 34
Figure 3.2 The general structure of operational planning and control problems in FAPSs 36
Figure 3.3 The number of studies found in all databases by using keywords via the Web of Science 43
Figure 3.4 The number and ratio of publications by years 43
Figure 3.5 The number and ratio of publication types 44
Figure 3.6. The number of studies carried out by different countries/regions 44
Figure 3.7 The number of studies based on research area 45
Figure 4.1 The general structure of the problem considered in the thesis 52
Figure 4.2 Floor structure and slots layout of the considered FAPS 62
Figure 4.3 The number of customers based on days of the week 65
Figure 4.4 Arrival and departure pattern of the customers based on days of the week 67
Figure 4.5 Parking duration of the customers based on days of the week 70
Figure 4.6 The main components of the developed simulation model 73
Figure 4.7 An overview of the system at the end of the 14 days simulation run 74

Figure 5.1 The design similarities between FAPSs and fully automated warehouse systems 78
Figure 5.2 Operations in warehouses and FAPSs 79
Figure 5.3 Main control algorithm and embedded heuristics and rules 84
Figure 5.4 The main components of the developed simulation model 86
Figure 5.5 Performance of Allocation Rules in terms of capacity utilization and system efficiency 93
Figure 5.6 Performance of Sequencing Rules in terms of capacity utilization and system efficiency 93
Figure 5.7 Performance of Allocation Rules in terms of capacity utilization and system efficiency 94
Figure 5.8 Performance of Sequencing Rules in terms of capacity utilization and system efficiency 95
Figure 5.9 The distribution function used for parking durations and its parameter values 96
Figure 5.10 Performance of Allocation Rules in terms of capacity utilization and system efficiency 97
Figure 5.11 Performance of Sequencing Rules in terms of capacity utilization and system efficiency 97
Figure 5.12 The distribution function used for parking durations and its parameter values 98
Figure 5.13 Performance of Allocation Rules in terms of capacity utilization and system efficiency 99
Figure 5.14 Performance of Sequencing Rules in terms of capacity utilization and system efficiency 99
Figure 6.1 A general diagram of operational decisions and flow in FAPS 109
Figure 6.2 Components of the optimization-based planning approach 112
Figure 6.3 Pseudo code of the allocation-optimization algorithm 119
Figure 6.4 Two examples for the time window *(t-T)* that will be forecasted 120
Figure 6.5 An example of a customer matrix constituted by customer vectors that include information 121
Figure 6.6 An example of a location matrix constituted by slot vectors 122

Figure 6.7 An example of que_wait matrix constituted by vectors of customers waiting in the queue 122
Figure 6.8 An example of a solution vector where slots are assigned 123
Figure 6.9 The main components of the developed simulation model 124
Figure 6.10 Performance improvements by optimization-based approach..... 129
Figure 6.11 Performance comparison in terms of capacity utilization 130
Figure 6.12 Performance comparison in terms of customer satisfaction 131
Figure 6.13 Performance comparison in terms of system utilization..... 131
Figure 6.14 Solution quality depending on iteration number 132
Figure 6.15 Computational time depending on iteration number 133
Figure 6.16 The impact of additional information about the parking time on the system 134

LIST OF TABLES

Page

Table 2.1 Basic classification of FAPS based on design features 26
Table 3.1 The number of studies found and filtered as a result of the literature review 42
Table 3.2 Summary of the closely related studies 47
Table 4.1 Example of the data used for statistical analysis 56
Table 4.2 Results of normality test 57
Table 4.3 Results of correlation test..... 58
Table 4.4 Results of regression test..... 59
Table 4.5 Results of Adjusted R Square 60
Table 4.6 Results of ANOVA Test 60
Table 4.7 Distribution functions of customer numbers that are used in the experimental study 66
Table 4.8 Distribution functions of arrival patterns of the days 68
Table 4.9 Distribution functions of departure patterns of the days..... 69
Table 4.10 Distribution functions of parking durations of customers depending on days of the week 71
Table 5.1 Comparison of fully automated warehouses and parking systems 80
Table 5.2 Candidate dispatching and heuristic rules..... 82
Table 5.3 All possible combinations of the proposed dispatching rules and their performance results 88
Table 5.4 The overall performance of allocation rules 90
Table 5.5 The overall performance of sequencing rules 90
Table 5.6 Impact of allocation and sequencing rules/strategies on performance improvement..... 91
Table 6.1 Performance variation depending on main operation decisions 109
Table 6.2 Performance comparision of rule-based allocation and optimization-based allocation 126
Table 6.3 The normality test for performance criteria (proposed approach) 127
Table 6.4 The results of the two related samples test (proposed approach) 128

Table 6.5 The improvement provided by the proposed approach to the main performance criteria 129
Table 6.6 The normality test for performance criteria (additional information)..... 135
Table 6.7 The results of the two related samples test (additional information)..... 136

CHAPTER 1
INTRODUCTION

The number of vehicles, especially in big cities, causes serious traffic problems in those days. The vehicles in the cities are in traffic only for 1.5-2 hours, and they spend 90% of their time in parks on average during the day. Thus, the other significant problem related to urban transportation arises as to where and how these vehicles are to be parked (Yardım & Ağrikli, 2005). When adequate and correct planning is not done in this regard, the roads that need to fulfill the functions of access and movement turn into parking areas, and the traffic problem in the cities becomes even worse. Therefore, sustainable transportation and use of space/land have been at the forefront of the most important issues for cities and local governments for almost 40 years (Buehler & Pucher, 2011). Many OECD (Organization for Economic Cooperation and Development) countries have developed various policies to use the limited city areas more effectively and to provide sustainable urban transportation. Especially developed OECD countries promote sustainable transportation options such as walking, cycling, and public transport to reduce the number of individual motor vehicles. As a result of these efforts, the average annual increase in motor vehicles in OECD countries was 3.9% in the 1970s but declined to 0.9% in the 2000s (Buehler et al., 2017). Despite this, the number of vehicles continues to increase every year. On the other hand, Turkey has higher growth rates as a developing country. According to TUIK data, the annual average increase in motor vehicles in Turkey was 4.7% between 2002 and 2010, while it was 3.7% between 2011 and 2018 (TUİK, 2019).

Under these conditions, while the need for parking in cities is increasing daily, the available empty spaces are gradually decreasing. Accessible real estate areas are small and expensive, especially in city centers. The necessity of using these small but precious areas more beneficially has made the studies on park areas a critical issue for local governments (Ibeas et al., 2011). In this context, many parking space models (Ahamed & Jovanov, 2009) and supporting parking fee policies (Marsden, 2006) have been developed to solve the parking problem in cities, or at least to relieve cities in this regard. Although some improvements have been achieved thanks to these studies,

the parking problem still continues in most cities. However, the complaints of citizens living in cities about finding parking spaces are increasing. In addition, the time spent searching for a parking space is also an important complaint issue (Jog et al., 2015). Recent surveys on parking problems show that the complaint rate reaches 90% in metropolitan areas (Downtown Parking Survey, 2017).

In today's conditions, where traditional car parks are insufficient, new generation car park systems (such as mechanical, semi-automatic, and fully automatic car parks) have been developed, which enables more efficient use of limited spaces with the help of technological developments. Among these, Fully Automatic Parking Systems (FAPS) offer the most effective solution to the parking lot problem, in which sensor technology is used, and the parking process is carried out with automatic carriers (such as elevators and robots). However, the number of scientific studies on the performance and efficiency of these systems, which can still be considered in the development stage, is very few, both in Turkey and the world. Furthermore, when the scientific literature on the subject is examined, it is seen that the number of studies on the operation management of the system is relatively low, although there are various studies on the design of FAPS and the technologies to be used in FAPS. In this context, studies are needed to improve or develop the systems that plan and control the operations of these systems.

1.1 Motivation

As everyone can realize that car parking problem in cities is becoming one of the most troubling problems for both citizens and governances. The reason is the rapid growth in the urban population and, consequently, a dramatic increase in car numbers. Buehler et al.'s research (2017) showed in Figure 1.1 that the motorization rate in OECD countries is still increasing even though the growth rate has slowed since the 1980s. In contrast to this increase, the available space in cities is dramatically decreasing, and limited space remains even for residents.

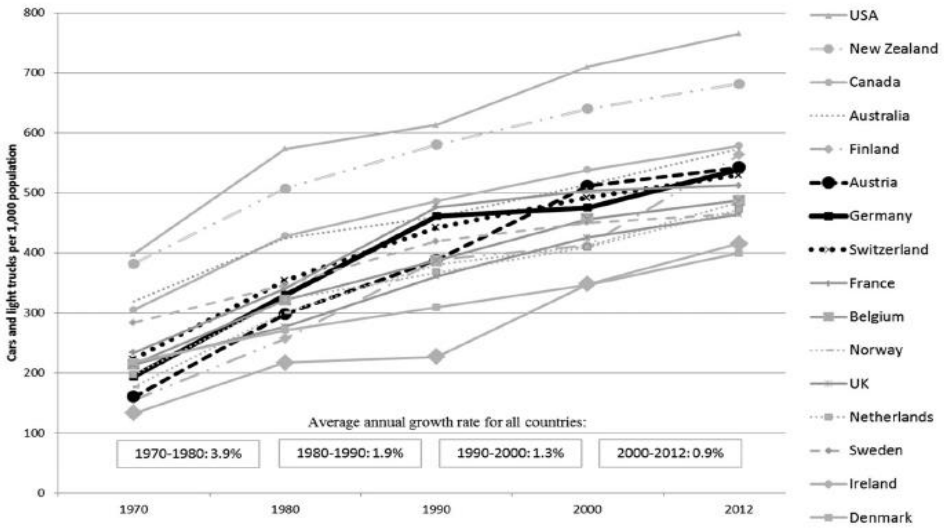


Figure 1.1 The trend in motorization in OECD countries, 1970-2012 (Buehler et al., 2017)

The limited space utilization issue and the sustainable concerns have forced most of the OECD countries to spend their effort on reducing the motorization rate. Sustainable transport and land use have been more important issues for cities almost for 40 years (Buehler & Pucher, 2011). Significantly decreased motorization growth rate in developed countries resulted from encouraging sustainable transportation modes like walking, cycling, and public transport. As a result of these efforts, the average annual increase in motor vehicles in OECD countries was 3.9% in the 1970s but declined to 0.9% in the 2000s (Buehler et al., 2017). Despite this, the number of vehicles continues to increase every year.

On the other hand, Turkey has higher growth rates as a developing country. According to TUIK data, the annual average increase in motor vehicles in Turkey was 4.7% between 2002-2010 and 3.7% between 2011-2018 (TUİK, 2019). Under these conditions, while the need for parking in cities is increasing daily, the available empty spaces are gradually decreasing. Thus, these efforts are still insufficient, and the existing cars cause severe traffic congestion and city parking problems. Therefore, parking issues and parking zone research have gotten more attention and become essential topics for researchers and governments (Ibeas et al., 2011). With this motivation, so many parking models (Ahamed & Jovanov, 2009) and pricing policies (Barter, 2012; Marsden, 2006; Pierce et al., 2015; Van Ommeren et al., 2011; R. Zhang

et al., 2016) are proposed and implemented to relieve the cities about this problem. Most of these studies have attempted to handle the parking problems arising in cities by considering traditional parking systems, which are summarized as follows:

- Flat parking
  - On-Street
  - Off Street
- Multi-story parking

Despite these research and efforts, the parking issue is still unresolved in cities. Especially considering the limited area in highly populated cities, traditional flat systems are unable to meet the demand due to the large space they need. The need to utilize the scarce real estate space in downtowns leads to building multi-story parking structures (Pypno, 2008). Such systems offer a certain degree of relief by making it possible to use the vertical space instead of the horizontal space. However, a significant area is still wasted for large parking slots, access ramps, stairs, or elevators in such conventional systems. Consequently, citizens still complain about insufficient parking space areas in most cities. These complaints reach 90 % of metropolitans. Some of the recent surveys related to parking concerns are presented below.

- North Sydney – Australia (*Survey of North Sydney*, 2016).
  - 57% of citizens complain that there are not enough parking lots.
- Portsmouth – England (*Survey of Portsmouth*, 2017).
  - 71% of citizens complained about off-street parking availability.
- Wolfville – Scotland (*Survey of Wolfville*, 2015).
  - 83% of citizens complained about finding a sufficient parking area.
- Washington – USA (*Survey of Washington*, 2017).
  - 90% of citizens complained about the difficulty of finding a parking area.
- India – parking issues (Jog et al., 2015)
  - 49% of citizens complained about space availability.
  - 40% of citizens complained about searching for an available parking lot.
  - 11% of citizens complained about security concerns.

As mentioned before, rapid growth in urban population and dramatic increase in vehicle numbers cause traffic jams and severe vehicle parking problems. Especially considering the limited area in highly populated cities, traditional flat systems cannot meet the demand due to the large space they need. Although multi-story parking structures constructed in downtowns provide a certain degree of relief, a significant area is wasted for large parking slots, access ramps, stairs, or elevators in such conventional systems. In addition, these systems still lead to wasting a considerable amount of time and fuel, leading to pollution and vehicle wear due to the search for available parking slots.

In this case, all clues clearly show that traditional parking systems are inadequate since they require very large spaces. Moreover, these systems waste considerable time and resources (such as gas and fuel), resulting in pollution and vehicle wear while searching for available parking slots. Therefore, many new technologies have been developed (Olia et al., 2016; Y. J. Wu et al., 2015) to avoid such problems. The top of these solutions is the Fully Automated Parking Systems (FAPSs), wherein sensor technology is utilized, and the parking process is carried out with automatic carriers (robots). FAPS integrates software systems with mechanical lifts and pallets to store and retrieve vehicles in multi-level modular garages. FAPSs use vertical and horizontal space efficiently and utilize up to 84% of total space by staking the cars together more closely than conventional parking systems (Serpen & Dou, 2015). This way, FAPSs utilize limited areas more efficiently and provide an environment-friendly solution.

Interest in FAPS, which offers an effective, economical, and environmentally friendly solution to the parking space problem in cities, is increasing worldwide. Mainly thanks to the technological developments in the last twenty years, FAPS has started to take place in our daily lives as a new generation of parking systems. In addition to Japan and Korea, the prevalence of these systems continues with increasing momentum in countries such as China and India, mainly due to the population density in cities. Furthermore, the interest in these systems in Europe and America has increased since the 2000s. For example, the total number of FAPS established in the USA between 2000 and 2012 was 15, 6 of which were in 2011. It is possible to talk

about the same trend in Turkey. Turkey's first and Europe's largest FAPS was established in Istanbul in 2001 (Parkolay, 2018). This garage was followed by the one established in Istanbul in 2010, Izmir in 2014, and Manisa and Balikesir in 2016. There are currently five commercially used FAPS in Turkey (Parkolay, 2019). However, this number will undoubtedly increase. İSPARK, which seeks solutions to the parking problem in Istanbul, plans to establish fully automatic parking lots by making considerable investments in addition to its semi-automatic parking systems (İSPARK, 2014a, 2014b). Figure 1.2 shows different types of FAPSs (a,b,c has rectangular, and d has a circular design), and it can be seen how efficiently the vertical and horizontal space is used.

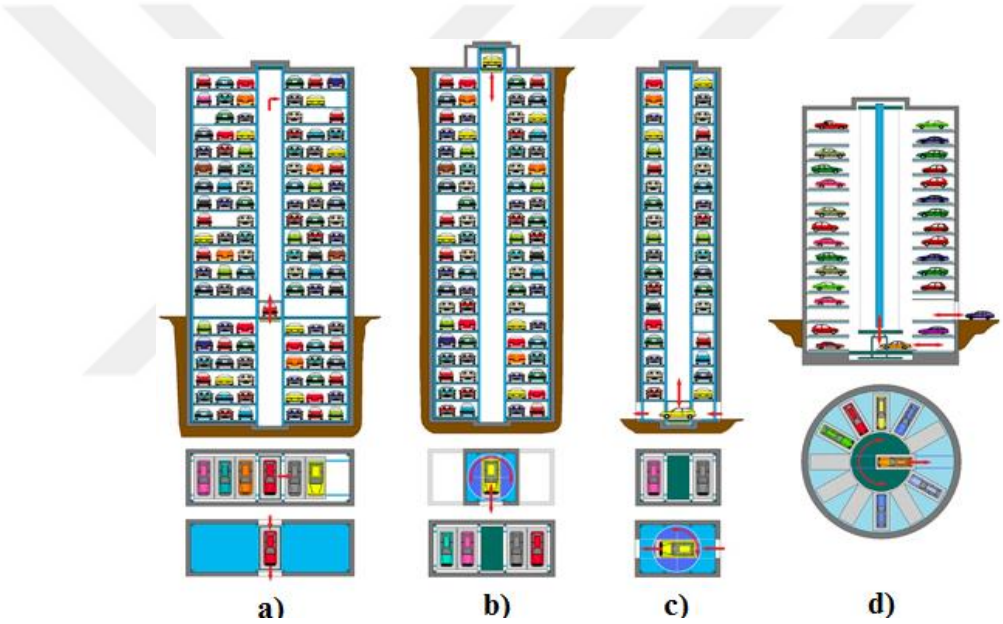


Figure 1.2 Different FASPs that have different designs and slot layouts (GIVT, 2017)

In addition to maximizing space utilization in FAPSs, time and energy savings are ensured simultaneously by avoiding available slot searching. This way, FAPSs provide an effective and environmentally friendly solution to the car parking problem arising in cities. Compared with conventional parking lots, some advantages of FAPSs can be listed as follows.

- More efficient land use
- Time and fuel savings

- Energy saving because no lighting and ventilation system is needed
- Low operating costs
- Inherent security, lower risk & liability

As a result of these benefits, mainly due to efficient space utilization, interest in such systems is increasing all over the world. However, some operational issues have resulted in high fees and long service times. In order to make these systems more preferable and create the desired impact in the cities, these concerns should be addressed. In this manner, FAPSs will provide many advantages for the public and convenience for citizens.

Considering the limited number of studies that deal with planning, scheduling, and control of FAPS operations, academic research is required to increase the operational efficiency of FAPSs. Thus, this thesis aims to develop methods and algorithms that improve the performance of FAPSs by improving operational efficiency.

1.2 Importance of the Study

The service times and costs of FAPSs are directly related to how effectively these operations are performed. In practice, one of the most important problems of these systems is the long wait for customers to receive service and relatively high parking fees. This situation causes FAPSs to be less preferred. However, the efficient use of these systems; will create many positive social, economic and environmental effects by saving time, energy, and cost. In this context, the current thesis's general purpose is to contribute practically and academically to this issue by developing methods and algorithms that can improve the operational planning and control of FAPS and improve them. Thus, the efficient operation of these systems, which offer smart and sustainable solutions for the parking problem in cities, will contribute to the spread of FAPS.

Today, where full automation is aimed at Industry 4.0, the importance of intelligent systems where big data (Big Data) is used and more effective decisions are made thanks to the Internet of Things/IoT has increased. FAPS's technological infrastructure

is very convenient for developing an application. Therefore, the study's main purpose is to develop an artificial intelligence algorithm that proactively places vehicles in the most appropriate place in the system, using the information and data at hand.

As one can see from the related literature, most related studies have focused on the design of FAPS and the technologies used in these systems. Nevertheless, a few publications focus on operational issues such as low operational efficiency and long service times.

Considering all these, we can summarize the aims of the thesis and the steps to be followed in line with these aims as follows:

- First, a dynamic algorithm will be developed based on heuristic rules that can plan and control operations according to the system's complex and dynamic structure.
- As mentioned before, there is operational uncertainty in FAPS due to the stochastic behavior of customers, and therefore the efficiency of operational decisions is very low. By managing this uncertainty effectively and efficiently, statistical analyses will be made about the behavior of customers (arrival times, parking times, and departure times) to provide sufficient control to the system in light of healthy data.
- The innovative optimization approach developed to place the vehicles in the right place in the system constitutes the most crucial stage of the study (see Method). At this stage, an artificial intelligence algorithm will be developed that places the vehicles in the most appropriate place by using the system and customer behavior information with a proactive planning approach.
- In the final stage, a simulation study will be conducted to compare the performance of the developed artificial intelligence (optimization-based) algorithm with the classical (rule-based) algorithm developed in the first stage and used in practice.

- Thanks to this new algorithm developed for the operational planning and control of FAPS, significant improvements are expected in the system, especially in terms of customer satisfaction and operating costs.

In addition to the aims of the thesis, the goals can be listed as follows:

- For a more concrete and quantitative performance evaluation within the study's scope, customer waiting times and total distance covered in the system will be considered performance criteria of interest.
- It is seen that reducing customer-waiting times will increase customer satisfaction. On the other hand, reducing the total distance covered by the carriers in the system while conducting the operations will increase the speed of the system and thus customer satisfaction. In addition, reducing the total distance traveled will reduce the wear rate, consequently extending the system's life and reducing maintenance and repair costs of the system.
- The procedures and algorithms developed as a result of the research are aimed to achieve an improvement (decrease) of 5%-10% in the average waiting time of customers and an improvement (reduction) of 2%-3% in the total distance covered in the system.
- When considering the dynamic nature of the problem and the necessity of producing fast solutions for real-time control, it is aimed that the developed algorithm makes each operational decision within seconds (0-3 seconds).
- In order to strengthen the practical contributions of the study, the developed methods and algorithms will be coded in a standard programming language, thus aiming to provide flexible and easy use.
- In this frame, this thesis is planned to provide an academic contribution by publishing practical and scientific studies on the efficient use and dissemination of the systems mentioned above.

With this thesis, the problem in question will be considered an optimization problem, and the necessary solution methods will be developed, contrary to the existing practices and current studies on the subject. When the difficulties arising from

the combinatorial nature of the problem are added to the uncertainties regarding the inputs and outputs of the vehicles, it is understood that the problem cannot be solved with exact solution methods and/or it is quite challenging to solve. However, it has been reported in studies (Blum et al., 2011; Blum & Roli, 2003) that meta-heuristic methods have yielded very successful results. In addition, dynamic optimization techniques should be used when planning operations in a dynamic environment (Baykasoğlu & Ozsoydan, 2014; Baykasoğlu & Ozsoydan, 2017; Baykasoğlu & Ozsoydan, 2018).

This thesis aims to develop methods and algorithms that address these joint operational planning and control problems to improve the performance of FAPSs by increasing operational efficiency. Furthermore, it is clear that allocating and retrieving problems bring about several other challenging problems such as assignment, sequencing of parking robot movements, and real-time task assignments. In this context, it is clear that the mentioned operational problems (scheduling of parking robot, assignments to parking slots, task assignments) in FAPSs are combinatorial and they include uncertainty, which means that developed algorithms should be able to run under both dynamic and stochastic conditions to generate real-time solutions. For this purpose, heuristics and metaheuristics are employed to solve the mentioned problem in the present study.

In the light of this information, the scientific and technological original value of the study can be summarized as follows:

- Almost all of the existing studies on FAPS have focused on design and hardware issues to improve the performance of parking systems, and operational efficiency/effectiveness has been ignored. This study aims to operate the mentioned systems more efficiently by emphasizing the operational problems. Thus, an essential scientific theoretical contribution will be made to the subject.
- It has been observed that no optimization algorithm is used for decisions such as the allocation of vehicles and the sequencing of operations in the

aforementioned scientific literature and the software used. Therefore, within this study's scope, an optimization study will be carried out with an innovative approach, mainly to allocate the vehicles to the ideal place in the system.

- The proposed new approach also enables proactive allocation by considering the system's dynamic nature and the stochastic behavior of customers.
- Designing the artificial intelligence algorithm that is planned to be developed so that it can be integrated into existing commercial software and work in harmony with system data is among the practical contributions of the study.
- The proposed study targets more environmentally friendly and less energy-consuming FAPSs. At the same time, this study aims to increase customer satisfaction and facilitate the spread of FAPS. In this context, it is anticipated that the proposed study may have positive socio-cultural, economic, and environmental contributions.

The dissemination of energy and environment-friendly studies will have positive social and economic returns. It is thought that the proposed study has this feature. Furthermore, it is thought that the operational planning and control systems to be developed within the proposed study's scope may contribute to the efficient operation and dissemination of FAPS.

It can be concluded that the simultaneous use of technology, data, knowledge, and artificial intelligence, especially in the era of Industry 4.0, will increase the operational efficiency and efficiency of FAPS. As a result, it is thought that FAPSs will positively affect economic, socio-cultural, and environmental issues. Also, the scientific research carried out in this study's scope will contribute to relevant literature.

1.3 Outline of the Thesis

The thesis consists of four main phases: (i) motivation and scope determination, (ii) problem description, (iii) data gathering, and finally, (iv) analysis and discussion. First, a comprehensive literature review was carried out as the first phase of the thesis. Then, based on the relevant literature, the scope of the thesis, the problem's definition, and

the thesis's principal components were determined. The general frame and components of the thesis can be seen in Figure 1.3.

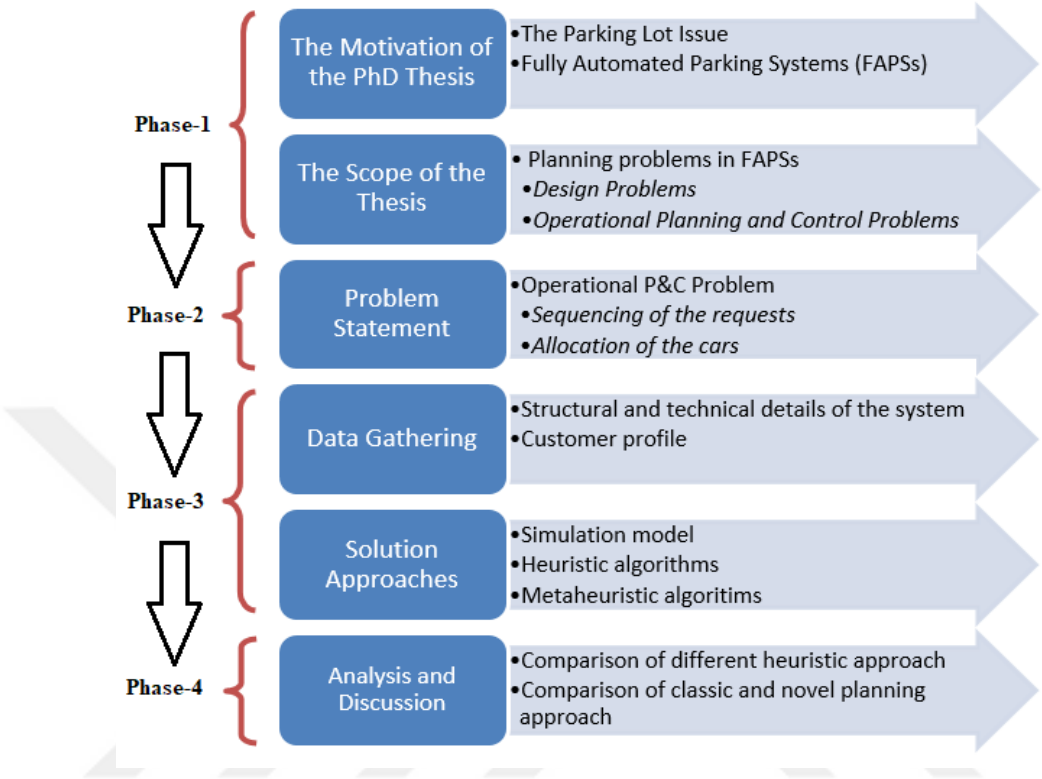


Figure 1.3 The general frame and components of the Ph.D. thesis

The research motivation and scope of the thesis were discussed extensively in the first stage. Besides, the problem was described depending on the aim and frame of the thesis. The research methodology, modeling approaches, system parameters, performance criteria, and potential planning approaches were clarified through this period. After the constitution, the general structure of the thesis and the research methodology, the system parameters, performance criteria, and the potential planning approaches that will be utilized for operations of FAPSs have been clarified.

As stated before, the thesis aims to develop methods and algorithms that improve the performance of tower-type FAPSs by increasing operational efficiency. For this purpose, the thesis utilized and analyzed two different planning approaches that enable the plan and control of FAPSs' operations. The first and conventional planning approach is based on dispatching rules and is widely used in practice, while the second

and novel planning approach is based on a new allocation procedure using optimization techniques.

The operational planning approaches are discussed in two main headings as (i) rule-based planning and (ii) optimization-based planning. Both planning approaches were tested on tower-type, fully automated parking structures in the scope of this thesis. Figure 1.4 present the general structure and flow of the thesis.

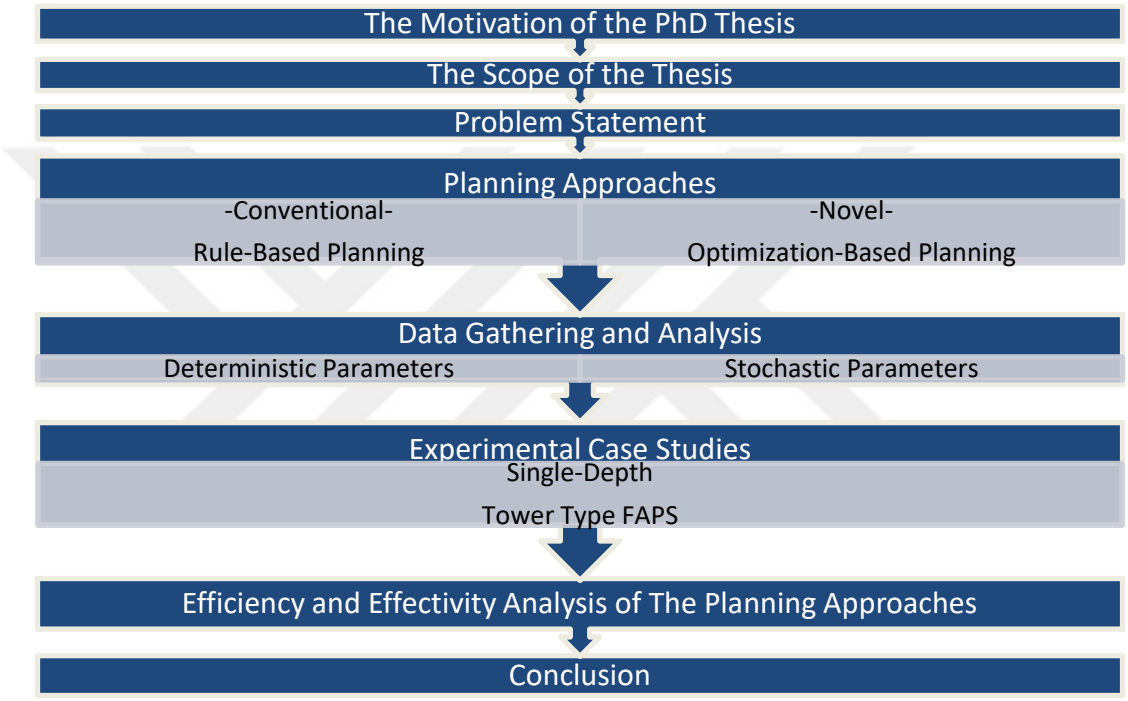


Figure 1.4 The general structure and flow of the Ph.D. thesis

A simulation of the rule-based planning approach and extensive analysis of the performance of the predetermined rules under different conditions were carried out. Additionally, the detail of the optimization-based planning approach based on a novel allocation procedure was determined. Finally, as an extension of the analysis, a more detailed investigation of the performance criteria of the proposed planning approach was made. On the other hand, the efficiency of the proposed optimization-based algorithm is also analyzed in terms of the time consumed and the solution quality measured by system performance metrics.

Based on this structure, the thesis is organized into seven chapters. The motivation and importance of the thesis have been discussed in the first chapter as the introduction section. The details of the remaining six chapters are given below.

Chapter 2: A comprehensive literature review and analysis were carried out in the second section of the thesis. Based on the relevant literature and observations on systems, a detailed Fully Automated Parking System (FAPS) description and classification were made. Different types of FAPSs were investigated in terms of technical and operational aspects, and potential research areas that could increase operational efficiency and effectivity are revealed in this chapter. In addition, the definition and classification of the problems which built the base of the thesis were introduced in this section. The concerns related to FAPSs mainly consist of planning problems. Planning problems can basically be grouped into two headings design and operational planning and control problems. In this regard, the Ph.D. thesis considers the latter group of problems, and the main aim of the thesis is to develop methods and algorithms that improve the performance of FAPSs by increasing operational efficiency.

Chapter 3: The thesis considers the operational planning and control problems of FAPS, and the main aim of the thesis is to develop methods and algorithms. Thus, the general structure and characteristics of operational planning and control were introduced in this chapter. Furthermore, some details related to the motivation and a detailed description of the problem were shared. Mainly, the standard operational planning and control problems, which consist of *assignment/allocation* and *request sequencing* decisions, are addressed in the scope of this thesis. Furthermore, a literature review was carried out on closely related studies considering the planning problems of FAPSs. Finally, the gap in the literature and the contribution of this study was presented in the last section of this chapter.

Chapter 4: In this section, the research methodology, modeling approaches, system parameters, performance criteria, and potential planning approaches were clarified. Additionally, the data collection process was introduced. In detail, the structural and

technical details related to Fully Automated Systems (FAPSs) have been obtained, and the customers' behaviors have been analyzed and modeled as a crucial system parameter. This way, a hypothetical case study was conducted to analyze the efficiency of different dispatching rules. As an extension of the analysis, that paper provided a more detailed investigation of the performance criteria. This chapter mainly investigated the correlation between two performance measures (customer waiting time and total distance traveled in the system). In detail, two research questions about the results and assumptions of the studies were raised.

- Is there a correlation between the system's two main performance metrics (customers' waiting time and transfer distance)? Consequently, can the minimization of the transfer distance be utilized as the sole objective of the optimization algorithm?

The results show that minimizing the traveled distance can be adequate for the optimization process as a sole objective depending on the positive correlation approved by statistical analysis. Additionally, the simulation model was developed in order to test the developed algorithms and to evaluate the performance of the dispatching rules and heuristics. Meanwhile, an essential part of the study, customer structure (behaviors) highly affect the performance of the proposed dispatching rules, were statistically analyzed and conveniently embedded in the simulation model. For this purpose, the customer data that ensures the results' validity and reliability were obtained from a real system. Finally, the verification and validation of the simulation model were investigated in the last section of the chapter.

Chapter 5: On the one hand, different dispatching rules that can be utilized for *assignment/allocation* and *request sequencing* decisions, which are common planning problems in FAPSs, were identified. In other words, different algorithms that utilize different dispatching rules were developed to carry out the operations in FAPSs. On the other hand, the performances of dispatching rule combinations were compared in terms of customer waiting times and operational efficiency. The results demonstrated that the combination of the NAS (Nearest Available Slot) as allocation rule and FCFS

(First Come, First Served) as sequencing rule outperforms all other combinations. Also, the results showed that the main differences between the results originate from assignment/allocation rules. The analysis showed that allocation decision significantly impacts the operational efficiency in FAPSs. Conclusively, the importance of allocation decisions was proven via this study. These findings implied that the research related to the operational efficiency of FAPSs mainly focus on assignment/allocation problem as they dramatically affect all system efficiency. These findings approved a need to consider allocation decisions as an optimization problem.

Chapter 6: Particularly, system parameters, performance criteria, and the potential planning approaches that will be utilized for operations of FAPSs had clarified in the second chapter. The operational planning approaches are discussed in two main headings as (i) rule-based planning and (ii) optimization-based planning. Both planning approaches were tested on tower-type, fully automated parking structures in the scope of the thesis. Thus, in the previous chapter, the performance of the rule-based planning approach, and in the current chapter, the performance of the novel optimization-based approach was investigated on tower type FAPS having single-depth slots as the experimental studies. This section presented the detail of the optimization-based planning approach based on a novel allocation procedure, and the results obtained on tower type FAPS having single-depth slots were shared. The simulation results showed that the proposed allocation procedure could be executed in a reasonable time; thus, the novel optimization-based planning approach is implementable in real systems. Besides, the improvements in performance criteria proved that the capability of the novel approach is quite promising.

Chapter 7: Finally, the summary of the research and the findings are introduced in the seventh section. Additionally, future works that will improve the research are discussed in this last chapter.

CHAPTER 2
FULLY AUTOMATED PARKING SYSTEMS

Sustainable transportation and use of space/land have been at the forefront of the most important issues for cities and local governments for almost 40 years (Buehler & Pucher, 2011). Many OECD (Organization for Economic Cooperation and Development) countries have developed various policies to use the limited city areas more effectively and provide sustainable urban transportation. The developed OECD countries promote sustainable transportation options such as walking, cycling, and public transport to reduce the number of individual motor vehicles. As a result of these efforts, the average annual increase in motor vehicles in OECD countries was 3.9% in the 1970s but declined to 0.9% in the 2000s (Buehler et al., 2017). Despite this, the number of vehicles continues to increase every year.

Under these conditions, while the need for parking in cities is increasing day by day, the available empty spaces are gradually decreasing. Accessible real estate areas, especially in city centers, are pretty small and very expensive. The necessity of using these small but precious areas more beneficially has made the studies on park areas a fundamental issue for local governments (Ibeas et al., 2011). In this context, many parking space models (Ahamed & Jovanov, 2009)and supporting parking fee policies (Marsden, 2006) have been developed to solve the parking problem in cities, or at least to relieve cities in this regard. Although some improvements have been achieved thanks to these studies, the parking problem continues in most cities. However, the complaints of citizens living in cities about finding parking spaces are increasing. In addition, the time spent searching for a parking space is also a critical complaint issue (Jog et al., 2015). Recent surveys on parking problems show that the complaint rate reaches 90% in metropolitan areas (Downtown Parking Survey, 2017).

In today's conditions, where traditional car parks are insufficient, new generation car park systems (such as mechanical, semi-automatic, and fully automatic car parks) have been developed that enable more efficient use of limited spaces with the help of technological developments. Among these, Fully Automatic Parking Systems (FAPS)

offer the most effective solution to the parking slot problem, in which sensor technology is used, and the parking process is carried out with automatic carriers (like elevators and robots). However, the number of scientific studies on the performance and efficiency of these systems, which can be considered at the stage of development, is very few, both in Turkey and the world. Furthermore, when the scientific literature on the subject is examined, it is seen that the number of studies on the operation management of the system is considerably low, although there are various studies on the design of FAPS and the technologies to be used in FAPS. In this context, studies are needed to improve or develop the systems that plan and control the operations of these systems.

In recent years, it has been understood that the parking problem, which has become one of the most critical problems related to urban transportation for citizens and administrators, cannot be solved with traditional parking systems. Although multi-story car parks have solved the problem to a certain extent by enabling more efficient use of limited spaces in city centers, a significant portion of the available space is still reserved for access ramps, stairs, and elevators in such systems. In addition, as in all conventional systems, searching for parking spaces and parking operations (parking and exiting the parking space) in such systems cause waste of time and fuel; This situation has various negative consequences for both the environment and vehicles.

Today, with the help of technological developments, various systems have been developed that use the field more effectively and avoid these problems. Among these, Fully Automatic Parking Systems (FAPS), which offers the most effective and environmentally friendly solution to the parking lot/area problem, appear as a new generation parking system. In these systems, which use sensor technology, all parking operations (such as turning the vehicle, lifting, transporting, and placing) are carried out with automatic carriers, namely robots. For this reason, FAPS can also be called robotic car parks or robotic valet systems.



Figure 2.1 An example of FAPS structure (Terra Nova Ventures LLC, 2019)

FAPSs are intelligent systems that integrate mechanical systems (like elevators and pallets) with various software to store and retrieve vehicles in multi-story modular garages. Structurally similar to warehouses, these systems consist of shelves and cells (slots) where the parked vehicles are placed. As can be seen in Figure 2.1, these systems do not require large parking bays and access ramps, stairs, and pedestrian elevators. In addition, vertical and horizontal space can be used more efficiently, thanks to robots that allow stacking vehicles closer to each other compared to traditional parking systems. Thus, a very large part of the available space in FAPS can be used to park vehicles. For example, while 41% of the horizontal (surface) area is used for parking vehicles in a conventional parking system, this ratio can be increased up to 84% with a FAPS (Serpen & Dou, 2015). In addition, the fact that the parking process is done with the help of robots saves time and fuel.

On the other hand, there is no need for lighting and ventilation systems in car parks also saves energy (Jog et al., 2015). Thus, FAPSs can be operated with advantageous costs while offering an environmentally friendly solution to the parking problem. In addition, FAPS offers a security advantage regarding risks that both vehicles and drivers may encounter (accident, theft, natural disasters). As a result, the benefits of FAPS can be summarized as follows when compared to traditional parking lots:

- ✓ More effective/efficient use of space
- ✓ Time and fuel savings
- ✓ Energy saving
- ✓ Lower operating cost
- ✓ Safer structures

In this context, interest in FAPS, which is seen as the future of parking systems, is increasing worldwide (Rosenblum et al., 2020). In addition to Japan and Korea, the number of these systems is constantly increasing in countries such as China and India due to the population density in their cities. Furthermore, in Europe and America, the interest in these systems, which are used to meet the parking needs of the buildings, has increased since the beginning of the 2000s. Although the initial installation cost of FAPS is higher than traditional car parks, as mentioned in the previous section, FAPS becomes a more advantageous option when space savings and operating costs are considered (UCLA, 2020; Yardım & Ağrikli, 2005).

2.1 Types of Fully Automated Parking Systems

In line with the needs and technological developments, many FAPS studies with different structural and functional designs have been developed and implemented by the manufacturers in the sector. These structures' initial setup costs, capacity, and operational speeds naturally differ due to their transportation systems and vehicle storage forms. Therefore, although FAPS can be classified according to their different features, they are generally classified according to their transport systems. In this context, the most common types of FAPS are listed and briefly explained below (Fata Automation, 2020b).

Tower/Lift Parking Systems: Tower/Lift type systems generally consist of a vehicle lift with parking cells on the right and left sides. In these systems, their drivers leave vehicles on the elevator in the transfer cabin. After the vehicles are appropriately rotated for the parking process, they are placed in an empty cell on the right or left side of the elevator after being taken up/down to the floor related to the elevator. The

retrieval process oppositely takes place: after the vehicle is taken and brought to the transfer cabin by elevator, it is delivered to the driver in a position to exit.

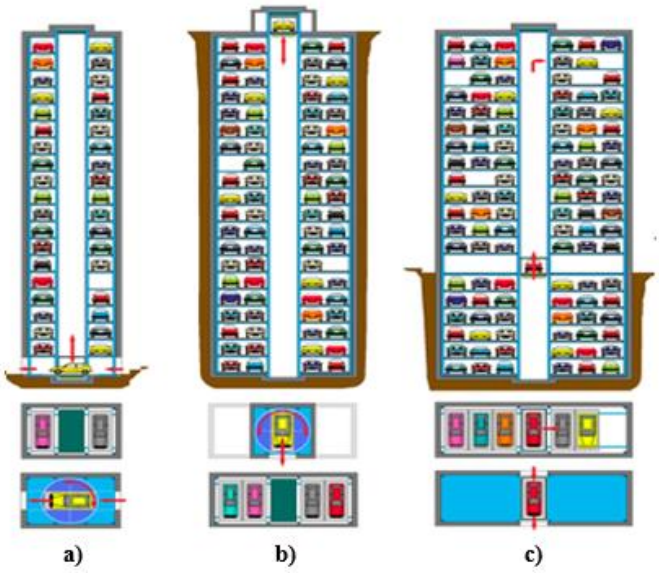
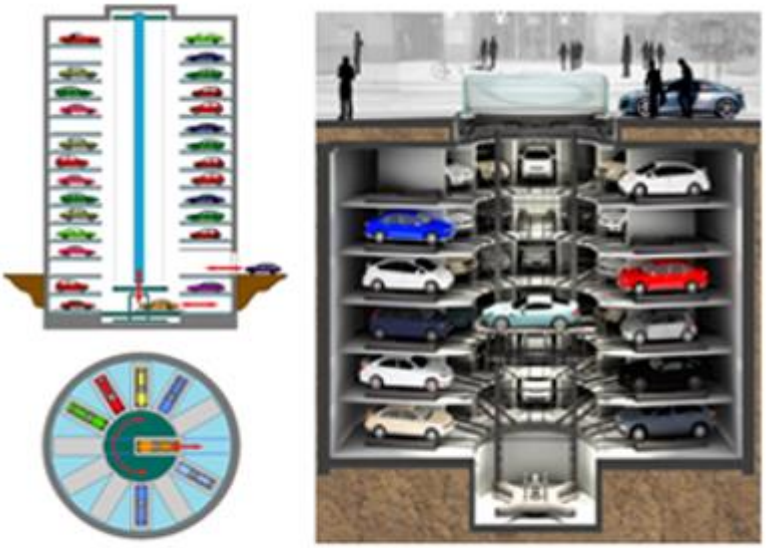


Figure 2.2 Tower type FAPS with different designs (GIVT, 2018)

Figure 2.2 shows tower-type fully automatic car park structures with different designs. These systems, which consist of a single corridor and elevator, can be entirely built above ground (2.2a), completely underground (2.2b), or partially underground (2.2c) (Munich, 2020). In addition, the number of cells on each floor reached by elevator may vary according to the need. In order to increase the capacity, deep rack systems (2.2b, 2.2c) can be designed so that more than one vehicle can be parked on the right and left sides of the elevator. The installation cost of tower-type systems is relatively lower than other systems. Since there is only one elevator in these systems, which can use the area quite effectively, the process/operation capacity of the system is low. Therefore, more than one tower can be built side by side to increase operational capacity (Automated Robotic Parking, 2018).

Silo Parking Systems: Silo-type systems are cylindrical systems with a single centrally located mechanism for parking and retrieving vehicles. Although these systems are similar to tower-type systems in general, they differ in terms of the shape of the structure and the transport system used. While the vehicles are parked on the outer

surface of the cylindrical structure, there is a mechanism in the center of the structure that can simultaneously perform the up/down and circular movements of the vehicles (see Figure 2.3). Thus, the transition from one cell to the next can occur quickly (Fata Automation, 2020b).



a) (GIVT, 2018) **b)** (AIM, 2019)

Figure 2.3 Silo Type FAPS with different designs

Although more than one platform can be added to the central transport system, only one vehicle can usually be parked or retrieved at a time in silo-type systems. As in tower-type systems, more than one system can be installed side by side to increase the processing capacity.

Crane Parking System: In such systems, parking operations are carried out with the help of cranes located in the center of the structure, which can move vertically and horizontally. As seen in Figure 2.4, while the crane mechanism moves horizontally on the rails on the floor and ceiling, the elevator/platform it is on also moves vertically. This way, vehicles are delivered to the designated parking place (cell) very quickly (Pari Parking, 2019).



a) (Auto Evolution, 2019) **b)** (Pari Parking, 2019)

Figure 2.4 Crane type FAPS with different designs

Shuttle Parking Systems: Elevators are used for transportation between floors in shuttle-type systems. Shuttles moving on horizontal strips are used to take the vehicles from the elevator to the relevant floor and place them in a suitable place. The shuttles move horizontally to reach the cells on the floors and leave the vehicle. Different equipment such as robots, pallets, and conveyor belts can be used to place the vehicles on the shuttle, move them and leave them in the parking lot (Fata Automation, 2020b).



a) (Karin Tetlow, 2012) **b)** (Industriais, 2019)

Figure 2.5 Shuttle type FAPS with different designs

Depending on the size of the building, there is usually a shuttle on each floor, with a certain number of elevators. Therefore, it can be said that the processing capacity of these systems is higher than other systems. In addition, although there is usually one parking space on either side of the shuttle lane (see Figure 2.5a), a second or even a third row can be added to the sides of the lane to provide more parking space (see Figure 2.5b). Therefore, these systems, which are very effective in processing capacity and efficient use of space, may have a slightly higher cost of establishment than other systems (Automated Robotic Parking, 2018).

Puzzle Parking Systems: Among all the parking systems, the systems with the highest density of vehicle parking are the horizontal puzzle-type systems (Fata Automation, 2020b). These fully automatic systems, which can effectively use approximately 95% of the surface area for parking, should not be confused with mechanical or semi-automatic vertical puzzle systems. These systems, which can be installed even in tiny areas, basically consist of pallets moving on the surface and cells where these pallets are placed (see Figure 2.6). Pallets are maneuverable in four directions. The pallets move by sliding from one cell to another and reach their final destination (such as an elevator, designated parking lot, and entry-exit room). For these movements to be possible, there must be at least one empty cell in the system, and the path/route must be created to enable the pallets to reach the desired point. This puzzling problem to be solved gives the system its name (Serpen & Dou, 2015).



Figure 2.6 Puzzle type FAPS (Fata Automation, 2020a)

One of the most extensive advantages of the system consisting of moving pallets is that it provides flexibility to the structure. The structure/building need not be square or rectangular as long as the pallets can be maneuvered in any direction. However, the puzzle-type system is one of the systems with the highest processing capacity. The number of empty cells in the system, elevators, and entry/exit points are the parameters used to adjust the processing capacity. In addition to these advantages, the higher cost of installation and operation compared to other systems and the more complex parking/retrieval processes can be counted among the disadvantages of this system.

AGV Parking Systems: Although AGV (Automated Guided Vehicle) technology has been used in warehouses for many years, the idea of using it for parking vehicles is

considered relatively new. AGVs, which are used to move pallets carrying vehicles, are not restricted to a particular direction or lane, unlike carriers in other systems (Fata Automation, 2020b). In these systems, vehicles can be picked up from their location by any AGV to be parked or delivered and transported to their destination by any route (see Figure 2.7).



Figure 2.7 AGV parking system (Mhedemag, 2019)

The fact that any AGV can transport any vehicle. AGVs can use the same road simultaneously and are not limited to a single route. These features provide a great deal of flexibility to the system. Therefore, the system's processing capacity can be notably high depending on the number of AGVs.

2.2 The Design Features of FAPSs

The design decisions of FAPS are taken by considering many issues/criteria such as optimum capacity, usage density, and system performance (Serpen & Debnath, 2019; G. Wu, Xu et al., 2019; G. Wu, Zou, et al., 2019). Apart from the design mentioned above objectives, the cost, the structural conditions of the study area, the relationship of the parking lot with the traffic flow, the resources that can be used, and the environmental and legal regulations are also issues to be considered during the design phase (Can et al., 2019). When considering the needs, budget, and physical and technical constraints, decisions are made regarding the system features listed in Table 2.1 for the ideal design (Hrabovský, 2019; Nayak et al., 2013; Serpen & Debnath, 2019; G. Wu, Xu et al., 2019; G. Wu, Zou, et al., 2019).

Table 2.1 Basic classification of FAPS based on design features

*Design features	Possible options
The shape of the garage	Circular vs. rectangular
Transport system	Silo, tower, shuttle, crane, puzzle, AGV
Shelves depth	Single vs. multiple
Number of the robots	Single vs. multiple
Number of the entrance/exit point	Single vs. multiple

*There is no particular hierarchy among the features; each depends on another to a certain degree.

Issues such as the shape and layout of the building and the transport system to be used constitute the major design decisions of FAPS (Hrabovský, 2019; Nayak et al., 2013; G. Wu, Xu et al., 2019). In addition, the number of carriers (such as AGVs, elevators, and robots) to be used in the system, the number of corridors, and the number of entry/exit points of the building. It is among other important design decisions (Debnath & Serpen, 2015; Serpen & Debnath, 2019). Although there is no definite hierarchy among decisions, design decisions are interconnected to a certain extent. For example, a circular structure is built if a silo-type transport system is used. Other options related to design features (such as the number of carriers and entry-exit points) are evaluated by considering performance and cost (Benardos et al., 2009).

On the other hand, if a rectangular structure is to be built, very different transport systems can be installed with very different rack configurations (Hrabovský & Dluhoš, 2020). The design features determined by taking into account the needs (capacity, usage intensity) and various constraints (physical and technical constraints, budget) are also the most critical parameters that affect the operational activities to be carried out in the system and the performance of the system (Mathijssen et al., 2007; Serpen & Debnath, 2019). The design issue of FAPS becomes a challenging problem due to the inverse relationship between operational efficiency and efficient use of space. When considering capacity, performance, and cost, the ideal design plan should be created by considering the advantages and disadvantages of design options. The design features of FAPS are examined in the following sub-headings within the framework of efficient use of space and operational conveniences/difficulties.

The Shape of the Structure: In order to use the area more effectively and shorten the processing time, parking lots are designed/designed in different ways. However, as mentioned above, there is an inverse relationship between efficient use of space and operational convenience/speed. For example, although the operational processes are executed easier and faster in circular design systems, the space utilization rate of these systems is considerably lower than in rectangular structures (see Figure 2.8). For this reason, despite their operational difficulties, rectangular FAPSs are more preferred in practice because they use limited parking spaces more efficiently.

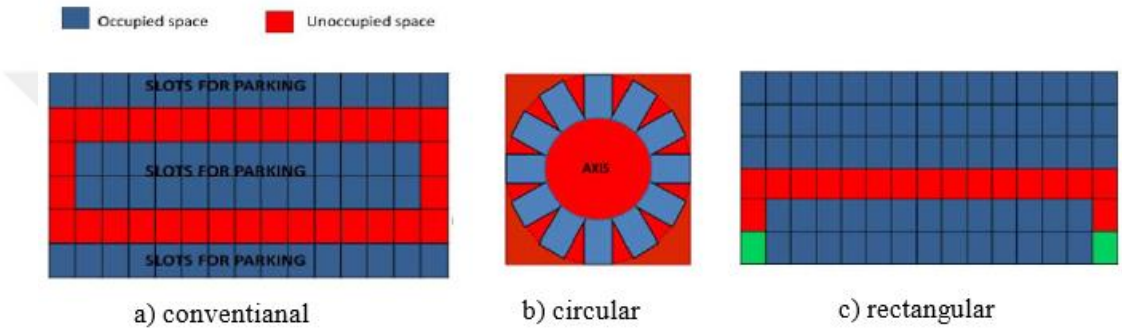


Figure 2.8 Horizontal space utilization of different FAPS designs (Nayak et al., 2013)

Figure 2.8b shows a section from a silo-type circular FAPS, and in Figure 2.2(b-c), a section from a rectangular FAPS with a deep shelf system. Various studies are comparing the effectiveness of the two basic designs regarding space utilization. For example, Nayak et al. (2013) showed in their study that a circular FAPS uses only 34% of the floor area, while a rectangular FAPS uses 78%. Another study (Serpen & Dou, 2015) reveals that a rectangular FAPS can use up to 84% of its surface area. On the other hand, puzzle-type systems, which allow the establishment of more flexible structures in shape, are generally rectangular and can effectively use 95% of the surface area (Fata Automation, 2020b). In such systems that can use the space so effectively, parking and retrieving operations are much more complex and slower than circular systems providing direct and fast access to each vehicle (Serpen & Dou, 2015).
Shelves Layout: In addition to the standard features of the buildings, the shelf systems and vehicle parking arrangements of FAPS are also important parameters that affect the beneficial use of the area. Most FAPSs have shelves and cells/slots where each vehicle is parked, as in warehouse systems. Likewise, as in warehouses, these racking

systems can be single-depth (see Figures 2.2a, 2.3a, 2.4a, 2.5a) or multi-depth (see Figures 2.2b, 2.2c, 2.4b, 2.5b). While the space utilization rate is 67% in structures with a single-deep shelf system, this rate can be increased up to 84% with multi-deep shelves (Serpen & Dou, 2015). In systems with single-deep shelves, direct access to each vehicle is possible for carriers moving in the corridor. At the same time, in such systems, static storage can be mentioned as the parked vehicles will stay at the same point during the park. However, in systems with multi-depth racks, a new parking process has a dynamic storage process that requires shifting and relocating vehicles in the slots (GIVT, 2018). In addition, it is more difficult in such systems to access the tools in the inner slots during retrieval. Especially if a vehicle is in front of the vehicle to be released, the processing time will be considerably longer as this vehicle will need to be relocated first. In such a case, the planning control of these complex operations become an even more important issue for the performance of FAPSs.

Transport Systems: Another design issue as crucial as the use of space is the determination of the transport system to be used in the building. As mentioned before, FAPS are new generation vehicle storage systems in which all transportation, allocation, and retrieval operations related to parking are carried out with automatic carriers. Researchers and manufacturers in the industry have proposed and implemented many different technologies and systems that automatically perform operations in the parking lot. In this context, there are scientific studies investigating the effectiveness of FAPS with different designs and technologies (Eswaran et al., 2013; Jog et al., 2015; Nayak et al., 2013; Pypno, 2008). While deciding on the transportation system to be used in the building, the study area, building structure, capacity requirement, usage density, and budget are considered. The shape of the building, the rack/park arrangement, and the equipment used depend on the transport system used, but vice versa. Although different classifications can be made according to the equipment used (with the palette or card), transportation systems are mainly classified according to the systems that transport and place the vehicles (such as lift/tower, shuttle/shuttle, crane/crane, AGV) (Automated Robotic Parking, 2018; Fata Automation, 2018c; GIVT, 2018).

Other Design Parameters (number of entrance-exit bay, lifts/elevators, transporters, empty slots): The number of entrance-exit cabins, the number of elevators/corridors/carriers, and the number of empty cells, which determine the system's processing capacity, are among the essential issues that should be evaluated together with the significant design decisions. At this point, the usage intensity of the system, that is, the customer density, emerges as the most critical factor to be considered while making these decisions (Debnath & Serpen, 2015; Serpen & Debnath, 2019; G. Wu, Xu et al., 2019). Increasing the number of mentioned design elements will increase the processing capacity and thus the system's speed but will also require allocating some of the areas reserved for vehicle parking to these structures. Therefore, appropriate decisions are tried to be taken by considering this balance between the efficient use of the space and the processing capacity of the system (Serpen & Debnath, 2019). In addition, the budget constraint should also be considered since each one of the design elements will create additional costs (Can et al., 2019).

2.3 Planning Problems of FAPSs

Fully Automated Parking Systems effectively solve the parking problem in cities by allowing many vehicles to be parked in limited areas and volumes. Despite this, FAPSs face problems from poor planning during the design and/or operation phase. For this reason, many studies focus on design and hardware issues in the scientific literature (Debnath & Serpen, 2015; Eswaran et al., 2013; Hrabovský, 2019; Hrabovský & Dluhoš, 2020; Nayak et al., 2013).

2.3.1 The Design Problems of FAPS

Different building shapes, transport systems, and several possible slot (cell) layouts can be arranged to maximize capacity and minimize retrieval time in FAPSs. However, there is a conflict between space efficiency and operational convenience. For example, a circular design is more convenient operationally than a rectangular one, but the space efficiency is much below a rectangular building. Some researchers have presented the space utilization efficiency of different FAPS designs (Nayak et al., 2013; Serpen &

Dou, 2015). Parking and retrieval operations conducted by robots are more complex than those rectangular garages.

Conversely, operations are executed easier in circular buildings as robots can easily reach all parking lots (Nayak et al., 2013). To summarize, on the one hand, there is space efficiency, and on the other, there is operational simplicity. Therefore, the FAPS design is challenging due to the conflict between space utilization and operation management. Therefore, the systems in the rectangular structure, which is the subject of this research, are preferred in practice because they use the entire area more effectively.

Some studies focus on the space utilization efficiency of different FAPS designs. For example, Nayak et al. (2013) report a study that compares parking floor utilization rates amongst conventional garage, circular, and rectangular fully automated garages. They show that parking floor utilizations are %62.2, %34.1, and %78.9 respectively for conventional garage, circular, and rectangular fully automated garages. In another study, Serpen and Dou (2015) report that a rectangular, fully automated system could utilize up to 84% of floor space. Both studies prove that rectangular FAPS outperforms the others in terms of efficient floor utilization. Although results show that conventional garages utilize floor space more efficiently than automated circular garages, circular garages utilize the total space more efficiently since vehicles are stacked together closely. Therefore, there is no need for access ramps, stairs, or elevators as in conventional systems. As another advantage of circular FAPSs, vehicle shelves are directly accessible. However, horizontal space utilization in circular design is not as efficient as in rectangular FAPS design. For this reason, the rectangular design is mainly preferred by decision-makers. In this regard, also the present study focuses on this type of design.

The transport system used in garages strongly depends on the shape of the building and vice versa (Fata Automation, 2020b). As stated, FAPSs are state-of-art vehicle storage systems where robots perform tasks like lifting, setting down, rotation, transport, and allocation. Therefore, they can also be referred to as robotic parking or

valet systems. In this context, FAPS can be classified according to carriers used to transport vehicles, such as lifts, AGV, and cranes (Automated Robotic Parking, 2018; Fata Automation, 2020b; GIVT, 2018; Parking Network, n.d.; Westfalia Parking, n.d.). Table 2.1 summarizes the essential design characteristics of FAPSs. Among these systems, the puzzle systems offer higher density with up to 95% utilization of available parking space. However, these systems bring about operational challenges. Therefore, it should be stressed that there is a trade-off between space efficiency and operational simplicity.

The other important design feature is the slot layout. In FAPSs, there are shelves and slots where cars are parked. Similar to warehouse systems, these shelf structures can be single-depth or multiple-depth. In single-depth shelves, the storage process becomes static as the parked car remains at the same position until retrieval. In the other case, a dynamic storage process should be conducted since cars might be shifted when other cars need to be parked (GIVT, 2018). In such cases, planning, scheduling, and controlling robots for car allocation and retrieval become more complex. There are several publications (Eswaran et al., 2013; Jog et al., 2015; Mathijssen et al., 2007; Nayak et al., 2013; Petsch et al., 2012; Pypno, 2008; Pypno & Sierpiński, 2017; Srikanth et al., 2009) focusing on these issues in detail.

2.3.2 The Operational Problems of FAPS

Although the method of bringing the vehicles to and from the parking lot (cell) differs according to the transportation system, the parking process is performed in the same way in all FAPS, regardless of the technology used. In these systems, drivers leave their vehicles in the parking room. After this point, customers do not need to wait for the transaction to finish; vehicles are placed in empty cells without drivers, with the help of carriers, randomly or according to predetermined rules. Later, when customers want to come back and pick up their vehicles, the vehicles are taken from the cells they are in with the help of carriers and delivered to the customer in the parking room. However, during the take-back process, customers must wait until the vehicle is delivered to them from the moment they want to take the vehicle. This

waiting period, which is directly related to the operational effectiveness and efficiency of the system, is very important in terms of customer satisfaction. With correct operational planning, these waiting times can be significantly reduced, and customer satisfaction can be increased (Serpen & Debnath, 2019; G. Wu et al., 2020; G. Wu, Xu et al., 2019; G. Wu, Zou, et al., 2019).

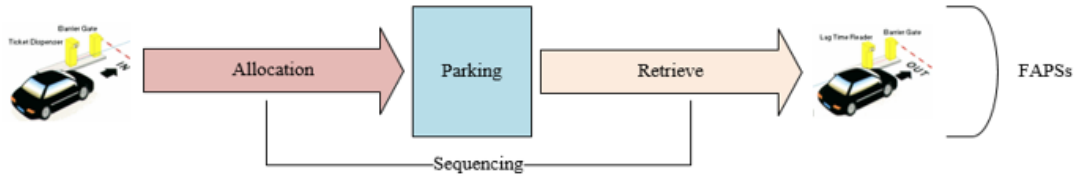


Figure 2.9 The fundamental operational processes in FAPSs

As shown in Figure 2.9, the two primary operations are performed on FAPS, regardless of design and transport system: (i) placing vehicles and (ii) retrieving vehicles. While the operations are being carried out in this process, two main decision problems are encountered: the order in which the operations will be performed (sequencing) and where the parked vehicle will be placed (allocation). Vehicle allocation and retrieval are carried out by the system simultaneously and generally according to the first come, first served policy. During the allocation process, vehicles are usually placed in the nearest empty place. In case there is more than one entry/exit point and more than one carrier in the system, it is also necessary to determine and schedule the movements of the robots (Serpen & Dou, 2015; G. Wu, Xu et al., 2019). If these operations are not managed well, this can lead to low operational efficiency, long service times, inefficient energy use, and high indirect costs.

CHAPTER 3
OPERATIONAL PLANNING AND CONTROL PROBLEMS

The technological advancements of the last two decades and the benefits of FAPS have made FAPS more attractive all over the world. Still, these systems have some issues that should be handled. As a relatively new and promising topic, problems of these systems are getting more attention from researchers (Chen et al., 2021; Debnath & Serpen, 2015; Mirzaei et al., 2017; Serpen & Dou, 2015; G. Wu et al., 2020; Yalcin et al., 2018; J. Zhang et al., 2020). Except for the high installation cost, these systems have operational concerns like long service times (Dudakli & Baykasoglu, 2020). Especially in rush hours, when people commute to/from work, customers can wait too long to park or retrieve their cars. The main reason for the dissatisfied customers is poor planning related to the design or operational phases (Dudakli & Baykasoglu, 2020). The FAPS design is one of the challenging issues due to the conflict between space utilization and simplicity of operations. The concern of this research is operations management of FAPSs, including operational planning and control.

In FAPS, vehicle allocation and retrieval operations are carried out by control and coordinating systems of many mechanical and electronic equipment such as sensors, elevators, and pallets. A general process and flow diagram of these systems are given in Figure 2.14. Regardless of the design and system features, when performing operations in FAPS, two main decision problems are encountered such as *(i)* the order in which the operations will be performed (sequencing) and *(ii)* where the parked vehicle will be placed (allocation). In addition, the number of operational transactions and decisions may increase. In addition to the fundamental decision/planning problems mentioned, in FAPS with more than one carrier, *(iii)* carrier scheduling; *(iv)* reallocation in FAPS with deep rack system; and FAPS with some unique transport systems (for example, Puzzle type FAPS); *(v)* path planning problems may also be encountered (Debnath & Serpen, 2015; Mirzaei et al., 2017). Within the scope of this article, especially the first two planning problems encountered in FAPS are emphasized. Solution methods that are used/can be used to solve these problems in existing systems have been researched.

If the operations and the related decisions are not managed well, significant problems may arise regarding the performance and costs of the system. Although similar problems have been studied in different systems for many years, the issue of operation planning in fully automatic car parks is considered relatively new. Also, most existing studies deal with only one of the insertion and retrieval processes. The number of studies that deal with simultaneous demands and operations in parking lots within the scope of operational planning and control is limited (Chen et al., 2021; Serpen & Debnath, 2019; Serpen & Dou, 2015; G. Wu, Zou, et al., 2019).

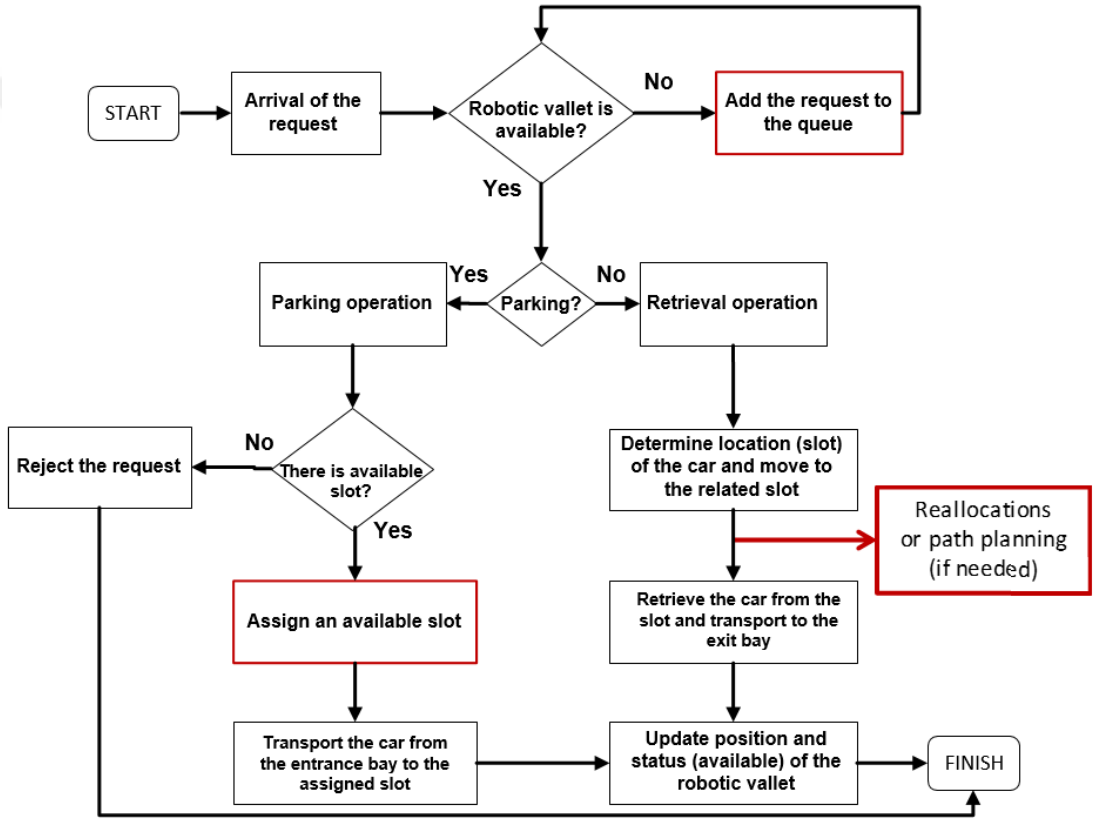


Figure 3.1 The general process flow diagram of FAPSs

FAPS integrates software systems with mechanical lifts and pallets to store and retrieve vehicles in multi-level modular garages. The car parking and retrieval process executed in FAPS can be summarized as follows: drivers leave their cars in the entrance bay. Then, vehicles are transported to one empty slot by the robot (carrier) without a driver based on arbitrary or predetermined rules. Later, when the customers return and want to retrieve their cars, they are taken from their parking slots and moved

to the exit bay. The basic process flow diagram, which comprises the primary operations and constitutes the core of the algorithms, is presented in Figure 3.1.

Here, it should be reminded that the basic process flow and intermediate decisions should be extended to multi-depth shelves and puzzle-type FAPSs. While retrieving a car, reallocation and path planning problems arise, especially for multi-depth shelves and puzzle-type systems. Except that, as highlighted in red in Figure 3.1, there are generally only two points where the system driver makes some operational decisions. The reasons for this limited control will be discussed in the following section. In this regard, two main planning problems arise for all FAPSs executing these operations: sequencing and allocation decision problems, which are inherently complicated because of their dynamic and uncertain nature.

3.1 General Structure of Operational Problems in FAPSs

Current studies on parking garages emphasize that FAPS use parking spaces much more efficiently than conventional parking lots (González-González et al., 2020; Rosenblum et al., 2020; Shoeibi & Shoeibi, 2020). However, despite all the advantages they provide, some issues reduce the preference for FAPS by users. For example, FAPS parking fees are slightly higher than traditional parking lots. However, the most dissatisfaction for users regarding FAPSs is the system's uptime; In other words, it is the customers' waiting time. Customers may have to wait a long time to park or retrieve their cars at certain times of the day, especially during peak hours such as business entry-exit times (Chen et al., 2021; Mahmood & Hajjaj, 2019; G. Wu et al., 2020).

Technological developments (like sensors, wireless, and RFID) (Aydin et al., 2018; Kanmaz & Aydin, 2018; Ozgonul & Seçmen, 2020) have provided the opportunity to establish systems that work well in technical terms and can perform parking operations in a very short time (70 - 200 seconds) (Parkolay, 2019). As a result, it is understood that the reason for the long waiting times of the customers is the processing capacity determined at the design stage rather than the system's operation (process) speed. Generally, there is an inverse relationship between the space usage of FAPSs and their

operational capacity and ease of management. Therefore, in addition to technical and physical constraints during the design phase, processing capacity may not be determined at the highest level when a high space utilization rate is targeted. Despite this, service times can be kept at the planned level by using the determined/available processing capacity in the most effective way with correct operational planning. In this context, the parameters of the operational planning and control problem, the main decision variables, performance criteria, and the hierarchical relationship between them are shown in Figure 3.2.

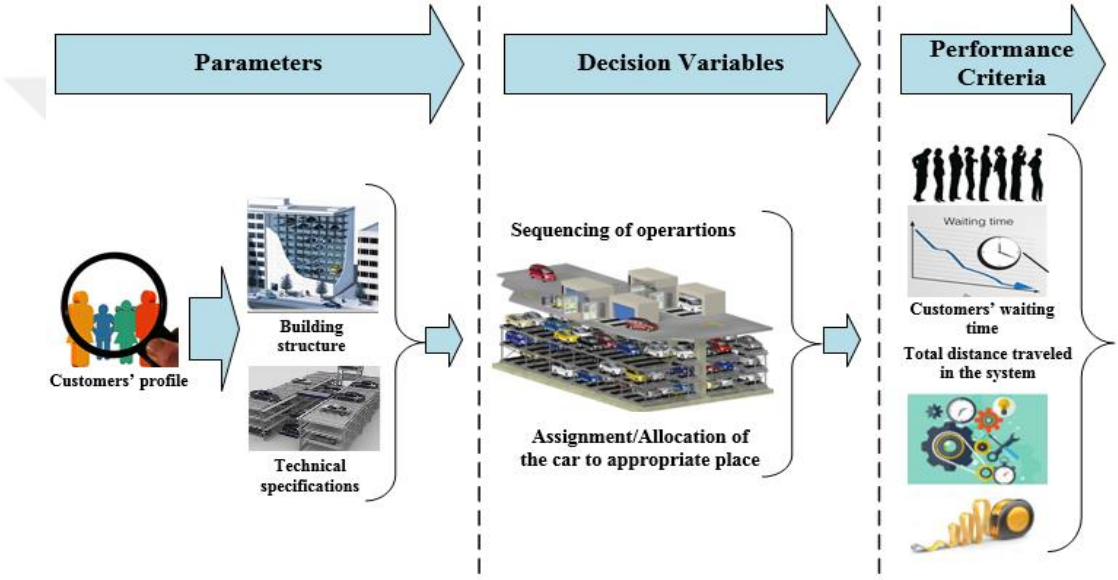


Figure 3.2 The general structure of operational planning and control problems in FAPSs

The findings show that the physical and technical characteristics of the system shape operations and operational problems. Therefore, the system's design (physical and technical) features are/should be determined according to the customer profile at the first stage. Then, the system's overall performance is related to the compatibility of the customer profile with the design features and how effectively the operational problems are solved. In this case, it is understood that customer behaviors, directly and indirectly, affect operational decisions and system performance. Therefore, increasing the operational performance of FAPSs will increase customer satisfaction and significantly reduce operating costs. In terms of customer satisfaction, the waiting time of customers in the system is an important performance measure. The waiting time is

directly related to the operational efficiency of the system. For example, the customer waiting time is related to the total distance traveled in the system or the average transaction time (Chen et al., 2021; G. Wu et al., 2020; G. Wu, Zou, et al., 2019). For this reason, developing methods and algorithms that address operational planning and control problems become as crucial as the system's design phase.

3.1.1 Fundamental Planning and Control Problems

Sequencing of Operations: In FAPS, many parking and retrieval requests can come simultaneously. If there is only one carrier in the system, these processes should be ordered, and if there is more than one carrier, they should be scheduled. FAPS generally operate according to the first come, first served (FCFS) rule to solve sequencing and scheduling problems. However, different sequencing (distribution) rules may perform better depending on customer profile and system design. Given the sequencing problem, the first come, first served approach can yield good results in terms of individual waiting times. However, customers' total/average wait time is a better indicator of system performance and overall satisfaction. On the other hand, the system's total/average waiting time is directly related to efficiency. A sequence that will reduce the total distance traveled by the carrier will reduce the total waiting time, hence the average customer waiting time (Chen et al., 2021; G. Wu et al., 2020).

Allocation of Vehicles: Most existing systems use a simple heuristic, the "nearest neighbor method (NNM)" rule, when deciding where to place vehicles. This approach reduces the distance traveled by the carrier during the said operation. However, the assignment in the first stage (allocation of vehicles) significantly determines the number of movements the carriers have to perform later and the total distance and time they will travel (Dudakli & Baykasoglu, 2020; Zou et al., 2019). For example, vehicles close to the exit point for short-term parking and far from the exit point for long-term parking will significantly reduce the distance traveled by the carrier and customers' waiting time. On the other hand, in systems where deep shelves are used, it may be necessary to relocate the vehicles in the front rows of the shelves in order to reach the vehicle to be retrieved (Hrabovský & Dluhoš, 2020).

In summary, where vehicles are placed in the system directly affects subsequent operations and decisions. Research and studies show that the performance of FAPSs in operational terms is affected by the vehicle allocation decision rather than the ranking decision (Dudakli & Baykasoglu, 2020; Zou et al., 2019). However, vehicle allocation decision becomes a much more critical issue in systems with more complex operations designed to use space more efficiently. For this reason, the performance of different allocation rules for different designs should be examined, taking into account customer behavior, and appropriate allocation decision(s) should be applied to the system (Baykasoğlu et al., 2017; Dudakli & Baykasoglu, 2020; Mirzaei et al., 2017).

3.1.2 Parameters and Constraints of the System

It has been emphasized in the previous sections that the performance of FAPSs is highly affected by operational decisions. Especially when different performance indicators are in question, it is not possible to talk about the absolute superiority of any of the mentioned strategies and rules or combinations of rules (Baykasoğlu et al., 2018; Serpen & Dou, 2015; G. Wu et al., 2020; G. Wu, Zou, et al., 2019). The effectiveness of strategy and rules largely depends on the system's design features (structure and layout of the building), the transportation system used, and customer behavior characteristics (such as entry-exit times and density).

The rule set to be used while executing the operations of FAPS is to be decided as a result of the analysis made by considering the mentioned system parameters. Parameters of the simulation study to be carried out for this purpose; can be examined in two groups as definite (deterministic) and imprecise (stochastic) parameters. For the first parameter group, the respective values are (mostly) precise, and it is relatively easy to collect data on the parameters. However, the second set of parameters contains randomness, and data on these parameters is relatively challenging to compile. In addition, the raw data collected is not suitable for direct use. Therefore, Pre-processing and additional analysis are needed to produce appropriate inputs for the system (Baykasoğlu et al., 2017, 2018; Chen et al., 2021; Dudakli & Baykasoglu, 2020; Serpen & Debnath, 2019; G. Wu et al., 2020).

(i) Deterministic System Parameters: The physical and technical characteristics of the system are examples of the first group of parameters mentioned above. The size and design of the structure and parking slots; the system's capacity (number of slots); the number of the entry-exit point and carriers; the speed of the carriers, and other mechanical equipment; are the parameters needed to be defined correctly. Such parameters are determined following the customer profile during the design and installation phase and have fixed / definite (deterministic) values.

(ii) Stochastic System Parameters: Unpredictable customer behaviors, which are the primary source of the uncertain and dynamic structure of the system, constitute this parameter group. An accurate customer/user analysis is essential for an efficient design and operating system. Customer behavior characteristics such as the number and density of customers, customers' arrival and departure patterns, and parking durations are critical system parameters that should be considered both in the system's design phase and the operations planning and control phase. In order to manage the operations of FAPS in an ideal way, the following data on the behavior of parking customers should be analyzed and made statistically significant.

- Customer density
- Arrival and departure patterns of customers and
- How long do they park their vehicles

The effectiveness of distribution rules is highly dependent on the behavioral characteristics of customers. However, all the parameters mentioned about these customer behaviors do not have exact values and take estimated values at certain time intervals. For example, during rush hour, when people commute to work, demand for parking and retrieval is quite high, while other hours are relatively more stable. However, it is still not possible to say anything definite about parameter values. Similarly, parking times vary from day to day, from customer to customer, and are generally less predictable.

3.1.3 Solution Approaches to Operational Planning & Control Problems

Considering the nature of the parking process and the density in the city, FAPS may need to serve too many customers in a short time. Responding to these instant demands of customers accurately and quickly can only be possible with good management of operations. Instead of using specific rules to solve these emerging operational problems, solving these problems as an optimization problem will improve the system's performance, especially in service times. In this context, operational planning and control problems must be solved in an integrated and simultaneous manner. However, allocation and sequencing problems to be solved in order to minimize the total distance/transfer time traveling within the system are complex computational problems. In addition, in parking systems, there is no certainty about how many vehicles will enter the system and when, and how long they will stay in the system. In this very dynamic and uncertain process, it is understood that it is complicated to plan and perform the operations in an ideal way. Therefore, while dealing with the operational planning and control problems of FAPS, various heuristic methods and rules are preferred because of the need for real-time, fast, and applicable solutions (Baykasoğlu et al., 2017; Chen et al., 2021; G. Wu, Zou, et al., 2019). Although the ideal solutions cannot be obtained with the methods used, it is possible to shorten the processing distances and times with a correct sequencing and allocation strategy. Thus, while the maintenance-repair and operating costs of the system are reduced, customers are served faster (Chen et al., 2021; Dudakli & Baykasoglu, 2020; Serpen & Debnath, 2019; G. Wu et al., 2020; G. Wu, Zou, et al., 2019).

According to the flowchart in Figure 2.14, the system must first decide which operation should be performed if parking and/or recovery operations are waiting in the queue. Four different rules can be applied to sort transactions. The sequencing can be made by the system that does not depend on the transaction type (FCFS and NRF), or the sequencing can be made by prioritizing the transaction types (PRF and RRF). Regarding customer satisfaction, a general priority can be given to parks or rollbacks in the system in different situations and conditions. Later, different priorities can be determined for sequencing transactions of the same type within themselves. For

example, in FAPS, customers are in a physical queue/queue for parking. However, there is usually no such queue during the retrieving process.

For this reason, transactions are naturally ordered according to the "first come, first served" rule during parking. The sequencing of the retrieve operations can be done according to different rules. After determining the next operation to be performed, if the operation is a parking operation, it is necessary to decide where the vehicle will be placed. Vehicles may be placed in the parking lot in a random empty cell, nearest or the furthest empty cell.

Considering the system features and parking process of FAPSs, the distribution rules can be used for the two main problems, sequencing and allocation decisions. These rules will be helpful for quickly planning and executing operations in single-entry-exit, single-aisle, single-depth, single-carrier systems. However, in the case of different systems or system features (multiple entry/exit points, carriers, deep shelves), additional rules/methods will be needed for issues such as scheduling carriers and doors and reallocating the vehicles. In such a case, the ideal rule combination for the system should be determined from the rule set to be created for all operational decisions. Simulation modeling is one of the most suitable methods to evaluate the performance of complex and dynamic systems such as FAPS (Chung, 2003; Nguyen et al., 2014). Almost all of the scientific studies on FAPS have been carried out on the simulation models of the system (Baykasoğlu et al., 2018; Chen et al., 2021; Serpen & Debnath, 2019; G. Wu, Zou, et al., 2019).

3.2 The Review and Analysis of Related Literature

The purpose of this section is to present a detailed review to researchers, especially about the operation planning and control of FAPS. In this context, it is aimed to (i) provide detailed information about fully automatic parking types and mechanical and technical features, (ii) define the design and operation planning problems of FAPSs, and (iii) reveal the general structure of the operation planning and control problems of FAPSs. The literature, the web pages of the companies that installed these systems,

the opinions of the experts on the subject, and the observations of the authors were used. A three-stage review method, search-filtering-classify, was used to identify and systematically evaluate the scientific literature on fully automated parking systems. In the first stage, queries were made using keywords in large databases such as the local "TRDizin" (TRDizin) (https://trdizin.gov.tr) and the international one such as "Scopus" (Scopus) (https://www.scopus.com), "Web of Science" (WOS) (https://apps.webofknowledge.com). After a comprehensive filtering process in the second stage, the scientific studies were classified and examined in the third phase. The number of studies found depending on keywords and database is listed in Table 3.1.

Table 3.1 The number of studies found and filtered as a result of the literature review

	All Results		**Filtered Results**	
Keywords	Scopus	WOS	Scopus	WOS
"Automate parking system"*	60	34	17	14
"Robotic parking"*	5	6	5	4
"Robotic Vallet"*	2	1	2	1
"Automated parking garage"*	6	3	3	3
"Automated parking structure"*	1	1	1	1
"Automated parking building"*	1	1	0	0
Combination	72	44	22	20
		Scopus+WOS (filtered)	28	

Inquiries were made to cover all areas between the years "1970-2020". Under these conditions, the word "otopark" was used in the query made in TRDizin's Science database, and a total of 20 studies were reached, 11 of which were in engineering, 6 in basic sciences, 3 in medicine, and 1 in agriculture. Unfortunately, none of these studies have focused on FAPS. On the other hand, the results of the searches conducted in Scopus and Web of Science databases in English with different keywords that may be relevant to the subject are given in Table 3.1. Regarding the studies on "fully" automated parking systems, 28 publications have been reached. Data for 2020* covers the first five months of the year. However, shown in Figure 3.3, 11 publications (40% of the total) were made in the last two years. On the other hand, the results of the searches made in Web of Science (WOS) databases with different keywords in English are given in Figure 3.3.

Set	Results	
# 8	72	#6 OR #5 OR #4 OR #3 OR #2 OR #1 *Databases= WOS, KJD, RSCI, SCIELO Timespan=All years* *Search language=Auto*
# 7	63	#5 OR #4 OR #3 OR #2 OR #1 *Databases= WOS, KJD, RSCI, SCIELO Timespan=All years* *Search language=Auto*
# 6	10	**TOPIC:** ("automated car parking system*") *Databases= WOS, KJD, RSCI, SCIELO Timespan=All years* *Search language=Auto*
# 5	6	**TOPIC:** ("robotic parking*") *Databases= WOS, KJD, RSCI, SCIELO Timespan=All years* *Search language=Auto*
# 4	3	**TOPIC:** ("automated parking garage*") *Databases= WOS, KJD, RSCI, SCIELO Timespan=All years* *Search language=Auto*
# 3	1	**TOPIC:** ("automated parking building*") *Databases= WOS, KJD, RSCI, SCIELO Timespan=All years* *Search language=Auto*
# 2	1	**TOPIC:** ("automated parking structure*") *Databases= WOS, KJD, RSCI, SCIELO Timespan=All years* *Search language=Auto*
# 1	53	**TOPIC:** ("automated parking system*") *Databases= WOS, KJD, RSCI, SCIELO Timespan=All years* *Search language=Auto*

Figure 3.3 The number of studies found in all databases by using keywords via the Web of Science

In addition to automated parking garages and all relevant systems, the “automated parking system” statement is a general term for autonomous parking systems that manage driverless parking. The same situation exists with a relatively lower ratio for other keywords that may be related to different concepts.

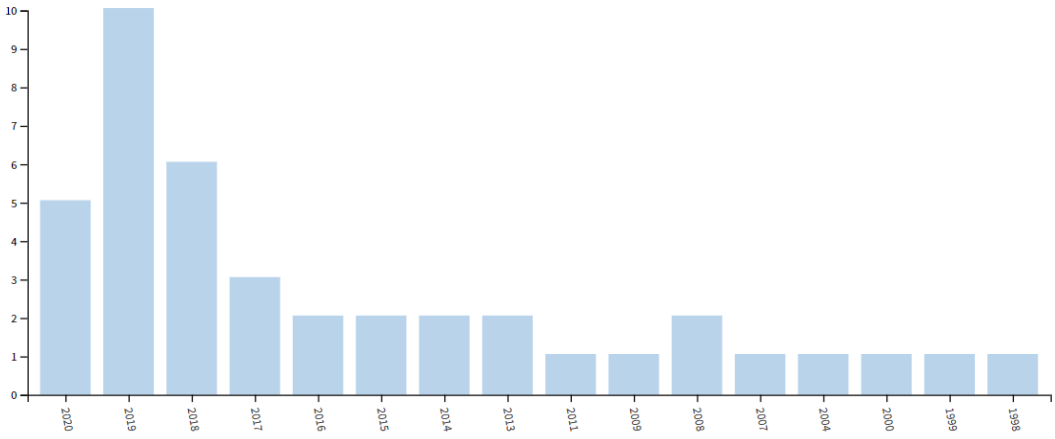


Figure 3.4 The number and ratio of publications by years (source: WOS)

When considering the studies on automated parking systems as parking slots (garage), 41 publications were reached in total. As can be seen in Figure 3.4, 21 of these publications (more than 50 % of the total publications) were made in the last three years. Also, the distribution of the types of publications can be seen in Figure 3.5. Almost 60 % of research is published as conference papers, while most of the remaining research was published in various journals, especially in the last two years.

Select	Field: Document Types	Record Count	% of 41	Bar Chart
☐	MEETING	24	58.537 %	
☐	ARTICLE	15	36.585 %	
☐	EARLY ACCESS	2	4.878 %	
☐	EDITORIAL	1	2.439 %	
☐	NEWS	1	2.439 %	

Figure 3.5 The number and ratio of publication types (source: WOS)

As stated in the previous sections, FAPSs are used in major cities worldwide, particularly in Asia, Europe, and North America, where parking space is limited and expensive (G. Wu, Xu et al., 2019). Figure 3.6 shows that research related to FAPS is densified, especially in highly populated countries.

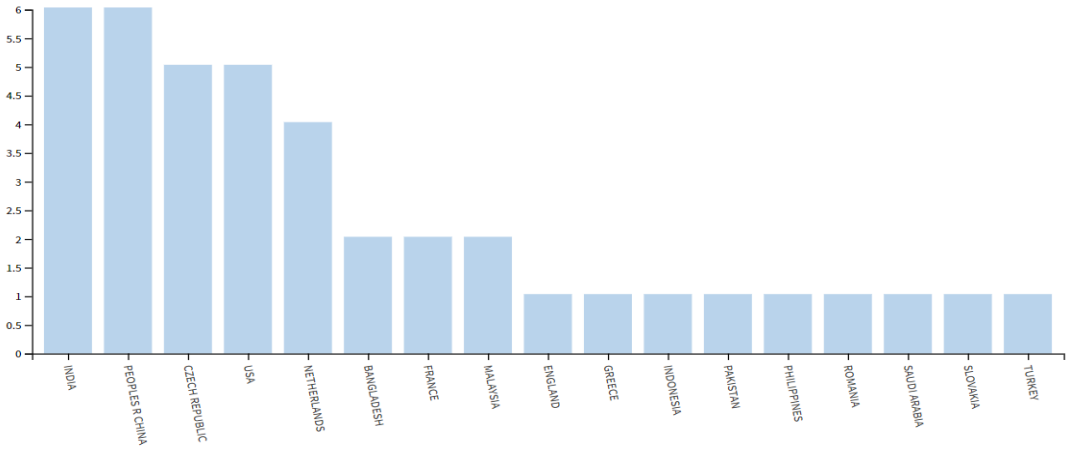


Figure 3.6. The number of studies carried out by different countries/regions (source: WOS)

In parallel to the usage rate of FAPSs, most research has emerged in Asian countries like highly populated India, China, the USA, and some technologically improved

European countries like the Czech Republic and the Netherlands. Almost 65 % of publications are made in these five countries. The single publication from Turkey is derived from this thesis, and we hope to make more publications from the research.

3.2.1 The Studies Closely Related to Our Study

A comprehensive literature review demonstrates that1 there have been many studies addressing the design problem of FAPSs and the technologies to be used in FAPSs. In parallel with technological progression, many parking automated systems have been proposed and implemented successfully. On the one hand, the literature on parking systems mainly focuses on traffic and economy, and the literature on automated parking systems related to the system performance (car retrieval time, the waiting time for the lifts, and the utilization of the lifts and shuttles) is limited (G. Wu, Zou, et al., 2019). Figure 3.7, FAPSs problems are new and rarely studied in operational research and management science. Until the last few years, construction and equipment used in FAPSs discussed in the literature as the design problem. However, especially in the last five years, the design problem has been addressed as an optimization problem that balanced operational efficiency and utilization of FAPSs by considering different arrival rates.



Figure 3.7 The number of studies based on research area (source: WOS)

On the other hand, there are also a limited number of studies concerning operational planning and control of FSPSs in a managerial aspect. Operational planning and control problems refer to allocating the car to the appropriate place, retrieving the parked car, and sequencing all operations and robot movements. Considering combinatorial nature, real-time operation tasks, and the necessity for rapid and applicable solutions, using dispatching rules/heuristics becomes inevitable. While the literature on parking systems and parking design exists, the literature on automated parking systems from operational planning and optimization is quite limited. In this context, the studies considering FAPSs and handling design and operational planning problem as decision problem is summarized in Table 3.2.

Except for the design optimization (6 of which), sequencing (2 of which), scheduling/routing (4 of which), and car allocation (1 of which) problems are studied as operational problems in literature. Based on the finding, it can be concluded that there are two dominant streams related to FAPSs. The first and most recent one is an optimal design problem that is solved by an analytical model (queuing theory) and validated with a simulation model. The second type of research focuses on dynamic operational planning and control problems and utilizes several heuristic and metaheuristic algorithms that a simulation model efficiently approves.

Table 3.2 Summary of the closely related studies

Research Paper	Type of FAPS	The Problem	Solution approach	Objective function	Operating policy
(G. Wu, Zou, et al., 2019)	Cellular (Shuttle)	Optimal system structure	Analytic model *Simulation model	Minimization of retrieval time	Dedicated/ Random lift assignment to operation
(G. Wu, Xu et al., 2019)	Cellular (CAP)	Optimal system configuration	Analytic model *Simulation model	Minimization of retrieval time	Dedicated/ Random lift assignment to region
(G. Wu et al., 2020)	Cellular (CRAP)	Optimal system configuration	Analytic model *Simulation model	Minimization of retrieval time	-
(J. Zhang et al., 2020)	Cellular	Optimal system configuration	Analytic model	Travel time/retrieval time	-
(Chen et al., 2021)	Rectangular	Service priority (sequencing of customers) Allocation policy Optimal system dimension	Analytic model Simulation model	Customer waiting time	Dedicated/shared slot allocation
(Pypno & Sierpiński, 2017)	Rectangular	Retrieval process (scheduling of platforms)	Metaheuristic algorithm Analytic model	Minimization of retrieval time	-
(Debnath & Serpen, 2015)	Puzzle	Elevator scheduling	An analytic model for elevator number Simulation model	Customer waiting time	-
(Serpen & Dou, 2015)	Puzzle	Storage and retrieval process	Path planning algorithms, heuristics, Simulations model	Min distance Min obstacle	-
(Serpen & Debnath, 2019)	Puzzle	Storage and retrieval process Optimal system configuration	Path planning algorithms, heuristics, Genetic algorithm Simulations model	Customer waiting time	-
(Chen & Sun, 2017)	Stereo (tower)	Sequencing of operation type	Simulation model	Storage waiting time Retrieval waiting time Average waiting time	FCFS Cross-access
(Zou et al., 2019)	Rotary	Allocation optimization	Genetic algorithm Simulation model	Total parking and pickup time	-

*Simulation model is used to validate developed analytic model

3.2.2 The Gap in Literature and Contribution of this Study

The concerns related to FAPSs mainly consist of planning problems, which can be grouped into two heading design and operational planning and control problems. In this regard, the Ph.D. thesis considers the latter group of problems and aims to develop methods and algorithms that improve the performance of FAPSs by increasing operational efficiency. Considering general operations in FAPSs, two main planning problems arise when executing these operations: sequencing and allocation decision problems which are inherently complicated due to their dynamic and uncertain nature. These problems must be solved by considering the specific constraints of the system.

Sequencing of the requests: The system performs car store and retrieval operations simultaneously and is usually based on the first-come-first-served (FCFS) approach. However, other heuristic/dispatching rules could improve performance depending on customer profile. So, the performance of different heuristic rules should be analyzed by considering specific system features and customer profiles. Unfortunately, there are only two studies that consider sequencing problems. Chen and Sun (2017) compared FCFS and cross-access strategies in terms of customer waiting time, whereas Chen et al. (2020) analyzed the impact of giving priority to the customer that booked before coming for the same performance criteria.

Allocation of the cars: The car allocation problem is related to determining the appropriate slot for the car that will be stored and is mainly determined based on the nearest-available-slot approach. Allocation of the car in the right place is a critical decision problem as it affects all subsequent decisions and operations. With this consideration, the problem should be addressed as an optimization problem instead of a decision problem. Although Chen et al. (2020) investigated the impact of the dedicated storage (allocation) policy, they did not decide on the optimal allocation of each car. The only study that resembles to aim of this research belongs to Zou et al. (2019). They decided on the optimal location of each car by a genetic algorithm for a rotary parking system as make total parking and retrieval times minimum.

This study focused on operational optimization instead of design optimization. Therefore, unlike the current literature, the sequencing and optimal allocation decision will be conducted for tower-type FAPSs. However, the most significant contribution of this study will solve these problems from a different perspective by placing daily customer behavior at the center of the research. As far as we know, the only study dealing with the imbalance between demand and supply of the FAPS was carried out by Kuda et al. (2022).

3.3 Conclusion and Remarks

Today, the increasing need for parking spaces in cities has become one of the fundamental problems that local administrators have to deal with in the context of sustainable urban transportation. It is understood that the parking problem, which has become a painful process for citizens, is challenging to solve with traditional parking systems. However, the need to use the limited spaces in city centers effectively and environmentally has enabled FAPS to take place in our daily lives as new generation parking systems. Furthermore, the fact that FAPS operations are carried out unmanned and with fully automatic carriers allows the vehicles to be stacked closer to each other while at the same time eliminating the need for ramps, elevators, ventilation, and lighting that should be found in traditional systems. This way, FAPSs use the limited space at hand much more efficiently and prevent other environmental problems (such as waste of time and fuel).

As a result of all these gains, FAPSs are seen as the future of parking systems. However, FAPS has several problems that lead to possible long service times, inefficient energy consumption, and indirectly high costs. For these systems, which are in the development stage, to create the targeted effects in cities, these problems must be resolved first. As a result of the examinations, it has been understood that most of the problems encountered in FAPSs are caused by poor planning in the design and/or operation (operation) phase of FAPSIn the scientific literature, there are many studies on the design of FAPS and the technological equipment to be used in FAPS. Still, studies handling operational planning and control problems are rare. At this

point, the operational efficiency and service times of FAPS have started to become more important issues.

In detail, operational planning and control problems of FAPS include allocating vehicles in a suitable location, retrieving parked vehicles in an appropriate combination, and sequencing all operations and robot movements. Solving the abovementioned problems will significantly improve the system's efficiency and performance, especially in terms of customer satisfaction. However, the nature of the parking process, system constraints, and the dynamic and uncertain nature of the problems make it very difficult to solve them in an ideal way. Therefore, in practice, software used to plan and execute operations in FAPS uses heuristics and/or rules.

Within the scope of this study, a general process flow diagram that can provide operational planning and control of FAPS is presented. In addition, various approaches used/can be used for vehicle allocation and sequencing decisions, which are common operational problems of all FAPS, are discussed. However, it has been emphasized that the effectiveness of the rules used while executing the operations, and thus the system's performance, is directly dependent on the system parameters. The structural (such as parameters, constraints, decision variables), properties, and interrelationships of operational planning and control problems are discussed in this context. In future studies on the subject, studies should be conducted to quickly get the most ideal/closest solutions instead of using simple heuristic rules for operational control systems. Unfortunately, there is a severe lack of research in this area. In order to manage the uncertainties arising from the system, intelligent systems that can use the available information and data should be developed. Considering the need to produce fast solutions for real-time control of operations in FAPS, it is predicted that the use of artificial intelligence-based algorithms will come to the fore for the integrated and simultaneous solution of most combinatorial and dynamic problems.

The literature review of FAPS was conducted in the present chapter. A list and summary of the studies closely related to our research are given by highlighting trends of the topic. Also, this chapter points out the gap in the literature, and the contribution

of this study is emphasized briefly. It is planned to write and publish more papers related to studies conducted so far in the scope of this thesis before completing experimental and computational studies. The literature review shows that there is limited study considering operational planning problems, and there is no research handling the problem from our perspective. Therefore, the rule-based and optimization-based planning approaches are introduced in Chapters 5 and 6, respectively, and the results are discussed. However, before that, the study's research methodology and modeling assumptions are presented in Chapter 4.

CHAPTER 4
RESEARCH METHODOLOGY AND MODELLING ASSUMPTIONS

This study analyzes the efficiency of different dispatching rules that can be used to address operational planning and control problems. First, a detailed literature review and observations on real systems are carried out to clearly define the problem's nature. Eventually, it was discovered that the service times and system performance are primarily affected by the allocation of vehicles and then sequencing of operations. Accordingly, the general framework and structure of the problem considered in this research are depicted in Figure 4.1.

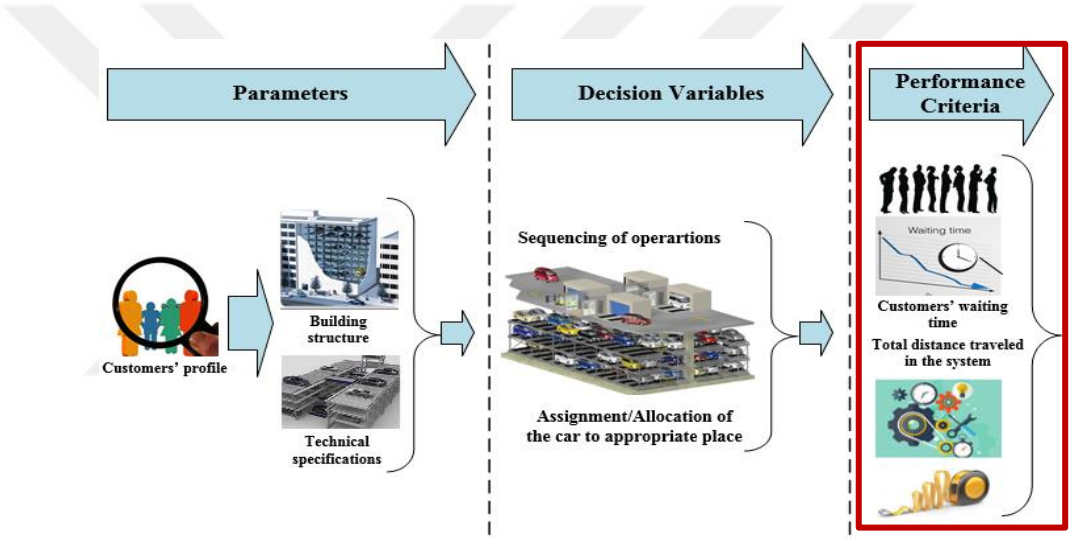


Figure 4.1 The general structure of the problem considered in the thesis

System features like the shape of the building and the number of entrance-exit points are the parameters related to building structure, whereas utilized transport systems like puzzle type and tower type with single or multiple depth selves correspond to technical specifications. In addition to decision variables, the decision-maker somehow controls these parameters in the system's design phase. However, there is another uncontrollable parameter and thus should be considered when both are designing and operating the system. This parameter is the customer profile related to customer density and customer behaviors such as the arrival/departure patterns and parking duration. It means that all these system parameters should be considered

carefully when addressing operational decision problems. On the other side, the dispatching rules used to handle common operational problems encountered in FAPSs are identified and described in the previous section. Furthermore, the proposed rules that help to sequence the requests and assign the cars to an appropriate place are embedded in the main control algorithm, as shown in Figure 3.1.

4.1 Performance Criteria

It was mentioned that two performance metrics would be used to evaluate the success of the planning approaches. Namely, the average waiting time of the customers (customer satisfaction) and the total distance covered in the system (efficiency of the system). In this context, "*the total distance traveled in the system,"* which has a deterministic structure and directly affects the customers' waiting time, is considered "*the objective function*" when deciding on the optimal location. Let us assume that $Transport(x,y,z)_t$ is the starting position (coordinates) of the carrier/transporter and $Transport(x',y',z')_{t'}$ is the position of the transporter at the end of the transportation process; and V_x, V_y, V_z, gives the velocity of the carrier on x-y-z axis, respectively. In this case, $\Delta \boldsymbol{d}$ represents the distance traveled by the transporter to perform the transaction (whether parking or retrieval), and $\Delta \boldsymbol{t}$ represents the time spent on the transaction. Then, depending on the system parameters (the structure's dimensions and the carriers' speed), the distance and time traveled in each allocation and retrieval process are calculated according to the following equations.

$$\mathbf{t \rightarrow t':}\ \Delta \mathbf{d_{(Transporter)}} = |x' - x| + |y' - y'| + |z' - z| \tag{4.1}$$

$$\Delta \mathbf{t(Transaction)} = t' - t = |x' - x| / Vx + |y' - y| / Vy + |z' - z| / Vz \tag{4.2}$$

Equations (4.1) and (4.2) ensure to measure performance criteria related to the distance traveled and the time spent for each transaction. As a result, the total distance traveled in the system and the total transaction time can be calculated by Eq. (4.3) and (4.4), respectively.

$$D_{total} = \sum_{i=1}^{Nt}(\Delta \mathbf{d_i}) \qquad i \in (PT \cup RT) \tag{4.3}$$

$$T_{total} = \sum_{i=1}^{Nt}(\Delta \mathbf{t_i}) \qquad i \in (PT \cup RT) \tag{4.4}$$

Where D_{total} represents "*total distance,*" T_{total} represents "*total time*" for the transactions. Sets of *PT* and *RT* include parking and retrieval transactions, respectively, and N_t is the total number of transactions within the considered period. The mean distance traveled per transaction and mean time spent per transaction (operation) can be calculated by equations (3.5) and (3.6).

$$D_{avg} = \sum_{i=1}^{Nv}(\Delta \mathbf{d_i})/N_v \qquad i \in (PT \cup RT) \tag{4.5}$$

$$T_{avg} = \sum_{i=1}^{Nv}(\Delta \mathbf{t_i})/N_v \qquad i \in (PT \cup RT) \tag{4.6}$$

The performance criterion related to customer satisfaction is measured by the customer waiting time. However, previous studies mainly considered and used the customer waiting times related to solely retrieval transactions. (Debnath & Serpen, 2015; Serpen & Debnath, 2019). In this thesis, we consider and plan both parking and retrieval transactions at the same time. Based on previous studies, we used the following two equations to calculate customer waiting times through the parking (4.7) and retrieval (4.8) operations, respectively.

$$w_i^p = t_i^d - t_i^a \qquad i \in C_a \tag{4.7}$$

$$w_i^r = t_i^d - t_i^a \qquad i \in C_d \tag{4.8}$$

Where t_i^a represents the customer's arrival time at the system, and t_i^d represents the customer's departure time from the system. C_a represents the set of customers parking their cars, while C_d represents the set of customers retrieving their cars. Based on these assumptions, the average waiting times per customer are calculated as follows: N_a and N_d represent the number of customers for each transaction type (parking or retrieval). Average waiting times per parking and retrieval operation is calculated by Eq. (4.9)-(4.10). Finally, *W* gives (4.11) the average waiting time per transaction (operation).

$$W^p = \sum_{i=1}^{N_a} w_i^p / N_a \qquad i \in C_a \tag{4.9}$$

$$W^r = \sum_{i=1}^{N_d} w_i^r / N_d \qquad i \in C_d \tag{4.10}$$

$$W = \frac{\sum_{i=1}^{N_a} w_i^p + \sum_{i=1}^{N_d} w_i^r}{N_a + N_d} \tag{4.11}$$

4.2 The Objective Function

With the innovative and novel approach proposed within the scope of the thesis, an computational intelligence algorithm is developed which can predict optimal allocation in accordance with the dynamic structure. Considering the combinatorial and dynamic nature of the problem and the necessity of being able to produce fast solutions for real-time decisions, the necessity of using metaphorical algorithms that work fast in this optimization module comes to the fore. At this point, considering the success of the Greedy Randomized Adaptive Search Procedure (GRASP) algorithm in such and similar problems, it is considered that the GRASP algorithm is appropriate as the solution method.

It was mentioned that two performance metrics would be used to evaluate the success of the thesis, namely the average waiting time of the customers (customer satisfaction) and the total distance covered in the system (efficiency of the system). In this context, "*the transfer distance"*, which has a deterministic structure and directly affects the waiting time of the customers, is considered as "*the objective function*" when deciding to the optimal location. Although this assumption has rational arguments, it should be tested and verified statistically. Thus, two statistical analyses are carried out in order to prove

(i) the positive correlation between operational efficiency and average waiting time
(ii) the linear relation between operational efficiency and average waiting time

Table 4.1 Example of the data used for statistical analysis

sim no	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	sim no	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)
1	2,78	91,93	3,33	14871,97	**41**	3,01	93,54	3,38	15117,30
2	2,88	91,35	3,31	15318,79	**42**	3,30	93,19	3,37	15311,45
3	2,77	92,08	3,34	15032,61	**43**	3,01	93,35	3,38	15175,26
4	2,72	92,02	3,33	15262,74	**44**	3,30	93,27	3,38	15260,06
5	2,76	91,48	3,32	14974,17	**45**	3,19	93,34	3,38	15305,44
6	2,71	92,40	3,35	15135,09	**46**	3,09	93,07	3,37	15411,27
7	2,64	91,60	3,32	14936,61	**47**	3,21	93,38	3,38	15274,44
8	2,81	91,46	3,32	15201,68	**48**	3,11	93,21	3,37	15244,59
9	2,74	91,80	3,33	14873,95	**49**	3,16	93,28	3,38	15322,99
10	2,69	92,07	3,34	15249,66	**50**	3,13	93,34	3,38	15309,34
11	3,23	92,11	3,34	15070,21	**51**	3,36	93,22	3,37	15204,46
12	3,54	92,02	3,33	15314,59	**52**	3,57	93,59	3,39	15628,91
13	3,56	92,27	3,34	15161,48	**53**	3,40	93,47	3,38	15383,48
14	3,38	92,35	3,35	15270,89	**54**	3,22	93,19	3,37	15374,59
15	6,07	92,45	3,35	15418,76	**55**	3,23	93,38	3,38	15451,06
16	3,58	91,80	3,33	15162,23	**56**	3,20	92,83	3,36	15317,68
17	3,34	92,64	3,35	15326,61	**57**	3,42	93,24	3,37	15584,20
18	3,52	92,14	3,34	15357,99	**58**	3,21	93,51	3,38	15338,05
19	3,54	92,46	3,35	15329,49	**59**	3,34	93,48	3,38	15377,26
20	3,32	91,96	3,33	14987,55	**60**	3,15	93,56	3,39	15588,16
21	3,05	92,39	3,35	15061,78	**61**	3,33	93,89	3,40	15400,05
22	3,18	92,19	3,34	14916,02	**62**	3,29	93,24	3,37	15368,27
23	3,09	92,39	3,35	15060,32	**63**	3,34	93,49	3,38	14992,79
24	2,91	92,22	3,34	15074,24	**64**	3,38	93,47	3,38	15448,75
25	3,05	92,62	3,35	15213,64	**65**	3,16	93,69	3,39	15503,03
26	2,96	92,61	3,35	15238,91	**66**	3,33	93,38	3,38	15520,60
27	3,21	92,34	3,34	15253,11	**67**	3,40	93,59	3,39	15499,16
28	2,99	92,15	3,34	15184,93	**68**	3,34	93,45	3,38	15602,41
29	3,16	92,37	3,35	14931,33	**69**	3,34	93,32	3,38	15308,78
30	3,12	92,33	3,34	15131,44	**70**	3,32	93,55	3,39	15474,33

In this regard, the outputs of the 240 (24 rule combinations **x** 10 replications) simulation runs are used as data for the statistical analysis. The correlation and the dependent relation between customers' waiting time per operation and different operational efficiency indicators are investigated. The operational efficiency indicators and data used for analysis are given in Table 4.1. SPSS Statistics software analyzes the given data related to performance metrics.

Correlation Analysis: Correlation is a bivariate analysis that measures the strength of association between two variables and the direction of the relationship. Regarding the relationship's strength, the correlation coefficient's value varies between (+1) and (-1). A value of (± 1) indicates a perfect association between the two variables. On the other hand, the relationship between the two variables will be weaker as the correlation

coefficient value goes towards 0 (zero). The coefficient sign indicates the direction of the relationship; a (+) sign indicates a positive relationship, and a (–) sign indicates a negative relationship.

Pearson r correlation is the most widely used correlation statistic to measure the degree of the relationship between linearly related variables. However, for the Pearson r correlation, both variables should be normally distributed. Thus, the distribution of the variables (waiting times, transfer distance, transfer time, daily transfer distance) is investigated to if it fits the normal distribution.

Table 4.2 Results of normality test

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
waiting_time	,172	240	,000	,903	240	,000
trans_dist	,215	240	,000	,825	240	,000
trans_time	,215	240	,000	,825	240	,000
daily_trans_dist	,200	240	,000	,846	240	,000

a. Lilliefors Significance Correction

The data containing 240 instances (for each variable) is tested in SPSS for normality, and the results are presented in Table 4.2. The sample size for both of these examples is 240, so the Shapiro-Wilk test should be used. For all variables, the significance level ($p < 0.05$) suggests strong evidence of non-normality. For this reason, a non-parametric correlation analysis like *Kendall rank correlation* or *Spearman correlation* should be used when examining the research question: "*Is there a statistically significant relationship between waiting time and other operational efficiency indicators?*". Thus, the correlation between performance metrics is investigated by mentioned statistical methods in SPSS. The Kendal and Spearman correlation test results are given in the following table.

As seen in the table, the correlation coefficients vary between 0.731 and 0.926, implying a strong positive relationship between customers' waiting times and the operational efficiency of the FAPSs. Also, it is seen in Table 4.3 that the strongest

relationship with waiting time belongs to the daily total transfer distance (total distance traveled in the system).

Table 4.3 Results of correlation test

Nonparametric Correlations

Correlations

			waiting_time	trans_dist	trans_time	daily_trans_dist
Kendall's tau_b	waiting_time	Correlation Coefficient	1,000	,731**	,748**	,754**
		Sig. (2-tailed)	.	,000	,000	,000
		N	240	240	240	240
	trans_dist	Correlation Coefficient	,731**	1,000	,975**	,819**
		Sig. (2-tailed)	,000	.	,000	,000
		N	240	240	240	240
	trans_time	Correlation Coefficient	,748**	,975**	1,000	,834**
		Sig. (2-tailed)	,000	,000	.	,000
		N	240	240	240	240
	daily_trans_dist	Correlation Coefficient	,754**	,819**	,834**	1,000
		Sig. (2-tailed)	,000	,000	,000	.
		N	240	240	240	240
Spearman's rho	waiting_time	Correlation Coefficient	1,000	,917**	,918**	,926**
		Sig. (2-tailed)	.	,000	,000	,000
		N	240	240	240	240
	trans_dist	Correlation Coefficient	,917**	1,000	,998**	,960**
		Sig. (2-tailed)	,000	.	,000	,000
		N	240	240	240	240
	trans_time	Correlation Coefficient	,918**	,998**	1,000	,960**
		Sig. (2-tailed)	,000	,000	.	,000
		N	240	240	240	240
	daily_trans_dist	Correlation Coefficient	,926**	,960**	,960**	1,000
		Sig. (2-tailed)	,000	,000	,000	.
		N	240	240	240	240

**. Correlation is significant at the 0.01 level (2-tailed).

In this way, the assumption that the average transfer distance can be determined and utilized as the objective of the optimization problem related to allocation decisions is supported by statistical analysis. However, another analysis is needed to support the argument that “the average transfer distance” directly affects the customers' waiting time. Thus, the linear relationships of the performance metrics are examined via regression analysis in the following subsection.

Regression Analysis: Regression analysis is a powerful statistical method for examining the relationship between two or more variables of interest. While there are many types of regression analysis, at their core, they all examine the influence of one or more independent variables on a dependent variable. In this section, the dependency

of the customers' waiting time on operational efficiency is examined. Thus, waiting times are considered a dependent variable while the other performance metrics are considered an independent variable. The analysis is conducted for single independent and single dependent variables.

Dependent Variable: average customers' waiting time per operation that we are trying to understand or predict.

Independent Variable(s): average transfer distance, transfer time per operation, and daily transfer distance (all are considered separately) that have an impact on your dependent variable (we hypothesize).

Table 4.4 Results of regression test

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-4,278	,211		-20,321	,000
	trans_dist	,086	,002	,927	38,142	,000

a. Dependent Variable: waiting_time

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-4,958	,228		-21,721	,000
	trans_time	2,568	,067	,927	38,111	,000

a. Dependent Variable: waiting_time

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-4,934	,226		-21,814	,000
	daily_trans_dist	,001	,000	,928	38,356	,000

a. Dependent Variable: waiting_time

The results of the regression models produced by SPSS are presented in Table 4.4 with the constants and coefficients of each model. The "Adjusted R Square" value in Table 4.5 shows the estimated power of the created equation. The models' estimated power is 85.9%, 85.9%, and 86% for transfer distance, transfer time per operation, and daily transfer distance, respectively.

Table 4.5 Results of Adjusted R Square

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,927[a]	,859	,859	,58970

a. Predictors: (Constant), trans_dist

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,927[a]	,859	,859	,59011

a. Predictors: (Constant), trans_time

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	,928[a]	,861	,860	,58687

a. Predictors: (Constant), daily_trans_dist

On the other hand, the ANOVA analysis helps to understand if the created model is meaningful. Since the significance values presented in Table 4.6 are (sig.) 0.000 <0.05, it can be interpreted that the equations created are meaningful models.

Table 4.6 Results of ANOVA Test

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	505,901	1	505,901	1454,784	,000[b]
	Residual	82,764	238	,348		
	Total	588,665	239			

a. Dependent Variable: waiting_time

b. Predictors: (Constant), trans_dist

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	505,787	1	505,787	1452,461	,000[b]
	Residual	82,878	238	,348		
	Total	588,665	239			

a. Dependent Variable: waiting_time

b. Predictors: (Constant), trans_time

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	506,694	1	506,694	1471,179	,000[b]
	Residual	81,971	238	,344		
	Total	588,665	239			

a. Dependent Variable: waiting_time

b. Predictors: (Constant), daily_trans_dist

After all, the decision to consider the transfer distance as an objective function of the optimization-based planning algorithm is supported by statistical analysis. The following hypotheses are laid behind this decision.

(i). There is a positive correlation between operational efficiency and average waiting time

(ii). The operational efficiency directly affects the customer waiting time are approved in this way.

4.3 System Parameters of the Experimental Study

Examining the parameters related to FAPSs in two categories as, deterministic and stochastic system parameters, is possible. For the first group of parameters, the corresponding values are (mostly) confident, and data acquisition is relatively easy. However, the second group of parameters is difficult to collect, and the raw data is not suitable for direct use. Therefore, there is a need for additional analyses to produce valid data for the system (Guo et al., 2016). Hence, the parameters of the FAPS considered in the experimental study are examined in two subsections.

4.3.1 Deterministic System Parameters

The system's aforementioned physical and technical features are the members of the first group parameters. The size and layout of the slots and building, the speed of the transporters and other mechanical equipment, and the capacity of the system -the number of the slots-are parameters that should be appropriately identified. These parameters have deterministic values that are decided at the design and installation phase. The other design assumptions related to the system considered for the experimental study can be summarized as follows. The FAPS has:

- ✓ Rectangular design
- ✓ Multi-story structure
- ✓ Single entrance/ exit point

- ✓ Single aisle
- ✓ Single depth slot layout
- ✓ Single transporter (robot) moving vertically on the z-axis and horizontally on the x-axis
- ✓ Conveyors move horizontally on the y-axis.

The following floor structure representation (Figure 4.2) might help to comprehend the system's dimensions. The horizontal moves carried out on each floor are considered on the (x-y) axis, whereas the vertical moves between floors are considered on the z-axis. In this case, the transporter is responsible for vertical and horizontal transportation on the z-axis and x-axis. Once the transportation on the x-axis is ended, the conveyors execute the horizontal transport on the y-axis. By ignoring the acceleration and deceleration, it is assumed that the speed of the transporter and conveyors on the corresponding axis is constant and the same as 0.5 meters in a second.

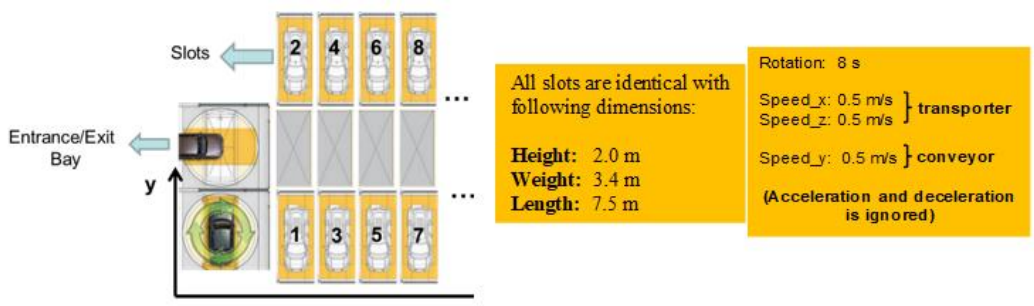


Figure 4.2 Floor structure and slots layout of the considered FAPS

Additionally, Figure 4.2 demonstrates the floor layout in terms of slots. The single entrance/exit bay is located on the grounded floor, and the cars are rotated in it so that they can be inserted into slots and transported to the upper floors. Similarly, the cars are rotated in the same bay at the end of the retrieve operation so drivers can leave the system. Because of these rotations, the bay has a square shape of 8x8 m size, except that all other slots are identical and have the same size indicated in Figure 4.2.

As a final issue, the specified multi-story FAPS consists of 10 floors. There are ten slots on each floor, five located at the right and left of the aisle. Therefore, the total capacity of the considered tower type FAPS is 100 slots, namely 100 cars.

4.3.2 Stochastic System Parameters

In addition to the physical and technical data, data, including required information about the customer, also should be provided before investigating system performance. The customer structure is discussed in Chapter 3 as the primary source of the system's uncertain and highly dynamic nature. Therefore, a detailed customer analysis should be conducted when designing the system and setting technical parameters. An accurate analysis is a crucial factor that leads to the efficient design and operating system. As a result of the analysis, critical parameters like the daily number of customers, arrival and departure pattern of customers, and the parking duration of customers should be mined from raw customers' data.

The performance of proposed dispatching rules highly depends on the customer's behavior. All parameters in question are not deterministic and have stochastic nature. The number of customers, arrival and departure times, and parking durations of the customers take probabilistic values within a day. For example, in rush hours, when people commute to and from work, the parking and retrieval demand would be pretty high, whereas other hours would be relatively balanced but never known exactly. Similarly, the parking durations differ from customer to customer and are generally not predictable. Therefore, the actual customer behavior data should be obtained and analyzed to construct a reliable simulation model and ultimately give credible results.

With this motivation, real data is provided from a FAPS located in Izmir/Alsancak. The provided data consists of customer records from the first three months (January, February, and March) of 2017, and the following statistical information is extracted from these records.

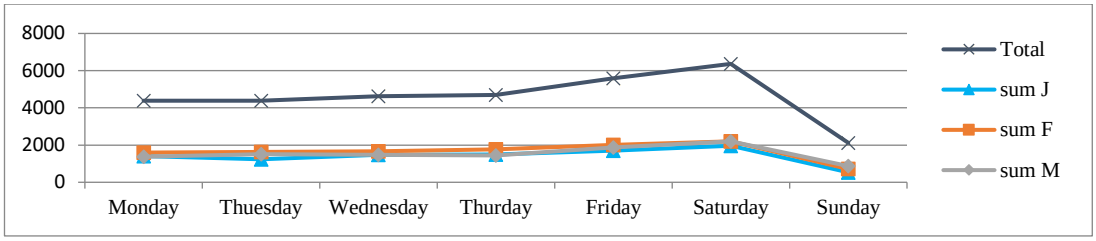
1. The number of customers
2. The arrival and departure patterns of these customers, and
3. How long do they park their cars (parking durations)

Primarily, these records are filtered and cleaned to ensure proper data sets, which enable to carry out overall analyses and, consequently, statistical analyses. Input Analyser of Arena® Simulation Software is utilized to determine the relevant statistical distributions of the customer profile. The software applies different goodness-of-fit tests like Chi-Square and Kolmogorov-Smirnov to the given data file and determines the distribution that will best fit the data. All applicable distributions are fitted to the data, and then the distributions are sorted based on their corresponding square errors (Chung, 2003; RockwellAutomation, n.d.; Zapcui, Miron; Gungi, 2015). In this way, the most suitable distribution functions for the case of Izmir are discovered. The detail of all analyses is clarified in the following subsections.

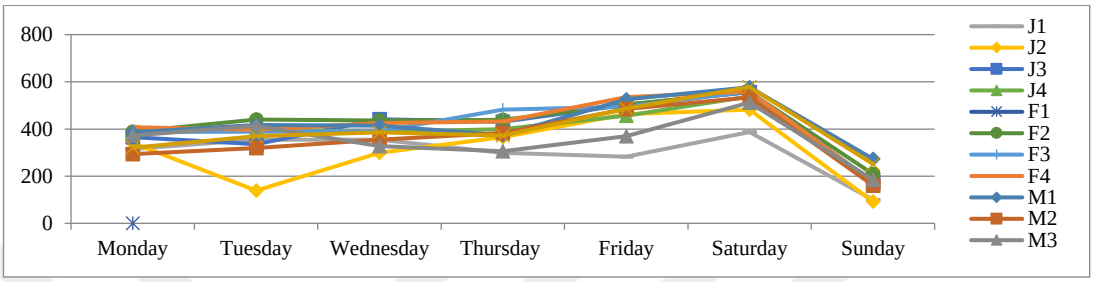
4.3.2.1 Analysis of Customer Number

According to the data for three months, more than 30,000 customers used the system at issue. The daily customer arrivals (demand) in the data examined varies from 92 to 578. This significant variability leads to investigating the cause of this situation and determining if variability depends on some variables. The first analysis of charts showed that (Figure 4.3a) there is no great difference between months regarding the number of customers. However, the same data, when visualized depending on the day of the week, indicates that the number of customers differentiates according to the days of the week. Moreover, a similar week pattern is observed within the three months (Figure 4.3b), except for very limited cases.

It is explicitly seen that there is a pattern for the week, in which the number of customers is varied on different days. The next step is statistically analyzing the number of customers varied on days of the week to determine the probability distribution functions that belong to each day. By the way, it is proved whether there are meaningful statistical differences between the number of daily arrivals.



(a)



(b)

Figure 4.3 The number of customers based on days of the week

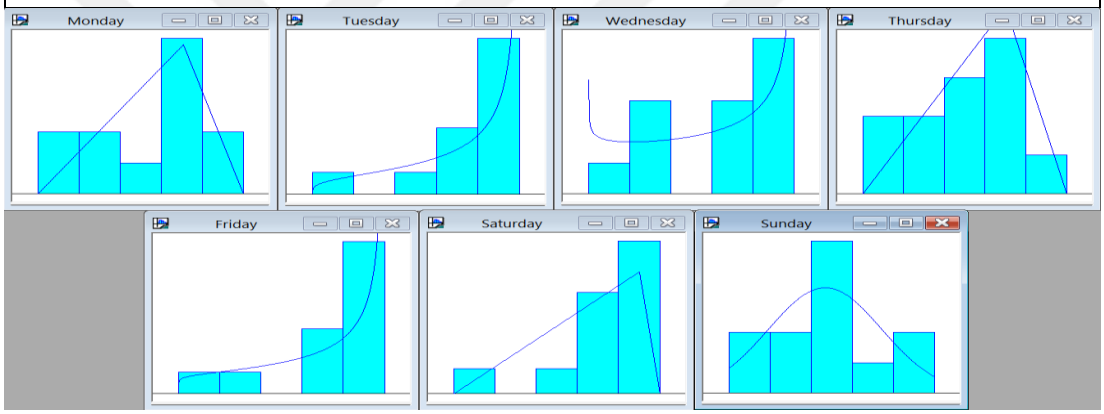
With the help of the Input Analyser of Arena® software, it is possible and easy to determine the best distribution function that represents the data set belonging to each day. The software applies the goodness of fit tests for all possible distributions and suggests the best-fit distribution function of the data based on square error. The detail of best-fit functions is introduced in Table 4.7.

The distribution functions are produced by using 12 samples (12 weeks' data) of each day to represent the variance of customer numbers depending on the days of the week (Guo et al., 2016). Based on the given data, the number of customer arrivals fits the triangular distribution (Monday, Thursday, Saturday) and the beta distribution (Tuesday, Wednesday, Friday) for six days of the week, and only Sunday fits the normal distribution.

Table 4.7 Distribution functions of customer numbers that are used in the experimental study

	Distributions' Parameters	Distribution Function	[3]SSE
Monday	Triangular $f(x; a, b, c)$	TRIA(294, 383, 419)	0.056548
Tuesday	[1]Beta $f(x; \alpha, \beta)$	139 + 301 * BETA(1.25, 0.413)	0.057014
Wednesday	[1]Beta $f(x; \alpha, \beta)$	299 + 142 * BETA(0.884, 0.563)	0.044574
Thursday	Triangular $f(x; a, b, c)$	TRIA(299, 427, 482)	0.016156
Friday	[1]Beta $f(x; \alpha, \beta)$	282 + 253 * BETA(1.09, 0.414)	0.044131
Saturday	Triangular $f(x; a, b, c)$	TRIA(387, 559, 578)	0.083642
Sunday	[2]Normal $f(x; \mu, \sigma)$	NORM(177, 49.9)	0.045688

[1] $Beta\ distribution: 0 \leq x \leq 1\ and\ \alpha, \beta > 0$
[2] $Normal\ distribution: \mu = mean, \sigma = standart\ deviation$
[3] $SSE: Sum\ of\ Square\ Error = \{fi - f(xi)\}^2$



The software provides all parameters of distribution functions discovered. The statistical test (Kolmogorov-Smirnov goodness-of-fit) results indicate a good fit for all cases according to acceptable SSE values. SSE is defined as the sum of $\{fi - f(xi)\}^2$ for overall histogram intervals and primarily represents the quality of a curve fit (Arena®). Thus, these distribution functions could be utilized in the simulation model to generate different customer numbers to ensure the validity of the experimental study and its results. However, there is an assumption about the number of customers in our experimental study. The number of customers that will arrive in our hypothetic system is assumed as half of the real system because the system considered in this study has half the capacity of Alsancak FAPS. Except for that situation, all other customer parameters are strictly used as they are discovered.

4.3.2.2 Analysis of Arrival and Departure Pattern of Customers

As stated before, customer arrivals and departures are not balanced in a day due to rush hours. Furthermore, as the commute to work is considered, most parking requests are higher than retrieval requests in the early morning and vice versa in the evening. This situation is valid for the downtowns where the car parking problem is an important issue. Of course, there are exceptions to this behavior due to residents settled near the FAPS and who park their cars after work. Regarding all these situations, the density of requests within a day should be analyzed carefully. Based on the data provided from the Alsancak FAPS, customer arrival and departure times belonging for one week are visualized in Figure 3.9.

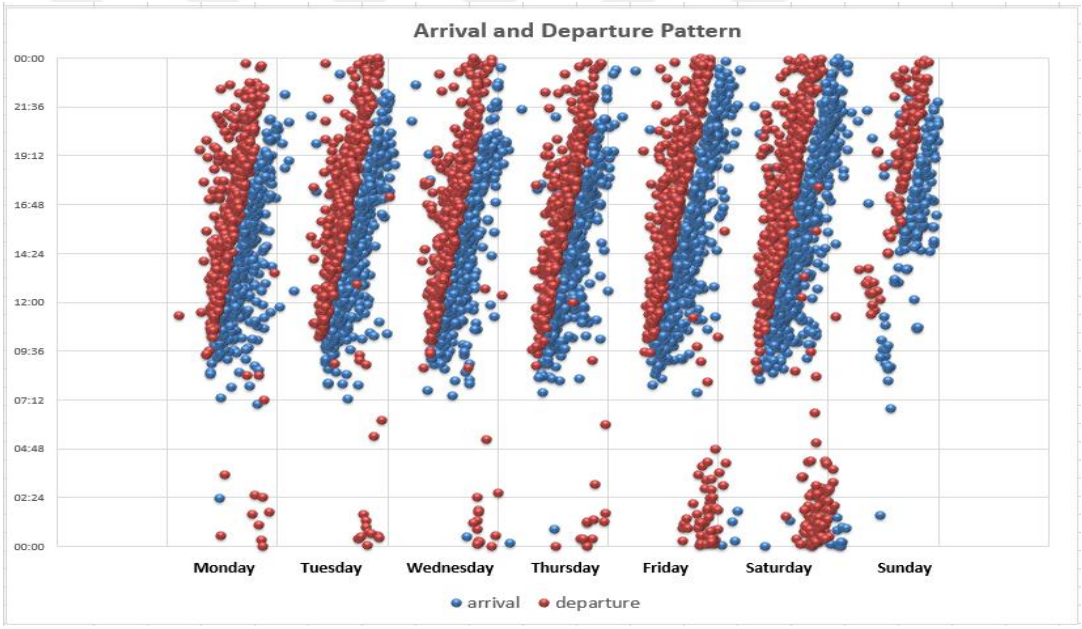


Figure 4.4 Arrival and departure pattern of the customers based on days of the week

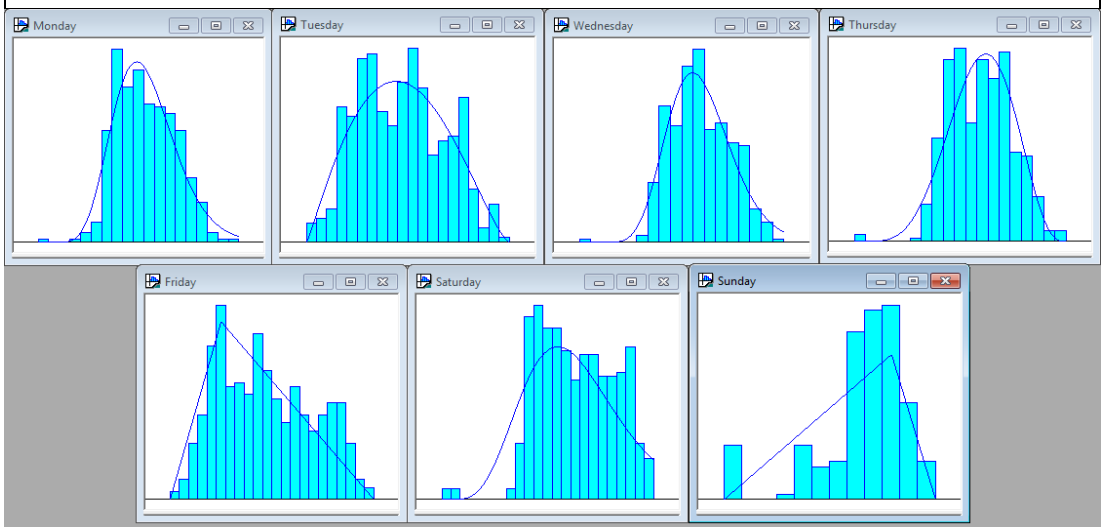
In addition to the pattern that depends on work hours, an additional parking and retrieval pattern arises on Friday and Saturday nights because customers' behavior is changed at the weekend. Parking requests are increased after 19:00, and some of the retrievals' requests sag to after midnight between 00:00-04:00. On the other side, Sunday has a quite different pattern from the arrival and departure patterns observed on other days. Fewer customers and more balanced but irregular arrival and departures are observed through this day.

The relevant data set is also analyzed in Arena® Input Analyser to discover underlying patterns and trends. However, a reminder is needed before starting statistical analyses about the arrival and departure pattern of the customer. Unlike the queueing theory, the inter-arrival times are not considered for the case of FAPSs since it is not possible to observe a homogeneous customer distribution spread all day; consequently, a single inter-arrival pattern for a day. Therefore, to be more practicable (Guo et al., 2016), the moment of the day is considered instead of the inter-arrival times of customers, and the number of requests that arrive at those moments is analyzed in this study. The detail of best-fit functions is introduced in Table 4.8.

Table 4.8 Distribution functions of arrival patterns of the days

	Distributions' Parameters	**Distribution Function**	**[3]SSE**
Monday	[1]Gamma $f(x;k,\theta)$	2 + GAMM(11.5, 1.02)	0.003987
Tuesday	[2]Beta $f(x;\alpha,\beta)$	7 + 16 * BETA(2.13, 2.43)	0.004665
Wednesday	[1]Gamma $f(x;k,\theta)$	GAMM(13.7, 1.04)	0.004272
Thursday	[2]Beta $f(x;\alpha,\beta)$	24 * BETA(6.07, 4.11)	0.006749
Friday	Triangular $f(x;a,b,c)$	TRIA(7, 11.3, 24)	0.004850
Saturday	[1]Gamma $f(x;k,\theta)$	-0.001 + GAMM(2.28, 6.69)	0.008231
Sunday	Triangular $f(x;a,b,c)$	TRIA(-0.001, 19, 24)	0.030448

[1] $Gamma\ distribution$: $k,\theta > 0$ $where\ k\ shape, \theta\ scale\ parameters\ and\ k * \theta = \mu$ (mean)
[2] $Beta\ distribution$: $0 \leq x \leq 1\ and\ \alpha,\beta > 0$ where α,β are shape parameters
[3] $SSE: Sum\ of\ Square\ Error = \{\text{fi} - \text{f(xi)}\}^2$

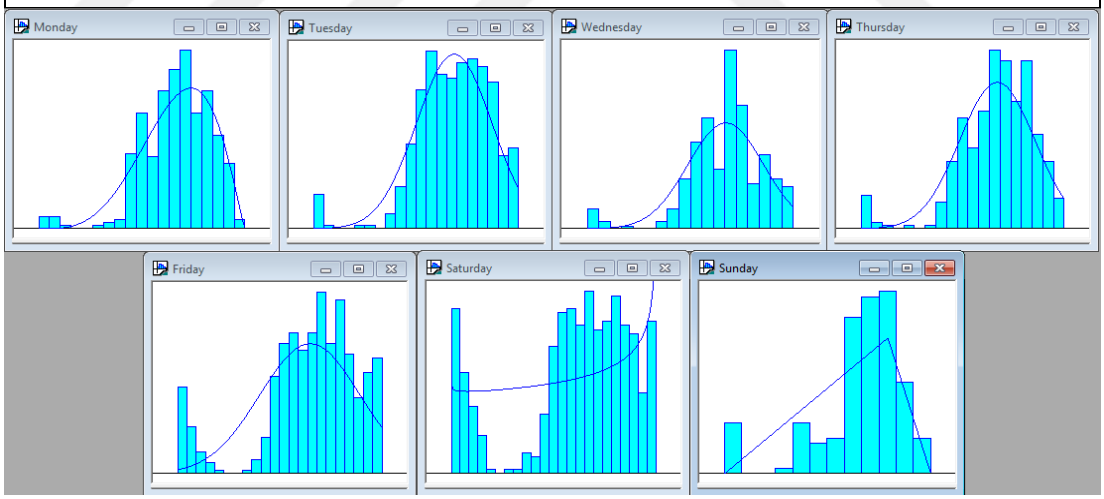


It can be seen from Table 4.9 that all distribution functions have a good fit according to SSE values. The reason is that the distribution functions' parameters and predicted variables are related to continuous moments between (00:00-24:00) of the day.

Table 4.9 Distribution functions of departure patterns of the days

	Distributions' Parameters	**Distribution Function**	**[3]SSE**
Monday	[1]Beta $f(x;\alpha,\beta)$	-0.001 + 24 * BETA(4.58, 2.29)	0.005597
Tuesday	[2]Normal $f(x;\mu,\sigma)$	NORM(16.4, 4.41)	0.003739
Wednesday	[2]Normal $f(x;\mu,\sigma)$	NORM(16.1, 4.41)	0.015429
Thursday	[2]Normal $f(x;\mu,\sigma)$	NORM(16.1, 4.43)	0.006464
Friday	[2]Normal $f(x;\mu,\sigma)$	NORM(15.5, 5.88)	0.011663
Saturday	[1]Beta $f(x;\alpha,\beta)$	-0.001 + 24 * BETA(0.983, 0.789)	0.015944
Sunday	Triangular $f(x;a,b,c)$	TRIA(-0.001, 19, 24)	0.030448

[1] $Beta\ distribution: 0 \leq x \leq 1\ and\ \alpha,\beta > 0$ where α,β are shape parameters
[2] $Normal\ distribution: \mu = mean, \sigma = standart\ deviation$
[3] $SSE: Sum\ of\ Square\ Error = \{fi - f(xi)\}^2$



Another great point is that in addition to the identical distributions having different parameters, there is a wide variety of arrival distribution patterns like Gamma, Beta, and Triangular distribution patterns. This situation is another convincing result that the customer attributes should be reflected in the simulation model according to the days

of the week. The same analysis was conducted for the data containing the customers' departure information. The detail of best-fit functions is introduced in Table 4.9.

4.3.2.3 Analysis of Parking Durations

Parking duration refers to how long the customers leave their cars in the system. On the one hand, this parameter is the key factor that shapes the departure pattern of the customer. On the other hand, this attribute highly affects the efficiency of allocation decisions and, consequently, the system's operational efficiency. Figure 4.5 illustrates customers' behavior in terms of parking durations.

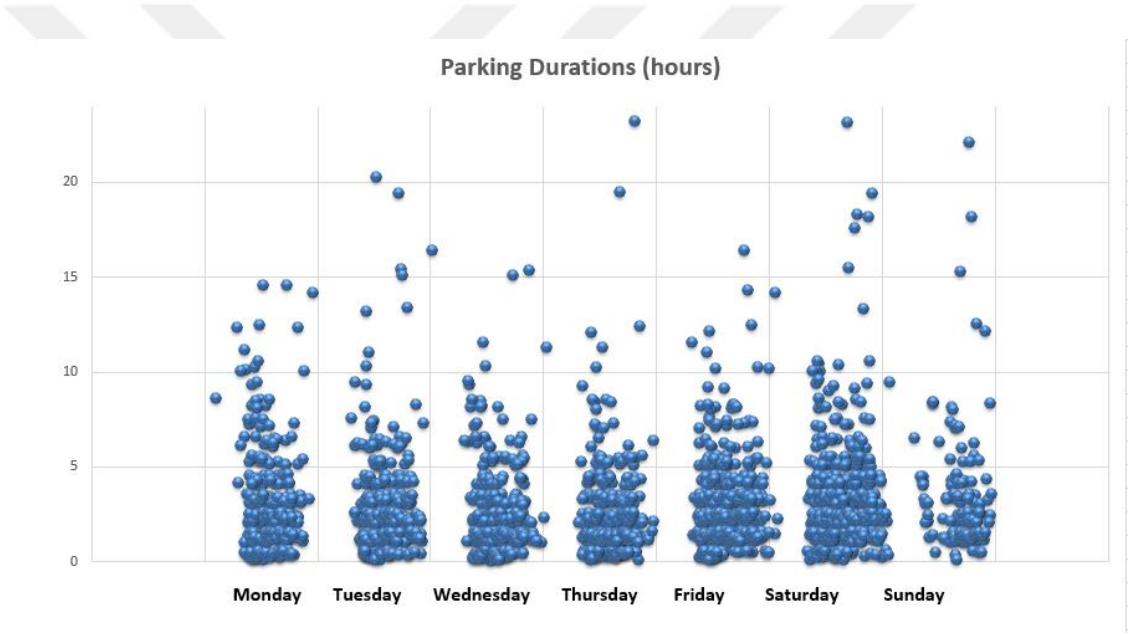


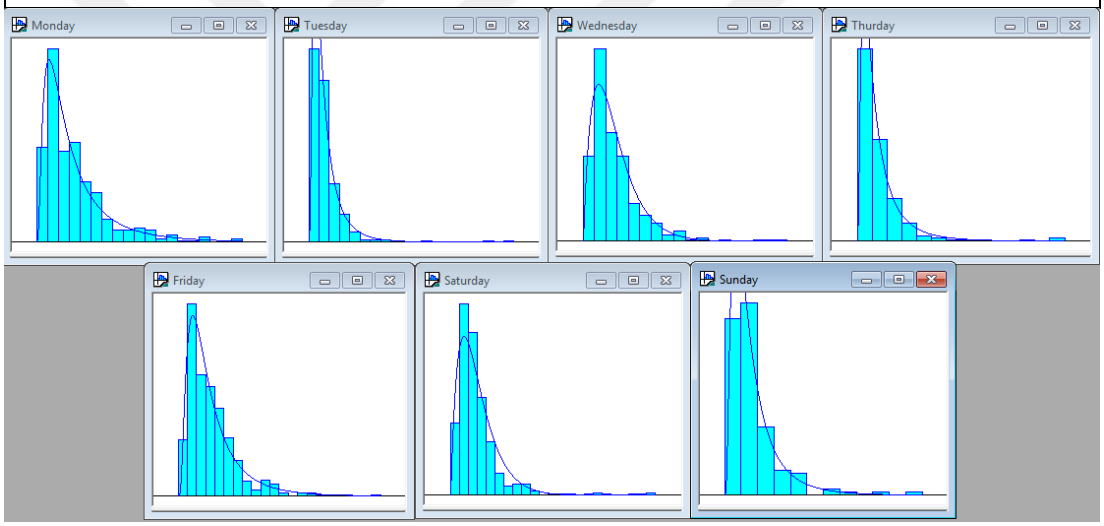
Figure 4.5 Parking duration of the customers based on days of the week

Although there are a few cases where durations are more than 20 hours, it is seen that the vast majority of the customers park their cars for less than 10 hours. Moreover, most of these customers do not exceed 5 hours of parking duration. On the other side, similar to the other attributes, different duration patterns are observed for different days of the week. When these patterns are analyzed statistically, the following probability distribution functions are obtained. The distribution functions are given with their parameter values in Table 4.10.

Table 4.10 Distribution functions of parking durations of customers depending on days of the week

	Distributions' Parameters	**Distribution Function**	**[3]SSE**
Monday	[1]Lognormal $f(x;\mu,\sigma)$	LOGN(2.96, 3.26)	0.004684
Tuesday	[1]Lognormal $f(x;\mu,\sigma)$	LOGN(2.79, 2.75)	0.001334
Wednesday	[2]Gamma $f(x;k,\theta)$	GAMM(1.52, 1.69)	0.013259
Thursday	[1]Lognormal $f(x;\mu,\sigma)$	LOGN(2.6, 2.97)	0.000498
Friday	[1]Lognormal $f(x;\mu,\sigma)$	LOGN(2.91, 2.58)	0.003551
Saturday	[2]Gamma $f(x;k,\theta)$	GAMM(1.77, 1.92)	0.011073
Sunday	[1]Lognormal $f(x;\mu,\sigma)$	LOGN(3.28, 3.09)	0.004846

[1] $Lognormal: 0 \leq x \; and \; \mu = mean, \sigma = standart \; deviation$
[2] $Gamma \; distribution: \;\; k, \theta > 0 \;\; where \; k \; shape, \theta \; scale \; parameters \; and \; k * \theta = \mu$ (mean)
[3] $SSE: Sum \; of \; Square \; Error = \{\text{fi} - \text{f(xi)}\}^2$



As seen in Table 4.10, two distribution functions, Lognormal and Gamma, can represent parking duration patterns for all days of the week with pretty low SSE values. The mean of the samples (μ) and standard deviation (σ) are the parameters of Lognormal, whereas a shape (k) and scale parameters (θ), where $* \theta = \mu$, are used in Erlang. As a practical interpretation, the discovered functions show that the mean parking duration and the variance of these durations are varied by day.

So far, all analyses are carried out to provide the required inputs for the simulation model that will be employed to compare the performance of different dispatching rules. In the first step, the deterministic system inputs and physical and technical features of the considered FAPS are specified. In the second step, a real data set containing customer information is attained and statistically analyzed to extract the stochastic customer behaviors. In this way, the input analysis, one of the most critical phases of simulation modeling, is completed. Hereafter, the simulation model simulation can be utilized to test the developed algorithms and evaluate the distribution rules' performance. Finally, the effects of different dispatching rules will be compared in terms of operational efficiency, measured mainly by customer waiting times and total distance traveled in the system in the following section.

4.4 The General Structure of the Simulation Model

In the next step, a simulation model is constituted to test the developed algorithm's validity and evaluate the performance of dispatching rules, as the simulation is probably the most convenient tool for analyzing such dynamic and stochastic systems. The developed simulation model and its essential components are presented in Figure 6. Based on the problem structure, on the one hand, physical and technical features of the considered FAPS and customer profile details are inputs of the simulation model. On the other hand, the following operation that will be handled and the place where the car will be placed constitute decision variables of the system. Here, the proposed algorithm and different combinations of the proposed dispatching rules are utilized as described in Figure 4.6. Finally, the efficiency of the candidate dispatching rules will be evaluated depending on performance measurements (system's output) like average customer waiting time and the average distance traveled in the system.

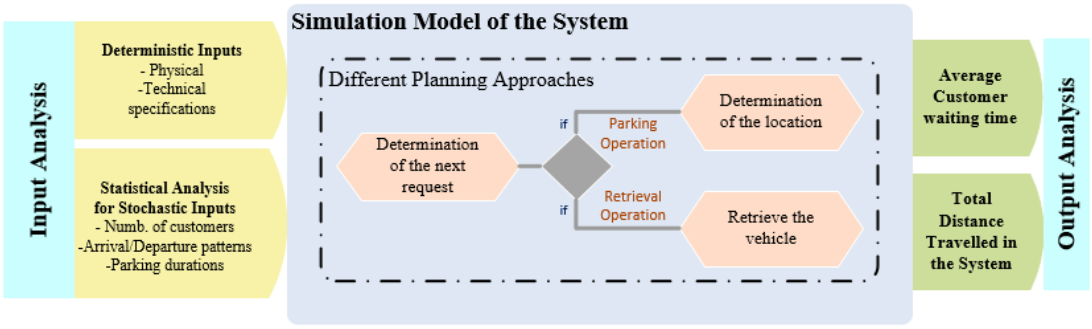


Figure 4.6 The main components of the developed simulation model

Considering the importance of the system parameters, it becomes more critical to consider their deterministic and stochastic natures when providing inputs to the simulation model. Therefore, the following section and subsections provide detailed information about the assumptions and other specifications of the FAPS considered in the experimental case study.

4.5 Verification and Validation of the Simulation Model

The simulation model is built on physical-technical details, and actual customer data analyzed statistically in the previous section. However, at this point, there is an important decision about the simulation modeling approach. There is no doubt that discrete event simulation is suitable for FAPSs as variables change in discrete times and by discrete steps. In addition, two simulation modeling approaches depend on the characteristics of the real system and the purpose of the simulation study. These approaches are terminating or non-terminating simulation modeling. Terminating systems have initial starting conditions, a natural terminating event. On the other hand, in general, non-terminating systems can either have a terminating event but keep entities in the system between periods and not have a terminating event and run continuously (Chung, 2003).

Considering customer behaviors and discovered data patterns, it could be thought that FAPSs should be modeled as a terminating system. However, we know that FAPSs are commonly open 7/24 most of the time, and customers can leave or retrieve their car anytime. Besides, interdependent events may not end within a day. An

excellent example of this situation is that the customers leave their car for the night and retrieve it early in the morning when the committee to work. Another example is that some customers retrieve their cars a couple of days after leaving. All these circumstances indicate that the FAPSs are continuous systems even though their parameters have a discrete nature. With this, the other features of the simulation model developed within the scope of the study are summarized as follows:

- The non-terminating simulation model of the system is developed.
- The considered system's capacity and the customers' density are balanced. That means customer arrivals generally do not exceed the capacity at any time.
- The customers waiting for parking in the queue do not leave the system or are not rejected unless the capacity is full.
- Stochastic parameters of the model, which are related to customers, vary depending on the week's days.

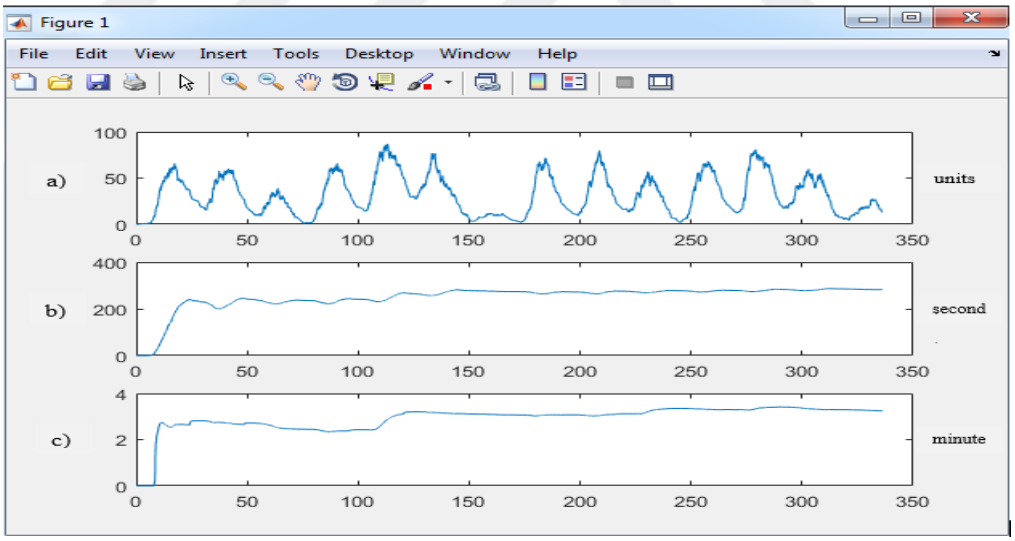


Figure 4.7 An overview of the system at the end of the 14 days simulation run: a) the number of cars in the system, b) the average time spent per operation, c) the average customer waiting time per operation

The simulation model is developed in MATLAB environments based on these facts and assumptions. After that, the model is run for two weeks (14 days) period of the system to check the pattern of system parameters and verify the simulation model. The state variables that denote the number of cars in the system (a), the average time spent

per operation (b), and the average customer waiting time per operation is depicted hourly through the simulation run length in Figure 4.7. In addition to the number of cars at a certain time in the system, Figure 4.7 (a) also indicates arrival and departure patterns.

The relevant graph (Figure 4.7) also shows that the customer behaviors are reflected successfully in the model with the help of the distribution functions. Besides, the figure proved that the system never turns to the starting condition at any time, which means the FAPS is a non-terminating system. Figure (b)-(c) reveals that the system reaches to steady-state after 120 hours (5 days) from the zero initial state. This period is entitled a warm-up period, and the effect of this period should be eliminated from the overall system (Özgün & Barlas, 2009). Thus, the simulation run length should be determined appropriately to ensure accurate results free of starting conditions. It is known that a long simulation run enhances the quality of the results. On the other hand, previous research suggests a 10-times warp-up period for the non-terminating simulation models (Chung, 2003).

CHAPTER 5
THE CLASSIC RULE-BASED PLANNING AND CONTROL APPROACH

The number of vehicles is still growing, and this causes severe traffic congestion and parking problems in cities. In contrast to the population growth and the motorization rate increases (Buehler et al., 2017), the available space in cities is dramatically decreasing. Thus, parking is becoming one of the most disturbing problems for citizens and governments. In order to relieve this problem, several parking models (Ahamed & Jovanov, 2009) and pricing policies (Barter, 2012; Baykasoğlu & Ercan, 2021; Marsden, 2006; Van Ommeren et al., 2011; R. Zhang et al., 2016) have been proposed. Unfortunately, traditional flat systems cannot meet the parking demands due to large space requirements. In this respect, the need to use the scarce real estate space in downtowns leads to building multi-story parking systems (Pypno, 2008). Such systems offer a certain degree of relief by using the vertical space instead of the horizontal space.

Some related surveys approve of insufficient conventional systems (Downtown Parking Survey, 2017; *Survey of North Sydney*, 2016; *Survey of Portsmouth*, 2017; *Survey of Washington*, 2017; *Survey of Wolfville*, 2015). Moreover, these systems waste considerable time and resources (such as gas and fuel), resulting in pollution and vehicle wear while searching for available parking slots. In order to avoid such problems, many new technologies have been developed (Olia et al., 2016; Y. J. Wu et al., 2015). One of them is the Fully Automated Parking Systems (FAPSs), where sensor technology is utilized, and the parking process is carried out via automatic carriers (robots). FAPSs integrate software systems with mechanical lifts and pallets to store/retrieve vehicles in multi-level modular garages. They use vertical and horizontal space efficiently and utilize up to 84% by staking cars together more closely than conventional parking systems (Serpen & Dou, 2015). In addition to high space utilization in FAPSs, time and energy savings are ensured by avoiding searching for available parking slots. These advantages provide drivers and governments with green and sustainable parking solutions.

The technological improvements in the past two decades have also increased the popularity of FAPS all over the world. However, in addition to high installation (setup) costs, these systems generally have long service times. Particularly during rush hours, parking and retrieving might take too long. The long waiting time is possibly due to three main reasons: technical issues, poor planning, and customer-oriented problems. Unless well-planned schedules and operational planning do not support mechanical and technological improvements, dissatisfied customers cannot be avoided due to long waiting times. The design of FAPS is a challenging issue; however, efficiently operating the designed FAPS is another challenging issue that directly affects the performance of the used system.

In this context, this study develops several dispatching rule-based algorithms capable of efficiently sequencing the requests of allocating/retrieving vehicles in FAPS. Furthermore, allocating and retrieving problems bring about several other challenging problems such as assignment, sequencing of parking robot movements, and real-time task assignments. In this context, the mentioned operational problems (such as sequencing, scheduling, and allocation) in FAPSs are combinatorial. Moreover, they include uncertainty, which means that the developed algorithms should be able to run under dynamic and stochastic conditions to generate real-time solutions. For this purpose, dispatching rules and heuristics are employed to solve the problem mentioned in the present study. Secondarily, a simulation model is generated to test the performances of the developed algorithms and dispatching rules considering the dynamic and stochastic nature of the problem. Thus, the most efficient operating rules among several strategies are found for FAPS. In this regard, this study is expected to fill an essential gap for FAPS.

The remaining of this paper is organized as follows. In section two, the problem is discussed, and contributions are highlighted to the gap in the literature. Then, candidate dispatching rules and heuristics are determined and defined in the following section. The simulation model and modeling assumptions are introduced in section two. Section three presents the results of the simulation study and the dispatching rules/heuristics performance. Performance analysis of dispatching rules is also

investigated in the same section. Finally, the research summary and the general conclusion are made in section four.

5.1 Candidate Dispatching Rules and Heuristics for FAPS's Operations

FAPSs are particular cases of warehouses using automated storage/retrieval systems (AS/RS). In both systems (Figure 5.1), the entities stored for a specific time are taken from an input-output (entry-exit) point and allocated to a predetermined location by automated carriers. Automated carriers also perform the retrieval operation and end at the input-output point after the transport. All operations are performed without an operator's need to be fully automated (Roodbergen & Vis, 2009).

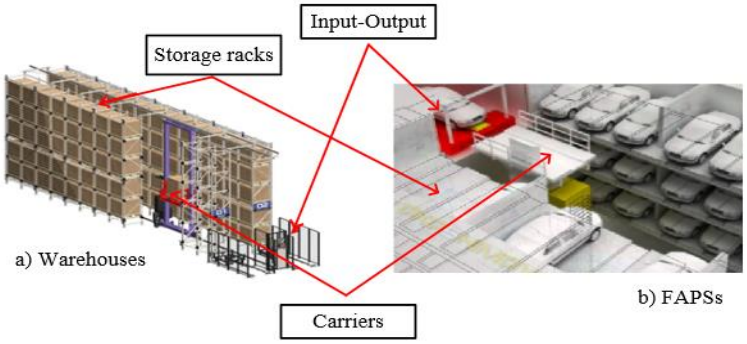


Figure 5.1 The design similarities between FAPSs and fully automated warehouse systems

Despite these design similarities, the system environments are quite different in terms of entities, the flow of these entities, and operations management. In order to explain these differences, it is necessary to mention the material flow, activities, and as a result, the operational problems encountered in warehouses. As can be seen in Figure 5.2, the material flow and activities in a warehouse can be divided into four categories: receiving, storage, order picking, and shipping (Barter, 2012; Bartholdi & Hackman, 2011; Berg & Zijm, 1999; Ertek, 2012; Hrabovský & Dluhoš, 2020; Manzini, 2012). At the same time, additional activities/decisions such as breakbulk consolidation, sequencing, sequencing, batching, and routing are also carried out to increase operational efficiency at different stages. All these external activities increase warehouse efficiency, flexibility, and response time (Berg & Zijm, 1999; De Koster et al., 2007; Gu et al., 2007; Serpen & Dou, 2015; Won & Olafsson, 2005).

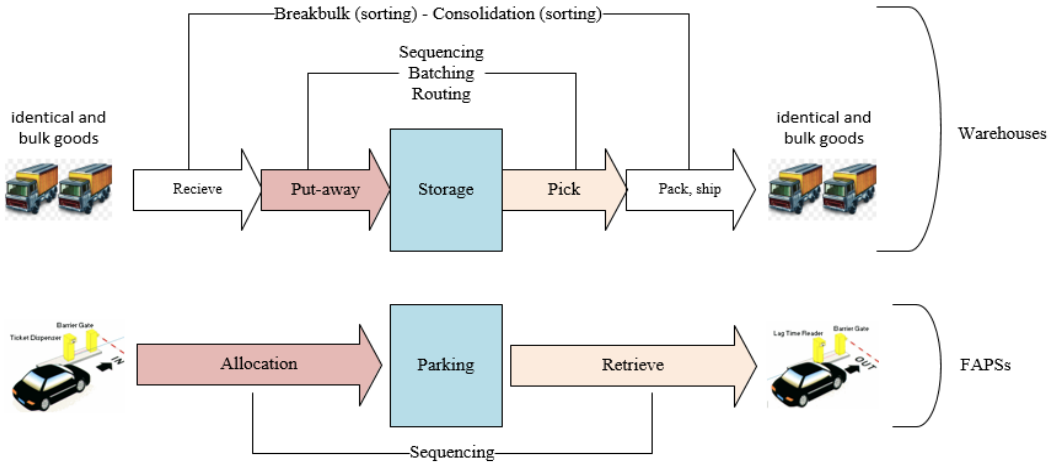


Figure 5.2 Operations in warehouses and FAPSs

In contrast to warehouses, FAPSs have a simple process flow as allocation, parking, and retrieve. In addition to these activities, only an operation/request sequencing decision might be an auxiliary managerial activity. Since the managerial decisions over the operations are very limited, the system's control and flexibility are considerably low. The other issue related to less flexibility in FAPSs is derived from the nature of the entities subject to the system. Unlike the products/materials in the warehouses, the nature of each vehicle stored in the FAPSs is entirely different. It is not possible to process vehicles as batches in FAPSs because of the nature of the entities and processes and other reasons mentioned above.

After all, it can be expressed that the most crucial point where FAPSs and warehouses are inherently separated is the control of entities and events in these systems. For example, there is complete or partial control over how many products/materials arrive at the warehouse and when and how long products are kept on the floor or the shelves as they are collected and shipped (Bartholdi & Hackman, 2011; Ertek, 2012; Manzini, 2012). However, it is not possible to talk about the same situation in FAPSs. There is no chance to decide how many vehicles will arrive in the system and when. How long each vehicle will be parked, and when it will be a departure? At this point, we can summarize that the most significant contribution of

this thesis is managing this uncertainty in an ideal way and providing an adequate level of control through the different dispatching rules.

In addition, to be an important source of uncertainty, the customer structure/profile is the most critical factor that pressures FAPSs. Unlike warehouses, FAPSs are in direct connection with the end customers. This situation makes it impossible to compensate for some mistakes in customer satisfaction. The customer's request must be adequately and quickly responded to as soon as it is realized. Moreover, since each vehicle in the system corresponds to a customer, and considering the nature of the allocation process with the city's density, it is necessary to serve many customers in a short time. In the case of this dynamic structure and uncertainty, it is not easy to perform operations effectively and efficiently. These features are the main reason for various heuristic methods, and these systems commonly utilize dispatching rules. On the other side, in the case of warehouses, competitive market conditions also create pressure on warehouses to be more reactive and more efficient. Therefore, in addition to the combinatorial structure of the warehouse problems, getting a quick solution makes heuristics and metaheuristics algorithms inevitable in these systems. Table 5.1 summarizes the differences in characteristics of warehouse and fully automated parking systems.

Table 5.1 Comparison of fully automated warehouses and parking systems

	Warehouses	**FAPSs**
Entities (items)	Identical and bulk	Single and non-identical
Customer profile	Supply chain members	End-Customers
Number of operations (relatively)	High	Low
Uncertainty	Low	High
Dynamicity	Medium	High

Numerous effective policies and strategies are proposed in the literature to address warehouse operations like storage and retrieval processes. For example, during the familiar storage (parking) and retrieval processes carried out in FAPSs, two decision problems emerge the sequencing of the requests (storage or retrieval) and the

allocation/allocation decision of vehicles. However, even though FAPSs are similar to automated warehouse systems in design, the unique operations and the entity structure makes it impossible to utilize some good-working operational policies and rules in warehouses. For example, allocation (storage) and picking (retrieval) operations in warehouses consist of two sub-operations: batching and routing. When orders are reasonably large, each order can be picked/allocated individually (*single order*). However, when orders are small, a set of orders can be picked/allocated in a single tour (*order batching*) to reduce travel time. For this purpose, several batching and picking/locating strategies/policies have been developed, which can be grouped into capacity-based, time-based, and proximity-based batching (Gu et al., 2007). On the other side, FIFO (first-in-first-out), LIFO (last-in, last-out), and NOF (Nearest one first) dispatching rules are used as order sequencing policies and/or item sequencing rules within the batches.

As stated before, there is no chance of batching the items (vehicles) in FAPSs since each item should be handled separately. In this case, it can be thought that parking operations are conducted as a single order having a single item. Thus, only some sequencing rules fitting parking lot operations like FIFO and NOF could be utilized as dispatching rules in these systems. Similarly, there are numerous ways to determine appropriate storage locations in warehouses, such as random storage, closest open location storage, dedicated storage, whole turnover storage, and class-based storage (De Koster et al., 2007; Gu et al., 2007; Mansuri & M Mansuri, 1997; Sarker, 1995). Still, only the first two worked in FAPSs because they handled independent and unique items (vehicles).

Considering the system and process characteristics of FAPSs, candidate rules described in Table 5.2 can be utilized for the operational problems. These proposed rules are compiled for a specific tower type FAPSs with single depth selves, a single entrance-exit bay, and a single transporter lift that can move in two dimensions, vertically and horizontally. In addition to these rules, in the case of different system features (for example, multiple entrance-exit points and transporters, multi-depth selves), there would be a need for different dispatching rules to meet plan & control

requirements (for example, transporter scheduling, reallocation process). However, as stated before, the two main operational problems that can be encountered in any FAPS type are considered in the scope of this study.

Table 5.2 Candidate dispatching and heuristic rules

	Dispatching Rules	Description
Request Sequencing Rules	First Come First Served (FCFS)	No matter the type of request, the priority always belongs first to come.
	*Parking Requests First (PRF)	No matter the arrival time, the priority always belongs to parking requests. If there is no parking request and more than one retrieval request, one of the retrieval rules is utilized.
	*Retrieval Requests First (RRF)	No matter arriving time of requests, the priority always belongs to retrieval requests. If there is more than one retrieval request at the same time, one of the retrieval rules is utilized.
	Nearest Request First (NRF)	No matter type and arrival time of requests, the priority always belongs to the request nearest to the robot's last position.
Allocation Rules	Random Available Slot (RAS)	The car that will be parked will be allocated randomly to any available slot in the garage.
	Nearest Available Slot (NAS)	The car that will be parked is allocated to the nearest available slot in the garage.
	Farthest Available Slot (FAS)	The car that will be parked is allocated to the farthest available slot in the garage.
Retrieval Rules	FCFS	The priority belongs to the first arrived one amongst the other awaiting retrieval requests.
	Nearest One First (NOF)	The priority belongs to the nearest one amongst the other awaiting retrieval requests.
	Farthest One First (FOF)	The priority belongs to the farthest one amongst the other awaiting retrieval requests.

* Additional rules are required for sequencing retrieval requests within themselves.

Depending on the process flow (see Figure 3.1), the subsequent request to be handled, whether parking or retrieval, must be decided. As described in Table 5.2, four different rules can be used. Due to the specific attribute (single entrance-exit point) of the system considered in the study, it is impossible to rearrange the sequence of parking requests because they are already in a physical queue formed based on the first come, first served (FCFS rule). Therefore, there is only one decision related to parking requests in this situation: the parking slot assignment for each parked car. On the other side, customers do not wait in a physical queue when they retrieve their vehicles. Thus,

an additional sequencing rule (except for FCFS) can be set to determine the subsequent retrieval in case of more than one retrieval request in the queue. Once the subsequent retrieval request is selected, the car can be picked up from its parking slot and left at the exit bay.

5.2 The Simulation Study

This study analyzes the efficiency of different dispatching rules that can be used to address operational planning and control problems. First, a detailed literature review and observations on real systems are carried out to clearly define the problem's nature. Eventually, it was discovered that the service times and system performance are primarily affected by the allocation of vehicles and then sequencing of operations.

System features like the shape of the building and the number of entrance-exit points are the parameters related to building structure, whereas utilized transport systems like puzzle type and tower type with single or multiple depth selves correspond to technical specifications. In addition to decision variables, the decision-maker somehow controls these parameters in the system's design phase. However, there is another uncontrollable parameter and thus should be considered when both are designing and operating the system. This parameter is the customer profile related to customer density and customer behaviors such as the arrival/departure patterns and parking duration. It means that all these system parameters should be considered carefully when addressing operational decision problems. On the other side, the dispatching rules used to handle common operational problems encountered in FAPSs are identified and described in the previous section. Furthermore, the proposed rules that help to sequence the requests and assign the cars to an appropriate place are embedded in the main control algorithm, as shown in Figure 5.3, to ensure the planning and control of FAPSs.

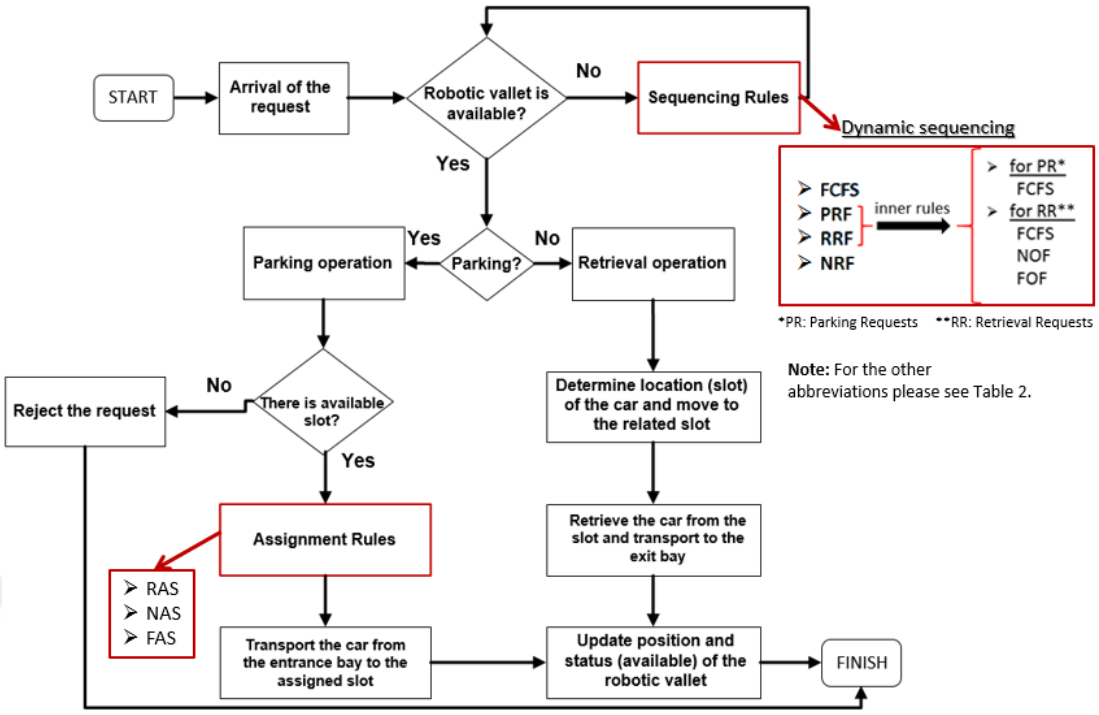


Figure 5.3 Main control algorithm and embedded heuristics and rules

It was mentioned that two performance metrics would be used to evaluate the success of the planning approaches. Namely, the average waiting time of the customers (customer satisfaction) and the total distance covered in the system (efficiency of the system). In this context, "*the total distance traveled in the system,"* which has a deterministic structure and directly affects the customers' waiting time, is considered "*the objective function*" when deciding on the optimal location. Let us assume that $Transport(x,y,z)_t$ is the starting position (coordinates) of the carrier/transporter and $Transport(x',y',z')_{t'}$ is the position of the carrier at the end of the transportation process; and V_x, V_y, V_z, gives the velocity of the carrier on x-y-z axis, respectively. In this case, $\Delta \boldsymbol{d}$ represents the distance traveled by the transporter to perform the transaction (whether parking or retrieval), and $\Delta \boldsymbol{t}$ represents the time spent on the transaction. Then, depending on the system parameters (the structure's dimensions and the carriers' speed), the distance and time traveled in each allocation and retrieval process are calculated according to the following equations.

$$\mathbf{t \rightarrow t':}\ \Delta \mathbf{d_{(Transporter)}} = |x' - x| + |y' - y'| + |z' - z| \tag{5.1}$$

$$\Delta \mathbf{t(Transaction)} = t' - t = |x' - x| / Vx + |y' - y| / Vy + |z' - z| / Vz \tag{5.2}$$

Equations (5.1) and (5.2) ensure to measure performance criteria related to the distance traveled and the time spent for each transaction. As a result, the total distance traveled in the system and the total transaction time can be calculated by Eq. (5.3) and (5.4), respectively.

$$D_{total} = \sum_{i=1}^{Nt}(\Delta \mathbf{d_i}) \qquad i \in (PT \cup RT) \tag{5.3}$$

$$T_{total} = \sum_{i=1}^{Nt}(\Delta \mathbf{t_i}) \qquad i \in (PT \cup RT) \tag{5.4}$$

Where D_{total} represents "*total distance,*" T_{total} represents "*total time*" for the transactions. Sets of *PT* and *RT* include parking and retrieval transactions, respectively, and N_t is the total number of transactions within the considered period. The mean distance traveled per transaction and mean time spent per transaction (operation) can be calculated by equations (5.5) and (5.6).

$$D_{avg} = \sum_{i=1}^{Nv}(\Delta \mathbf{d_i})/N_v \qquad i \in (PT \cup RT) \tag{5.5}$$

$$T_{avg} = \sum_{i=1}^{Nv}(\Delta \mathbf{t_i})/N_v \qquad i \in (PT \cup RT) \tag{5.6}$$

The performance criterion related to customer satisfaction is measured by the customer waiting time. However, previous studies mainly considered and used the customer waiting times related to solely retrieval transactions. (Debnath & Serpen, 2015; Serpen & Debnath, 2019). In this thesis, we consider and plan both parking and retrieval transactions at the same time. Based on previous studies, we used the following two equations to calculate customer waiting times through the parking (5.7) and retrieval (5.8) operations, respectively.

$$w_i^p = t_i^d - t_i^a \qquad i \in C_a \tag{5.7}$$

$$w_i^r = t_i^d - t_i^a \qquad i \in C_d \tag{5.8}$$

Where t_i^a represents the customer's arrival time at the system and t_i^d represents the customer's departure time from the system. C_a represents the set of customers parking

their cars, while Cd represents the set of customers retrieving their cars. Based on these assumptions, the average waiting times per customer are calculated as follows with Equations (5.9)-(5.10): N_a and N_d represent the number of customers for each transaction type (parking or retrieval). Finally, W gives (5.11) the average waiting time per transaction (operation).

$$W^p = \sum_{i=1}^{N_a} w_i^p / N_a \qquad i \in C_a \tag{5.9}$$

$$W^r = \sum_{i=1}^{N_d} w_i^r / N_d \qquad i \in C_a \tag{5.10}$$

$$W = \frac{\sum_{i=1}^{N_a} w_i^p + \sum_{i=1}^{N_d} w_i^r}{N_a + N_d} \tag{5.11}$$

In the next step, a simulation model is constituted to test the developed algorithm's validity and evaluate the performance of dispatching rules, as the simulation is probably the most convenient tool for analyzing such dynamic and stochastic systems. The developed simulation model and its essential components are presented in Figure 6. Based on the problem structure, on the one hand, physical and technical features of the considered FAPS and customer profile details are inputs of the simulation model. On the other hand, the following operation that will be handled and the place where the car will be placed constitute decision variables of the system. Here, the proposed algorithm and different combinations of the proposed dispatching rules are utilized as described in Figure 5.4. Finally, the efficiency of the candidate dispatching rules will be evaluated depending on performance measurements (system's output) like average customer waiting time and the average distance traveled in the system.

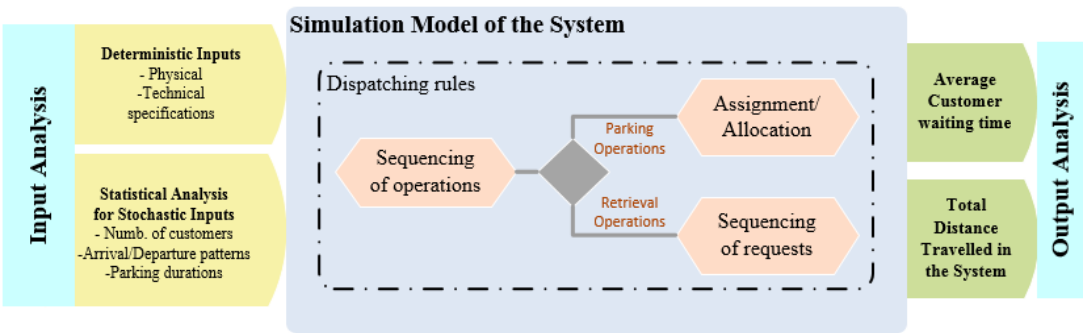


Figure 5.4 The main components of the developed simulation model

Considering the importance of the system parameters, it becomes more critical to consider their deterministic and stochastic natures when providing inputs to the simulation model. Therefore, the following section and subsections provide detailed information about the assumptions and other specifications of the FAPS considered in the experimental case study.

Previous research suggests a 10-times warp-up period for the non-terminating simulation models (Chung, 2003). On the other hand, it is known that a long simulation run enhances the quality of the results. With this motivation, the simulation run length is determined as six months (180 days) as system managers approve that the customer patterns analyzed in section 3.4 are valid for winter and spring, comprising six months. However, a single simulation run still refers to a single outcome. Therefore, to improve the quality and reliability of the outcomes, ten replications each of 6 months' length comprising the January-June period are performed based on the customer data provided.

With this consideration, the performance of the dispatching rules proposed for sequencing and allocation is evaluated based on the average of these ten replications. The average of 10 replications is introduced in Table 5.3. In addition, the entire results of the 10 replications are given in Appendix A.1. separately for each combination. For all performance criteria related to customers' waiting time and system utilization, the rules with the minimum values are preferable to others.

Table 5.3 All possible combinations of the proposed dispatching rules and their performance results

Simulation of the 6 months			# of customers			customers waits			system utilization					
			total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)
RAS	FCFS	-	29603.90	4.20	164.47	2.27	3.23	2.75	91.82	3.33	15085.73	546.72	2715.43	98408.73
	NRF	-	29447.80	2.70	163.60	3.87	2.43	3.15	93.30	3.38	15273.21	552.73	2749.18	99492.03
	PRF	FCFS	29735.50	52.30	165.20	1.32	5.62	3.71	92.22	3.34	15239.98	552.05	2743.20	99375.84
		NOF	29425.10	32.60	163.47	1.30	4.84	3.07	92.36	3.35	15106.57	547.15	2719.18	98486.12
		FOF	29706.70	51.50	165.04	1.30	5.58	3.44	92.15	3.34	15217.49	551.26	2739.15	99226.70
	RRF	FCFS	29715.90	1.30	165.09	4.21	2.41	3.31	93.35	3.38	15424.78	558.18	2776.46	100472.95
		NOF	29636.20	1.10	164.65	4.27	2.37	3.32	93.51	3.38	15411.82	557.63	2774.13	100373.88
		FOF	29637.00	1.00	164.65	3.95	2.43	3.19	93.19	3.37	15367.77	556.17	2766.20	100109.82
NAS	FCFS	-	29544.00	3.60	164.13	1.24	2.16	1.70	70.48	2.62	11801.80	437.16	2124.32	78689.20
	NRF	-	29771.10	0.50	165.40	1.80	1.80	1.80	71.41	2.65	12069.30	446.42	2172.47	80354.75
	PRF	FCFS	29404.00	89.50	163.36	0.89	3.89	2.39	70.96	2.63	11863.44	439.01	2135.42	79021.71
		NOF	29454.00	57.90	163.63	0.90	3.50	2.20	71.02	2.63	11896.06	440.17	2141.29	79230.77
		FOF	29551.60	130.80	164.18	0.93	4.72	2.82	71.41	2.65	11968.09	442.72	2154.26	79688.97
	RRF	FCFS	29722.20	2.40	165.12	1.85	1.78	1.82	71.58	2.65	12077.66	446.62	2173.98	80391.90
		NOF	29677.70	0.00	164.88	1.87	1.76	1.81	71.43	2.65	12044.45	445.45	2168.00	80180.74
		FOF	29621.60	2.20	164.56	1.75	1.78	1.77	71.28	2.64	12004.20	444.02	2160.76	79924.27
FAS	FCFS	-	29395.40	6.40	163.31	4.09	4.78	4.44	111.53	3.98	17930.31	641.23	3227.46	115420.62
	NRF	-	29584.60	6.60	164.36	9.25	3.05	6.15	113.62	4.05	18462.93	659.26	3323.33	118666.83
	PRF	FCFS	29603.70	49.60	164.47	1.75	8.66	5.21	111.49	3.98	18060.07	645.86	3250.81	116254.72
		NOF	29788.10	17.40	165.49	1.77	7.46	4.61	111.52	3.98	18178.05	650.07	3272.05	117011.79
		FOF	29661.80	65.40	164.79	1.76	9.41	5.58	111.38	3.98	18104.44	647.42	3258.80	116536.44
	RRF	FCFS	29438.20	3.80	163.55	9.12	3.04	6.08	113.73	4.06	18374.22	656.09	3307.36	118095.48
		NOF	29453.40	5.30	163.63	9.58	2.98	6.28	114.10	4.07	18458.67	658.92	3322.56	118606.24
		FOF	29549.80	4.20	164.17	9.50	3.05	6.27	113.83	4.06	18444.96	658.61	3320.09	118549.73

> the green painted cells are the best value of the corresponding performance criteria

***** daily performance measurements are kept for every day, then the mean of the 180 days is represented in the table

5.3 Results and Discussions of the Simulation Study

According to the results (Table 5.3), the internal rules that support PRF (Parking-Request-First) and RRF (Retrieval-Request-First) rules do not significantly impact the performance. However, the average results of the outcomes demonstrate that the combination of the NAS (Nearest-Available-Slot) allocation rule and FCFS (First-Come-First-Served) sequencing rule outperforms all other combinations. However, at this point, there is a need for further investigation into the underlying reason for these results. The research question is whether the rule combination (NAS+FCFS) performance is derived from any kind of rule or their combination. Besides, an interesting remark can be deduced from the table with served and rejected customer numbers. The PRF sequencing rule results in a highly increased number of rejected customers, no matter the allocation rule.

5.3.1 Comparison of Allocation and Sequencing Rules' Performances

As stated above, the best results were obtained by applying NAS and FCFS dispatching rules for allocation and sequencing decisions, respectively. Therefore, additional analysis is made in this section to determine if one of these rules is responsible for the excellent performance results. First of all, the results are analyzed according to allocation dispatching rules. In this regard, the results are compiled under RAS, NAS, and FAS allocation rules to eliminate the impact of all sequencing decision rules. For this purpose, the values of the corresponding allocation rule are computed by taking the average of all eight sequencing rule combinations. The computed average values constitute the overall performance of each allocation strategy, as can be found in Table 5.4.

The results show that the FAS strategy is the worst and most inefficient. On the other hand, the NAS strategy is by far the best and most effective strategy. Moreover, there is a clear superiority between strategies since they surpass each other in terms of all performance criteria in that order NAS>RAS>FAS.

Table 5.4 The overall performance of allocation rules

ALLOCATION RULES	# of customers			customers waits			system utilization					
Simulation of the 6-month period	total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist. (m) per operation	trans time (min) per operation	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)
Average of RAS	29613.51	18.34	164.52	2.81	3.61	3.24	92.74	3.36	15265.92	552.74	2747.87	99493.26
Average of NAS	29593.28	35.86	164.41	1.40	2.67	2.04	71.20	2.64	11965.63	442.70	2153.81	79685.29
Average of FAS	29559.38	19.84	164.22	5.85	5.30	5.58	112.65	4.02	18251.71	652.18	3285.31	117392.73

Table 5.5 The overall performance of sequencing rules

SEQUENCING RULES	# of customers			customers waits			system utilization					
Simulation of the 6-month period	total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist. (m) per operation	trans time (min) per operation	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)
Average of FCFS	29514.43	4.73	163.97	2.53	3.39	2.96	91.27	3.31	14939.28	541.70	2689.07	97506.18
Average of NRF	29601.17	3.27	164.45	4.97	2.42	3.70	92.78	3.36	15268.48	552.80	2748.33	99504.54
Average of PRF	29592.28	60.78	164.40	1.32	5.96	3.67	91.61	3.32	15070.46	546.19	2712.68	98314.79
Average of RRF	29605.78	2.37	164.48	5.12	2.40	3.76	92.89	3.36	15289.84	553.52	2752.17	99633.89

In contrast, when a similar process is carried out for sequencing rules, and the average performance values are computed as in Table 5.5, it is seen that there is no sharp line among sequencing strategies. The compiled results again clearly reveal that the PRF sequencing rule excessively increases the number of rejected customers compared with other sequencing rules.

As another issue, unlike the allocation rules, it is not possible to mention the clear superiority of sequencing rules. However, if the performance criteria are examined under two separate groups, it may be possible to refer to an exact order for system utilization criteria as FCFS>PRF>NRF>RRF. However, the same situation is not valid for customer waiting times, and the best performance values belong to different sequencing rules. Besides, there are no significant differences between the performances of sequencing strategies, even between the best and worst performance values related to each criterion.

Table 5.6 Impact of allocation and sequencing rules/strategies on performance improvement

	Variation of allocation rules		**Variation of sequencing rules**	
	Min imp. (%)	*Max imp. (%)*	*Min imp. (%)*	*Max imp. (%)*
Customer waits	37	63	1	21
System utilization	15	36	0	2

In order to figure out the limited impact of the sequencing strategies on the system's performance, improvement variation provided by implementing sequencing rules could be compared with the allocation rules. In that situation presented in Table 5.6, the best possible improvement that can be achieved by changing the sequencing strategy is around 21 %, while implementing the best allocation strategy can yield up to 63%. The minimum improvement provided by changing allocation rules is % 15, while changing sequencing rules may not yield any improvement.

Although it has been discussed literally in the problem statement section, this result numerically proves the importance and great impact of the allocation decisions for FAPSs. That means if the assignment/allocation problem of FAPSs is studied more

intensively, a significant improvement can be created in the operational efficiency of FAPSs. In this respect, future research directions can be shaped based on this fact.

5.3.2 Analysis of Dispatching Rules under Different Conditions

This section investigates the performance of the dispatching rules utilized for allocation decisions under different conditions such as arrival rates, parking duration, and arrival patterns. The values of parameters except the investigated one are kept constant to ensure reliable results. Details of the experiments are presented in each relevant case.

5.3.2.1 Performance Analysis Based on Mean Arrivals

When examining the performance of the allocation and dispatching rules, thoroughly the same distribution functions related to the arrival pattern and parking durations are used in the simulation study. In addition, however, the average number of customers who arrived each day is altered systematically to analyze the impact of customer arrival rates on the performance of rules.

(i) Comparison of Allocation Rules: Figure 5.5 illustrates the relative performance of allocation rules RAS, NAS, and FAS in terms of capacity utilization (for example, the total number of customers served, rejected, and left the system due to long queues) and system efficiency depending on daily customer arrivals varied from 90 to 640. Again, the results show that NAS outperforms the other as the customer arrival rate increases.

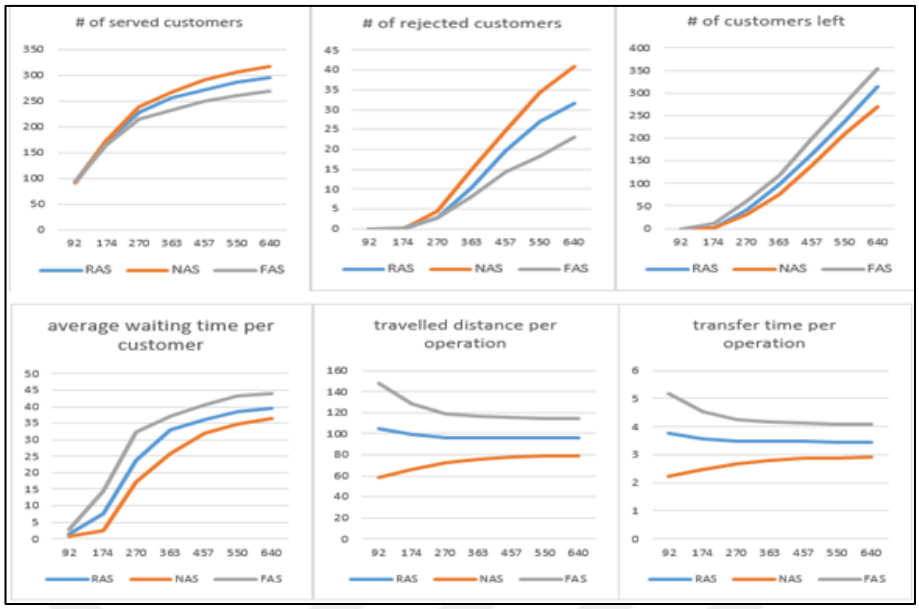


Figure 5.5 Performance of Allocation Rules in terms of capacity utilization and system efficiency

(ii) Comparison of Sequencing Rules: Similarly, Figure 5.6 demonstrates the relative performance of sequencing rules FCFS, NRF, PRF, and RRF in terms of capacity and system efficiency. Although there is no distinct superiority between dispatching rules, the aggregate performance of FCFS is better than the other since FCFS has average capacity utilization and system efficiency performance.

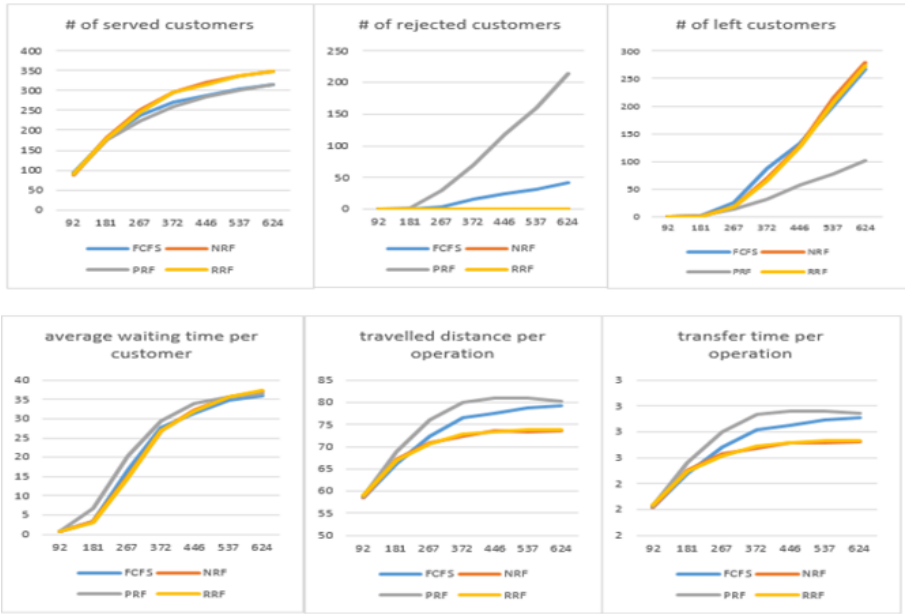


Figure 5.6 Performance of Sequencing Rules in terms of capacity utilization and system efficiency

3.6.2.2 Performance Analysis based on Mean Duration

When examining the performance of the allocation and dispatching rules, thoroughly the same distribution functions related to the arrival pattern&rates are used in the simulation study. In addition, the average parking duration per customer is altered systematically to analyze the impact of parking durations on the performance of rules.

(i) Comparison of Allocation Rules: Figure 5.7 illustrates the relative performance of allocation rules RAS, NAS, and FAS in terms of capacity utilization (for example, the total number of customers served, rejected, and left the system due to long queues) and system efficiency depending on the average parking duration of customers varied from 0.7 to12.6 hours. The results show that NAS outperforms the other in all performance criteria. However, as the parking duration of the customer is increased, the difference between the allocation strategies is decreased.

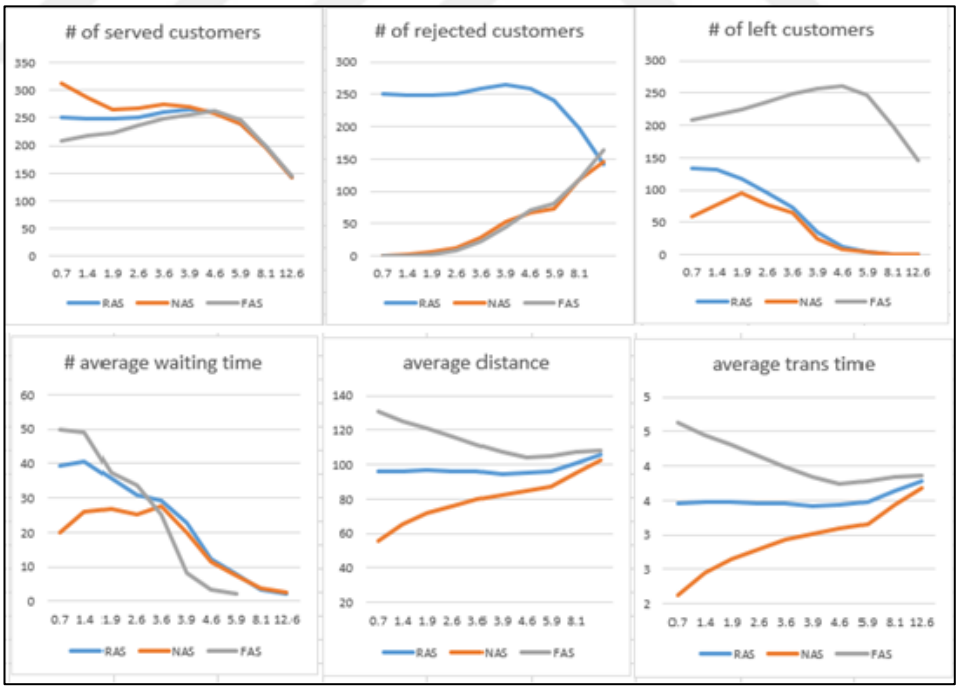


Figure 5.7 Performance of Allocation Rules in terms of capacity utilization and system efficiency

(ii). Comparison of Sequencing Rules: Similarly, Figure 5.8 demonstrates the relative performance of sequencing rules FCFS, NRF, PRF, and RRF in terms of capacity and system efficiency. Although FCFS and NRF outperform the other rules, especially in capacity utilization, the difference between them is decreased as customers leave their cars for a long time.

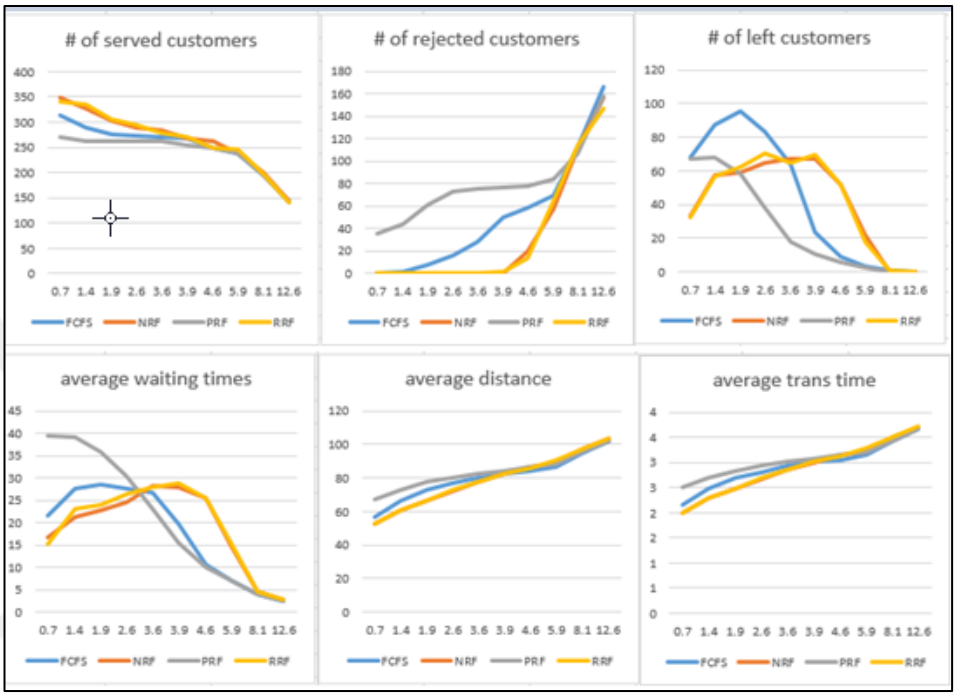
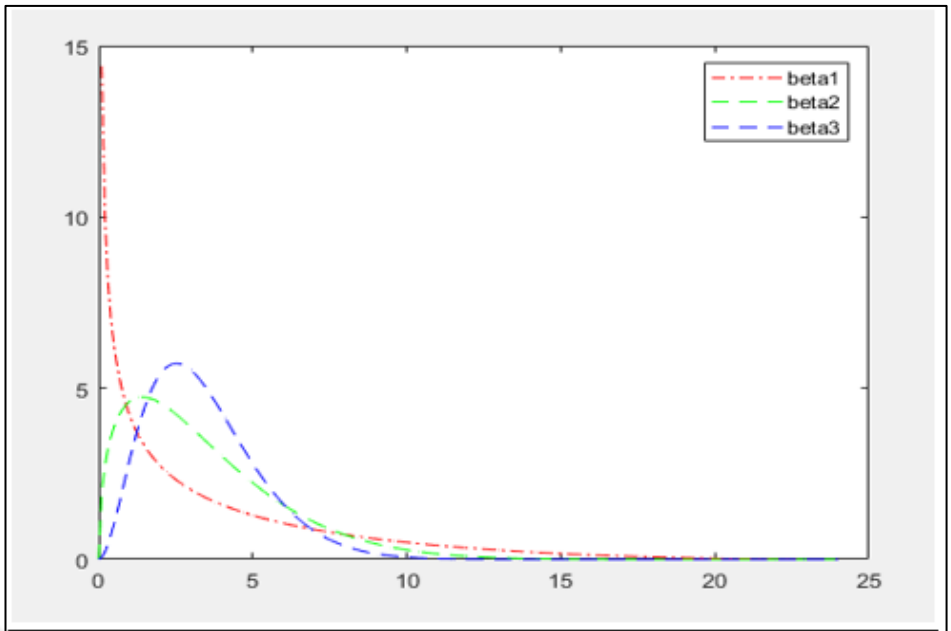


Figure 5.8 Performance of Sequencing Rules in terms of capacity utilization and system efficiency

5.3.2.3 Performance Analysis based on Duration Pattern

In the previous subsections, the performance of the dispatching rules is investigated based on the variation of the system inputs. In other words, the distribution functions related to system inputs are preserved, and only the mean values obtained from these functions are modified. In the following subsection, the parameter values of the functions are altered to provide the same mean value for distributions but with different standard deviations.



beta1(0.5,2.5)	beta2(1.5,7.5)	beta3(3,15)
mu=2.7 std=3.14	mu=2.7 std=1.9	mu=2.7 std=1.4

Figure 5.9 The distribution function used for parking durations and its parameter values

Performance of the rules is discussed as the function's standard deviation (std) is increased/decreased. The beta distribution function has a good fit for customer parking durations. The functions used for analysis and their parameter values are given in Figure 5.9.

(i) Comparison of Allocation Rules: As seen in Figure 5.10, all rules have better performance if the customer's parking durations are relatively steady and have a wide range. However, the impact of the deviations is higher on capacity utilization efficiency when relatively has a lower impact on system efficiency.

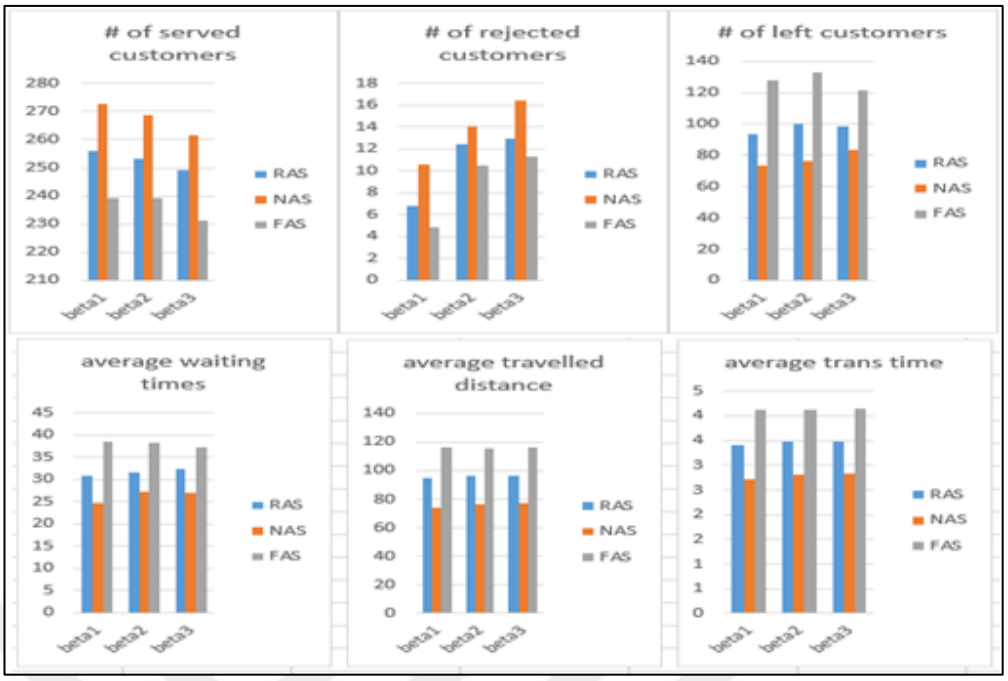


Figure 5.10 Performance of Allocation Rules in terms of capacity utilization and system efficiency

(ii) Comparison of Sequencing Rules: As seen in Figure 5.11, the efficiency of the sequencing rules is affected by the deviation in parking duration more than the allocation rules.

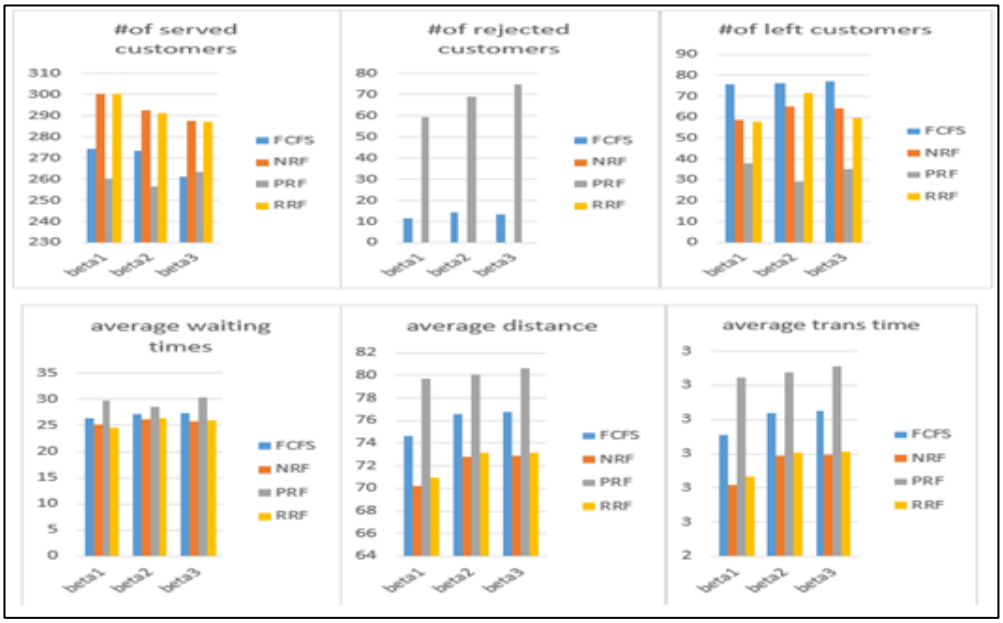
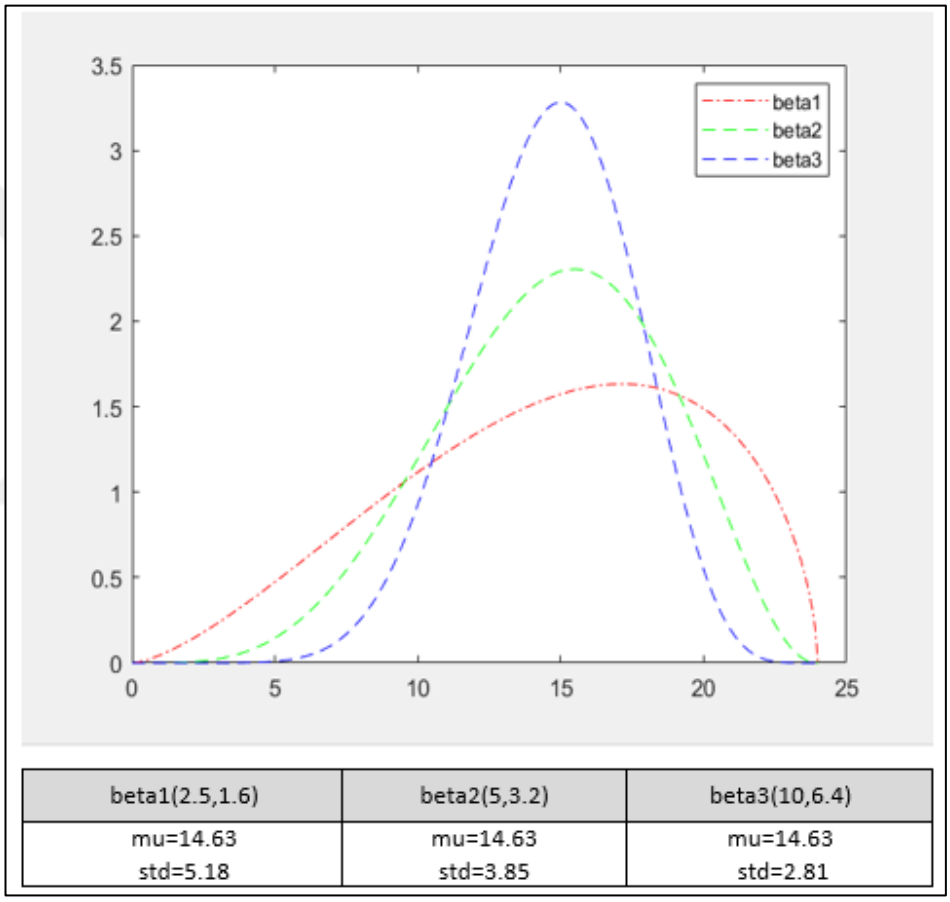


Figure 5.11 Performance of Sequencing Rules in terms of capacity utilization and system efficiency

5.3.2.4 Performance Analysis Based on Arrival Pattern

Finally, the last analysis is carried out for the customer arrival pattern within a day. The arrival pattern of the customer fits the Beta distribution too. The considered functions and their parameter values are given in Figure 5.12. Here, the performance of the rules is analyzed for a relatively regular arrival pattern (beta1) and a rush-hour pattern (beta3).



beta1(2.5,1.6)	beta2(5,3.2)	beta3(10,6.4)
mu=14.63 std=5.18	mu=14.63 std=3.85	mu=14.63 std=2.81

Figure 5.12 The distribution function used for parking durations and its parameter values

(i) Comparison of Allocation Rules: As seen in Figure 5.13, the efficiency of the allocation decision is highly affected by the arrival pattern of the customer. Moreover, the arrival pattern directly affects customer satisfaction since the system cannot respond to requests as the arrival rate of the customer increases in a small time interval.

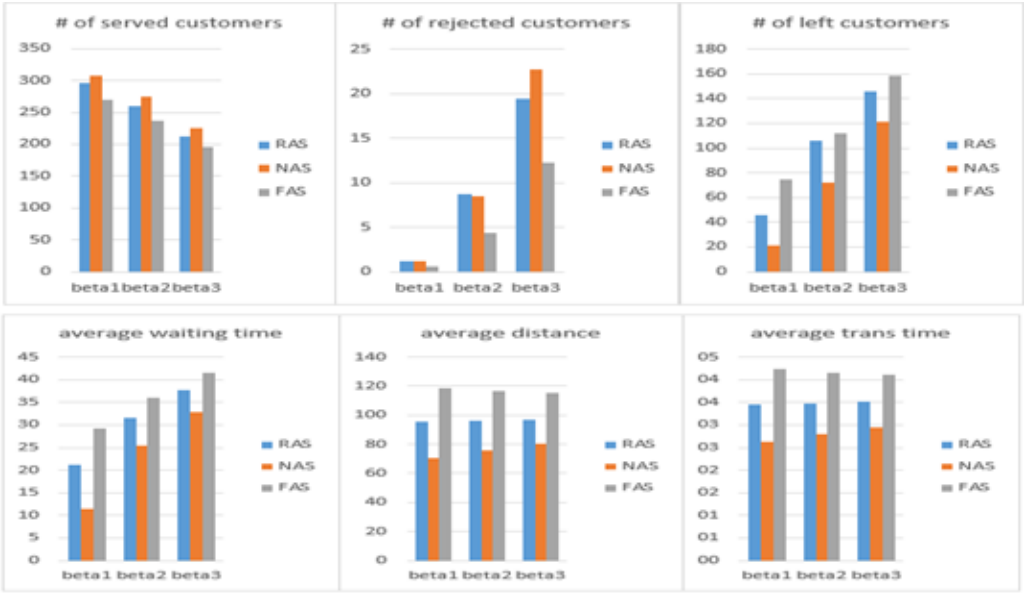


Figure 5.13 Performance of Allocation Rules in terms of capacity utilization and system efficiency

(ii) Comparison of Sequencing Rules: The same effect is observed for sequencing rules with a difference; these groups of rules have more impact on system efficiency as the arrivals are getting the rush pattern, as shown in Figure 5.14.

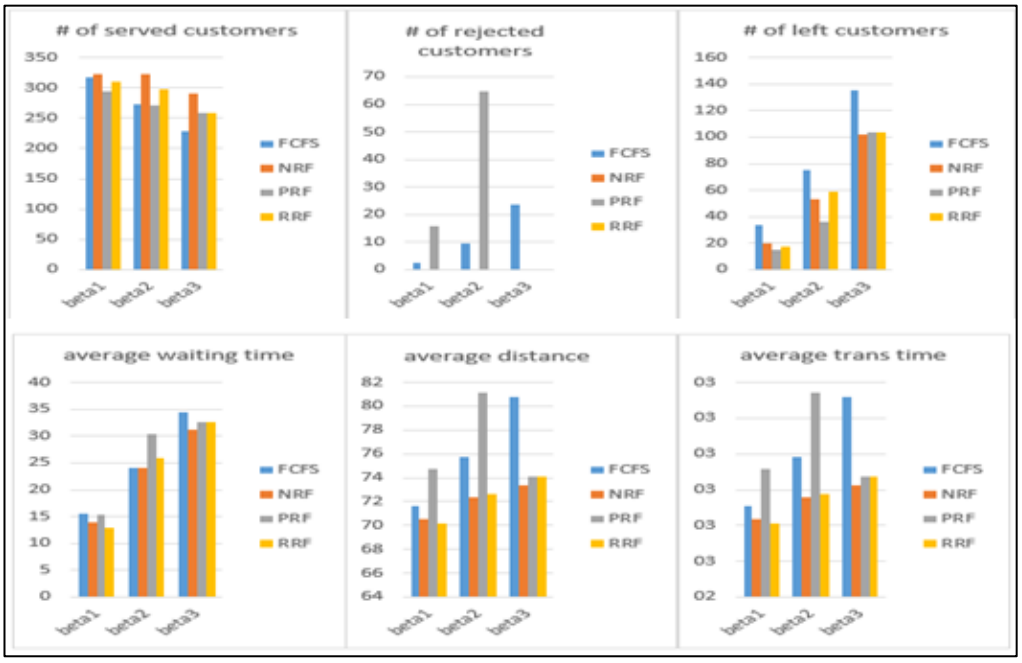


Figure 5.14 Performance of Sequencing Rules in terms of capacity utilization and system efficiency

5.4 Conclusion and Remarks

In this phase of the thesis, a generic algorithm is developed to plan and control operations in fully automated parking systems. On the one hand, different dispatching rules that can be utilized for *assignment/allocation* and *request sequencing* decisions, which are common planning problems in FAPSs, are identified. In other words, different dispatching rule-based algorithms are developed to carry out the operations in FAPSs. On the other hand, a simulation model is developed to test the developed rule-based algorithms and to evaluate the performance of the distribution rules and heuristics.

As an essential part of the study, customer structure (behaviors) that might highly affect the performance of the proposed dispatching rules are statistically analyzed and conveniently embedded in the simulation model. For this purpose, the customer data that ensures the results' validity and reliability is obtained from a real system. The simulation model's verification and validation and the dispatching rule combinations' performances are compared in terms of customer waiting times and operational efficiency.

The results demonstrate that the combination of the NAS (Nearest Available Slot) allocation rule and FCFS (First Come First Served) sequencing rule outperforms all other combinations. Additional analyses show that the main differences between the performances originate from assignment/allocation rules. The results clearly show that allocation decision significantly impacts the operational efficiency in FAPSs. Conclusively, the importance of allocation decisions is proven via this study.

On the one hand, the alternative dispatching rules needed to operate the system more efficiently are investigated in detail in this report. On the other hand, the most effective dispatching rules are selected and utilized as the classical planning (rule-based) approach. These findings imply that the research related to the operational efficiency of FAPSs mainly focuses on assignment/allocation problems, which dramatically affect all system efficiency.

These findings suggest a need to consider allocation decisions as an optimization problem. Whit this consideration, a novel allocation procedure is planned to be developed in future studies. On the other hand, the proposed approach will be performed on the same hypothetic case, and the results obtained from the case will be discussed in detail.

CHAPTER 6
THE NOVEL OPTIMIZATION-BASED PLANNING AND CONTROL APPROACH

Fully Automated Parking Systems (FAPSs) are new generation car parking systems where the sensor technology is used, and the parking process is carried out with the help of automated carriers (lifts, conveyors, robots). Especially in recent years, they have offered effective, economical, and environmentally friendly solutions to the car parking problem, which has become a severe problem in crowded cities. Unlike conventional systems, they use space more efficiently because they can park the cars on top of each other without the need for auxiliary structures like ramps and elevators. In addition, the parking process carried out with the help of automatic carriers provides time, fuel, and energy savings. Owing to all these reasons, FAPSs are seen as the future of the parking systems and becoming more prevalent day by day. However, although many studies have been carried out on the design of FAPSs and the technological equipment to be used in FAPSs, the number of studies on the operational planning and control problems of FAPS is very limited.

In FAPSs, two operations, which are car storage (allocation) and retrieval, are carried out. As a result, two fundamental decision problems are encountered in the system: (i) in which order the operations will be done (sequencing) and (ii) where the parked cars will be located (allocation). Once the operations and related decisions are not well managed, they may lead to long service times, inefficient energy usage, and high indirect costs. When the design and hardware problems of FAPSs are almost solved, the service time and operational efficiency become more important. However, While literature on parking systems and parking design exists, the literature on automated parking systems from operational planning and optimization is very limited. In this context, the studies considering FAPSs and handling design and operational planning problem as a decision problem is summarized in Table 3.2. Except for the design optimization (6 of which), sequencing (2 of which), scheduling/routing (4 of which) and car allocation (1 of which) problems are studied as operational problems in literature.

The previous studies have shown that the most crucial factor affecting service time and performance of the system is related to the location of the cars more than the sequence of the operations. In practice, the software used for planning and executing operations in FAPS utilizes simple dispatching/heuristic rules (such as nearest available lot, first come first served) for such decisions. However, solving these problems as an optimization problem instead of using specific rules will significantly improve system performance, especially in service time. Thus, we aim to develop dynamic and proactive methods for handling and solving the optimal allocation/assignment problem as an optimization problem in the scope of this thesis. For this purpose, the works to be done within the scope of this chapter can be summarized as follows:

1. Developing a dynamic algorithm that executes the operational planning and control of FAPS
2. Developing a computational intelligence algorithm that uses the previous data and available information for allocating cars proactively to the most appropriate place
3. Collecting the necessary data for the developed proactive method and extracting the statistical information
4. Comparing the performance of computational intelligence (simulation-based optimization) algorithm with classical (rule-based) algorithms via a simulation study and analyzing the results

With the proposed approach, the problem in question will be considered an optimization problem, and the necessary solution methods will be developed, contrary to the existing practices and current studies on the subject. When the difficulties arising from the combinatorial nature of the problem are added to the uncertainties regarding the inputs and outputs of the vehicles, it is understood that the problem cannot be solved with exact solution methods and/or it is quite challenging to solve. However, it has been reported in studies (Blum et al., 2011; Blum & Roli, 2003) that meta-heuristic methods have yielded very successful results. In addition, dynamic optimization

techniques should be used when planning operations in a dynamic environment (Baykasoğlu & Ozsoydan, 2017, 2018). In the light of this information, the scientific and technological original value of the study can be summarized as follows:

- ✓ Almost all of the existing studies on FAPS have focused on design and hardware issues to improve the performance of parking systems, and operational efficiency/effectiveness has been ignored. This study it is aimed to operate the mentioned systems more efficiently by emphasizing the operational problems. Thus, a scientific contribution will be made to the subject.
- ✓ It has been observed that no optimization algorithm is used for decisions such as the placement of vehicles and the sequencing of operations in the scientific literature and the software used. Therefore, within the scope of this study, an optimization study will be carried out with an innovative approach (see Method), especially to place the vehicles in the correct place in the system.
- ✓ This proposed new approach will also allow proactive placement by taking into account the system's dynamic nature and the customers' stochastic behavior.
- ✓ The computational intelligence algorithm, which is planned to be developed, is planned to be designed so that it can be integrated into existing commercial software and work in harmony with system data.
- ✓ The proposed study aims at more environmentally friendly and less energy-consuming FAPSs. At the same time, this study aims to increase customer satisfaction and will contribute to the spread of FAPS. In this context, it is anticipated that the proposed study may have positive socio-cultural, economic, and environmental contributions.

It is aimed to provide considerable improvements, especially in terms of customer satisfaction and operating costs in the system with the computational intelligence algorithm. When considering the combinatorial and dynamic nature of the problem and the need for a rapid solution for real-time control, it is planned to use heuristic/metaheuristic algorithms. At this point, when considering its success in solving problems with this structure, it is planned to use the Greedy Randomized Adaptive Search Procedure (GRASP) algorithm in the solution approach. A sufficient

background of the examined problem and detail of the proposed operational planning and control approach is introduced in the following sections. In this regard, the remainder of this chapter is organized as follows: Section 6.1 provides the main characteristic of the problem handled. Also, a review of the literature and the main contribution of the study is presented in this and sequent sections. In section 6.2, the proposed approach. Section 6.3 discusses the simulation study and its components in section 6.4, Results and Discussion. Finally, concluding remarks and suggestions for future studies are presented in section 6.5.

6.1 Characteristics of the Operational Planning and Control in FAPS

In the system, customers' vehicle placement and/or retrieval requests co-occur, and the system generally orders requests according to the FCFS (fisrt come first served) rule. During the placement process, vehicles are usually placed in the nearest available slot (NAS – nearest available slot). During the parking process, customers deliver their vehicles and leave the system without waiting for the end of the process. However, during the exit (take-back) process, the time from the moment the customer notifies his request until the vehicle is delivered to him is very important in terms of customer satisfaction. In other words, the customer's waiting time in the system is an important performance measure in terms of customer satisfaction. However, at this point, the operational efficiency and service times of FAPS, whose design and hardware-related problems are almost solved, have started to become important issues. The problems experienced in these matters, together with the high wages, are the situations that create dissatisfaction with these systems, especially in Turkey. When considering the inadequacy of scientific studies on this subject, improvements can be achieved with studies to be carried out within the scope of the study.

Given the sequencing problem, the FCFS approach can yield good results in terms of individual waiting times. However, considering the customers' total/average waiting time, the waiting time is directly related to the system performance. At this point, the most important factor affecting the performance of the system and the total/average waiting time of the customers is the location of the vehicles. Therefore, allocating

vehicles to the best possible position in the system will improve system performance and, directly and indirectly, customer waiting times. Especially in systems designed to use space efficiently and perform more complex operations, where vehicles are placed becomes a much more critical issue.

The allocation (assignment of vehicles) made in the first stage significantly determines the number of movements the robots must perform; thus, the total distance and time they will travel (Bartholdi & Hackman, 2011). For example, vehicles placed close to the exit gate for short-term parking operations and far from the exit point for long-term parking operations will significantly reduce the total distance traveled by the robot and the waiting time for customers. This situation reduces the maintenance, repair, and operating costs of the enterprise, while at the same time allowing it to provide faster service to its customers. In addition to all these, in systems where deep shelves are used, it is necessary to change the places of the vehicles in the front rows on the shelves to reach the vehicle to be retrieved. For this reason, assigning the vehicles to the right place becomes an even more important issue. However, parking systems have no control over how many vehicles will enter the system and when and how long they will stay in the system. Although not in control, this highly uncertain process and sequence of events makes it very difficult to manage operations and greatly reduces efficiency and effectiveness.

FAPSs are in direct contact with the end customer. For this reason, as soon as the customer demand occurs, this demand should be answered accurately and quickly. In addition, the fact that each vehicle in the system corresponds to a customer, the nature of the parking process, and the density in the city reveal the fact that too many customers should be served in a very short time. With this emerging dynamic structure and the uncertainty mentioned above, it is understood that it is very difficult to carry out the operations effectively and efficiently. This situation is one of the main reasons why various heuristics and distribution rules have been used so far in such systems. However, considering the system's dynamic nature and the customers' stochastic behavior, it is understood that using simple heuristic rules such as placing the incoming vehicle in the nearest empty place cannot provide satisfactory results. Therefore, the

proposed study it is aimed to solve the operational problems in question with innovative methods to be developed instead of simple, intuitive rules close to ideal. In this context, the most important possible contribution of the proposed study is to manage the uncertainty mentioned above effectively and efficiently, provide sufficient control to the system in the light of sound data, and enable proactive planning.

This study, which will be carried out to increase the operational performance of FAPS, is aimed to increase customer satisfaction and reduce operating costs ultimately. In order to clearly define the nature of the problem, a detailed literature review has been done, and real systems have been observed. As a result, it has been discovered that service times and system performance are primarily affected by where vehicles are placed and then by order of operations. However, the findings show that operational problems, decisions, and system performance greatly influence design features (like building structure, layout, transportation system) and customer profile. Therefore, customer behavior, directly and indirectly, impacts operational problems and system performance. Furthermore, because the most crucial parameter determines the operational problems encountered, the design features are also determined according to the customer profile. Accordingly, the parameters of the problem addressed in this study, decision variables, performance criteria, and the hierarchical relationship between them are shown in Figure 4.4.

Within the scope of the BAP study (2017.KB.FEN.027) that we have recently terminated, various studies have been carried out to reduce customer waiting times by improving the service times of FAPS, which provides service in Izmir. In this context, data regarding the system structure and customer profile were obtained from İzmir Alsancak FAPS, and the effect on the system of serving customers awaiting transactions according to different rules (dispatching rules) was investigated. During the studies, it was understood that the most critical factor affecting the service times and the performance of the system were related to the positioning of the vehicles in the system rather than the ordering of the requests to the system. Therefore, within the scope of this study, the proactive/dynamic vehicle placement/allocation problem will be emphasized. By effectively solving the problem, it aims to improve service times

(customer waiting times) and system efficiency (total distance traveled in the system). It is clearly seen that reducing customer waiting times will increase customer satisfaction. On the other hand, it is thought that reducing the total distance covered by the carriers in the system while carrying out the operations will increase the speed of the system and thus customer satisfaction. In addition, the decrease in the total distance traveled will significantly reduce the wear rate of the system while reducing the maintenance and repair costs and extending the system's life.

With the proposed study, the problem in question will be considered an optimization problem, and the necessary solution methods will be developed, contrary to the existing practices and current studies on the subject. When the difficulties arising from the combinatorial nature of the problem are added to the uncertainties regarding the inputs and outputs of the vehicles, it is understood that the problem cannot be solved with exact solution methods and/or it is quite challenging to solve. However, it has been reported in studies (Blum et al., 2011; Blum & Roli, 2003)that meta-heuristic methods have yielded very successful results. In addition, dynamic optimization techniques should be used when planning operations in a dynamic environment (Baykasoğlu & Ozsoydan, 2017, 2018).

6.1.1 The Decision Variables

Considering the system and process characteristics of FAPSs, some rules that can be utilized for the operational problems are described in the previous reports. The performance of 24 different rule combinations utilized for allocation and sequencing operations is evaluated based on 10 replications of each combination via a simulation model (see Chapter 5). In order to figure out the relative impact and importance of sequencing and allocation decisions, the performance variation of both decisions is compared. In addition to the literal argument stated above, the results have numerically proved that allocation decision has a greater impact on two performance criteria: mean customer waiting time and mean distance traveled distance per operation. The performance variations depending on the sequencing and allocation decisions are summarized in Table 6.1.

Table 6.1 Performance variation depending on main operation decisions

Performance variations (%)	Average transfer distance (per operation)	Average customer wait (per operation)
Sequencing strategies/rules	0-2%	15-36%
Allocation strategies/rules	1-21%	37-63%

That means if the assignment/allocation problem of FAPSs is studied more intensively, a significant improvement can be created in the operational efficiency of FAPSs. In this respect, the research is shaped based on this fact, and a novel operational planning approach is proposed considering a new allocation procedure.

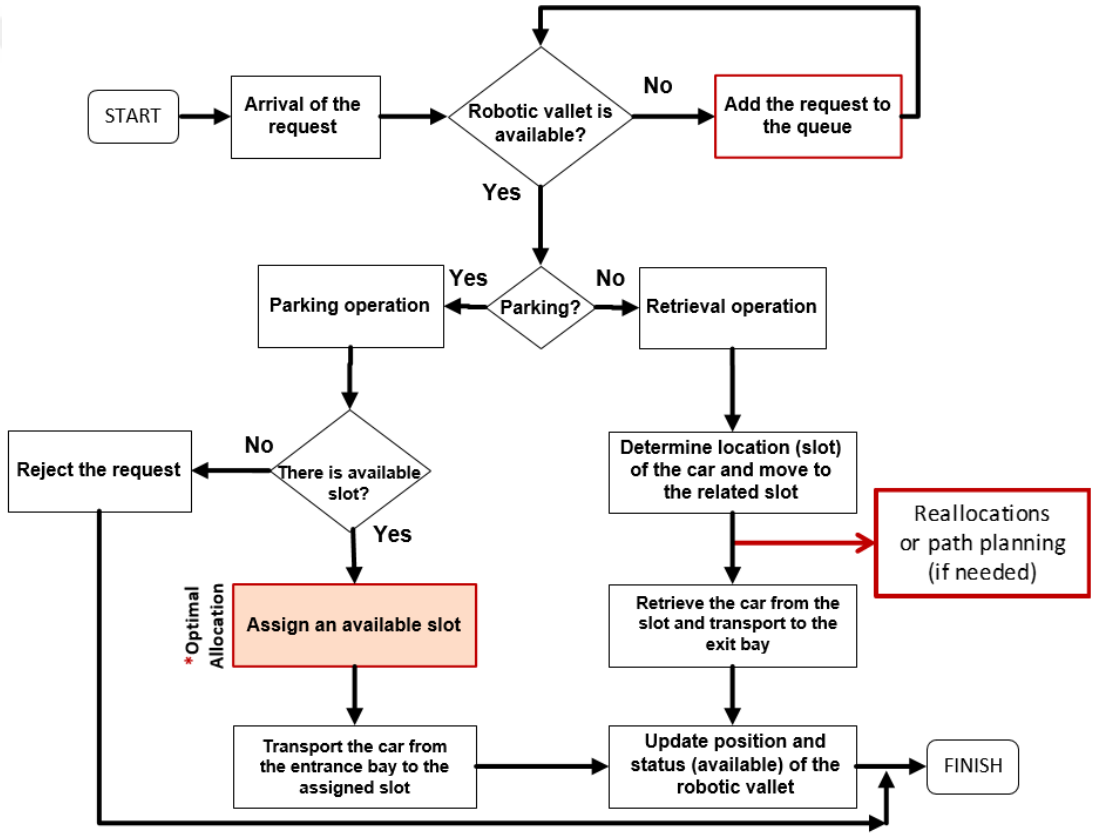


Figure 6.1 A general diagram of operational decisions and flow in FAPS

In all FAPS, drivers leave their vehicles in the parking room, and vehicles are placed in empty spaces randomly or according to predetermined rules with the help of a driver/robot. Later, when customers want to come back and pick up their vehicles, they are picked up from their current location with the help of a carrier/robot and delivered

to the customer in the parking room. The operation-decision flow diagram of FAPS for this process is presented in Figure 6.1. Within the scope of this thesis, the vehicle allocation problem, which is very important and encountered in all FAPS regardless of shape and design, will be considered.

6.1.2 The Objective Function

With the innovative and novel approach proposed within the scope of the thesis, an artificial intelligence algorithm is developed which can predict optimal allocation in accordance with the dynamic structure. Considering the combinatorial and dynamic nature of the problem and the necessity of producing fast solutions for real-time decisions, the necessity of using metaphorical algorithms that work fast in this optimization module comes to the fore. At this point, considering the success of the Greedy Randomized Adaptive Search Procedure (GRASP) algorithm in such and similar problems, it is considered that the GRASP algorithm is appropriate as the solution method. It was mentioned that two performance metrics would be used to evaluate the success of the thesis, namely the average waiting time of the customers (customer satisfaction) and the total distance covered in the system (efficiency of the system). In this context, "*the transfer distance,"* which has a deterministic structure and directly affects the customers' waiting time, is considered "*the objective function*" when deciding on the optimal location.

It was clearly seen in Table 4.7 that the most substantial relationship with waiting time belongs to the daily total transfer distance (total distance traveled in the system). In this way, the assumption that the average transfer distance can be determined and utilized as the objective of the optimization problem related to allocation decisions is supported by robust statistical analysis. However, another analysis is needed to support the argument that "*the average transfer distance"* directly affects the customers' waiting time. Thus, the linear relationships of the performance metrics were examined via regression analysis. After all, the decision to consider the transfer distance as an objective function of the optimization-based planning algorithm was supported by statistical analysis. The following hypotheses are laid behind this decision.

(i) There is a positive correlation between operational efficiency and average waiting time

(ii) The operational efficiency directly affects the customer waiting time are approved in this way.

These assumptions are rational arguments, and they were tested and verified statistically in Chapter 4, Section 4.2.

6.2 The Proposed Intelligent System

Generally, the software that plans and executes FAPSs' operations utilizes simple dispatching/heuristic rules (such as FCFS, NAS) discussed and analyzed in the previous section. However, the success of these methods is very limited, as it does not use data or information and cannot see the next time window. Therefore, with the innovative and novel approach proposed within the scope of the thesis, a computational intelligence algorithm is developed which can predict optimal allocation in accordance with the dynamic structure.

The developed algorithm that will be integrated with the real system has an optimization module that allows allocating vehicles to the most appropriate location. Contrary to existing practices and related studies, this study considers the allocation decision an optimization problem. In the proposed planning approach, the uncertainty and randomness of customers' behavior, which makes planning and control operations quite difficult, is considered during optimization. Moreover, all possible variations of allocation decisions are evaluated for optimal allocation by considering the number of customers, arrival, and departure of customers, not only at the time of decision but also through the time window that the vehicle is parked. The allocation module of the control algorithm (see Figure 4.7) enables to find of the most appropriate location for the vehicle in a proactive manner using historical data. For this purpose, the proactive allocation problem at issue is solved with simulation-based optimization. The general architecture of the proposed optimization-based control system and its components are illustrated in Figure 6.2.

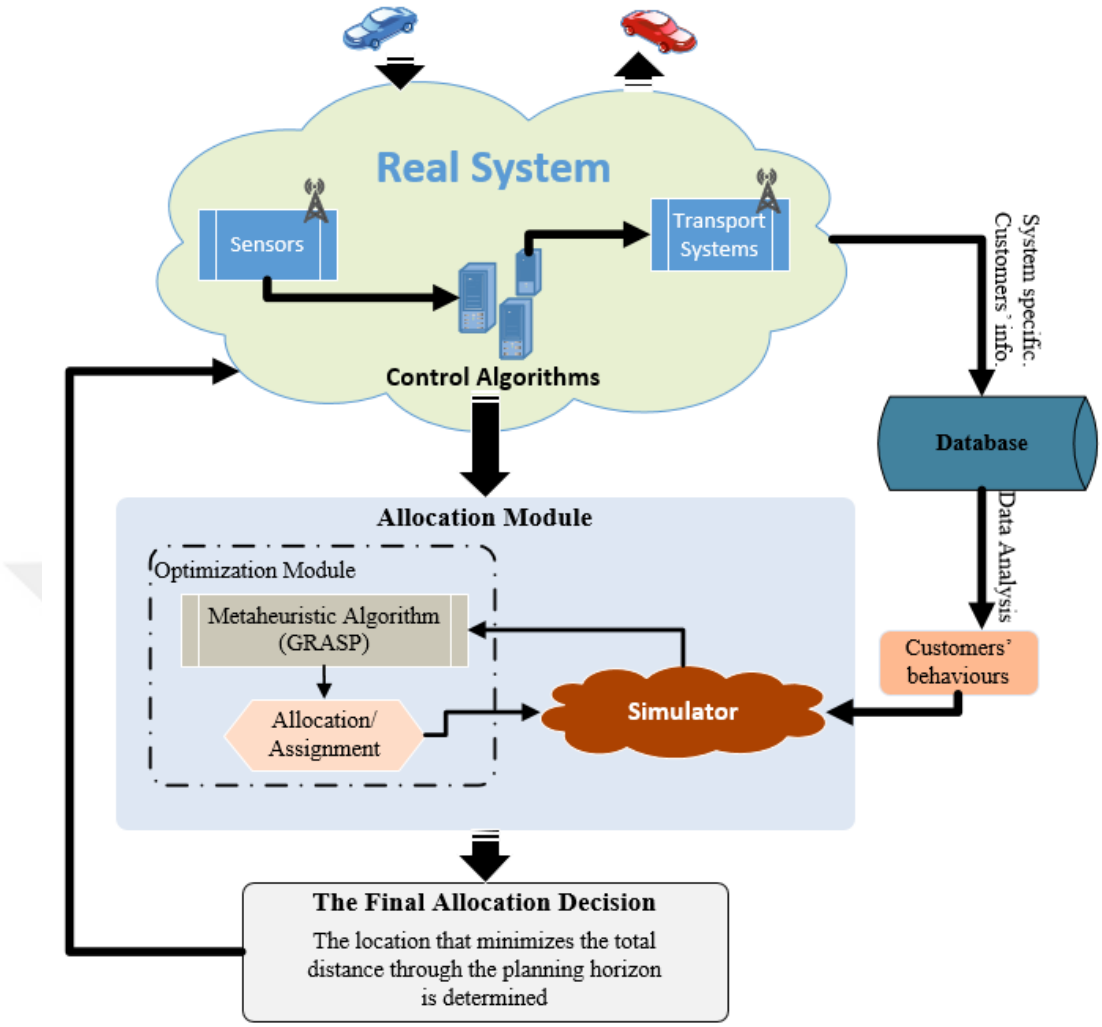


Figure 6.2 Components of the optimization-based planning approach

In the proposed planning approach, the uncertainty and randomness of customers' behavior, which makes planning and control operations quite difficult, is considered during optimization. Moreover, all possible variations of allocation decisions are evaluated for optimal allocation by considering the number of customers, arrival, and departure of customers, not only at the time of decision but also through the time window that the vehicle is parked. The allocation module of the control algorithm (see Figure 6.1) enables to find of the most appropriate location for the vehicle in a proactive manner using historical data. For this purpose, the proactive allocation problem at issue is solved with simulation-based optimization. Considering the combinatorial and dynamic nature of the problem and the necessity of producing fast

solutions for real-time decisions, the necessity of using metaphorical algorithms that work fast in this optimization module comes to the fore. At this point, considering the success of the Greedy Randomized Adaptive Search Procedure (GRASP) algorithm in such and similar problems, it is considered that the GRASP algorithm is appropriate as the solution method.

As mentioned in the previous sections, the structure of the building (like the shape of the building, the number of entrances and exits), the structure of the installed transport system (such as multi-depth shelf system, the number of carriers), and the customer profile (such as customer density, entry-exit hours). Issues such as these directly impact system performance and problem structure (see Figure 4.4). Therefore, all of these important system parameters will be considered within the scope of this thesis. With the proposed approach, the problem in question will be considered an optimization problem, contrary to existing practices and studies on the subject. In addition, all possible parameter changes (the number of customers entering/exiting, occupied/empty parking spaces) not only at the moment of decision but also in a certain time window, which are caused by customer behavior and which make the planning and control of operations very difficult, will be taken into account during optimization, will be taken into account when determining the vehicle location. The vehicle placement module (see Figure 4.6) to be developed for this purpose will solve the problem with a simulation-based optimization method while using historical data and ensure that vehicles are proactively assigned to the right place.

Simulation models are used to evaluate the performance of systems with many parameters/variables and complex objectives and/or constraints. However, simulation is the most suitable method for modeling dynamical systems whose parameters and/or values can change at any time (Nguyen et al., 2014). The FAPSs we discussed in the thesis are highly dynamic and complex systems. Therefore, almost all of the studies on FAPS within the scope of Operations Research (OR) were carried out on simulation models of the system (Debnath & Serpen, 2015; Mirzaei et al., 2017; Serpen & Dou, 2015).

The simulation study evaluates the effects of different variable (input) values on the system. In some cases, a simulation study can be done to find the most ideal (optimum) value the variables can take according to the system outputs. In studies conducted for this purpose, it is not a logical and practical way to run the simulation model for every possible state and value. Therefore, when solving such problems, a simulation-based optimization method where optimization techniques are integrated into simulation and used (Carson, Y., & Maria, 1997). Simulation-based optimization can be used to calculate the objective function in systems with a large number of parameters and complex relationships, as well as to solve the problem by creating random samples in dynamic systems with different parameter values at each state (Fu Editor, n.d.). With the proposed new planning method, an optimization study will be made for the placement decision, considering the time window in which the decision is effective. For this reason, it is planned to use a simulator in the vehicle placement module of the control system in order to both reflect the impact of the customers' stochastic behavior on the decision and to calculate the objective function value at the end of this period (see Figure 4.7).

For the solution of the mentioned optimization problem, a vector-based solution representation is emphasized. One of the important problems to be encountered while solving this optimization problem, which has a very dynamic structure, is the necessity of using vectors or matrices whose lengths are constantly changing due to structural variability. For example, processes waiting in line, vehicles entering/exiting the system, and vectors/matrices showing occupied, and empty parking spaces constantly change. In particular, the change in the number of empty parking spaces in the system means that there will be continuous variability in the size of the solution vector used for the vehicle placement decision. For this reason, it would be appropriate to use constructive algorithms that allow structural variability (mandatory change in solution representation length) within meta-heuristic algorithms to solve the problem discussed within the scope of the thesis.

Considering the combinatorial and dynamic nature of the problem and the necessity of producing fast solutions for real-time decisions, the necessity of using fast-running

metaheuristic algorithms in the mentioned optimization module comes to the fore. When considering the success of the Greedy Randomized Adaptive Search Procedure (GRASP) algorithm in problems with this and similar structure, it is thought that it would be appropriate to use it as a solution method. The relationship between the GRASP algorithm, which is planned to be used within the scope of the thesis, and the structure of the problem is discussed in detail in the following sub-titles.

6.2.1 The Proposed GRASP-Based Algorithm

There are two main reasons for this choice. The first is the need for a fast solution in a real-time system. Evolutionary algorithms are quite successful in a wide variety of problem types. However, waiting for these algorithms to learn from the problem space and enter into a convergence trend is necessary. GRASP, on the other hand, is an algorithm that can generate a solution quickly, step-by-step, and in one go, using simple heuristic rules. Local best solutions can also be avoided thanks to the multi-start and local search features. In other words, simple heuristic rules (dispatching rules) give the same solution every time they are run, while GRASP can produce much better results in a very close time to them. In this way, it is also not affected by the previous problem environment, so different solutions can be obtained at each start-up. During the solution creation phase, a feasible solution can be guaranteed. The second and more important reason is explained below.

Various algorithms have been proposed so far for solving discrete and combinatorial optimization problems. However, as mentioned above, they are difficult to adapt to problems involving variable-length solution vectors. The most important reason for this is that unpredictable dynamic events (such as parking or vehicle recall requests) may cause changes in the size of the cluster in which the problem is defined.

As a result, a solution vector (chromosome) (encoded solution, solution representation) designed for a meta-heuristic algorithm, in which all solution elements are displayed individually, can vary in size in the problem that is the subject of the thesis. For this reason, various evolutionary or non-evolutionary operators applied to the solution vectors of different sizes that may be encountered in successive iterations

to transfer informational inheritance may cause disruptions in the main flow of the algorithm. Therefore, although it is thought that it can be solved with other methods, this method was not preferred in the proposed approach due to the need for additional processes and causing a severe deterioration in the quality of the solution. For this reason, instead of showing the whole solution, it is thought that it will be easier and more applicable to show the existing and known part of the problem and to create the solution step by step. This solution constitutes one of the main ideas of the method to be applied.

One of the approaches to be proposed in the present thesis will be the use of constructive algorithms. Thus, with its variable length chromosome structure, it was thought that the problems could be solved effectively. For these reasons, studies will focus on a solution approach using the GRASP algorithm. The fact that this method can be successful in solving optimization problems with a similar structure and dynamics has been shown by some preliminary studies by the thesis supervisor, who revealed the method and discussed it in various scientific meetings (Baykasoğlu & Ozsoydan, 2017, 2018; Baykasoğlu & Ozsoydan, 2014).

6.2.2 The Proposed Allocation Procedure

It was mentioned in the previous sections that the average waiting time of the customers and the total distance covered in the system will be used as performance criteria to evaluate the success of the thesis. While the time customers wait while parking or retrieving their vehicles is a measure of customer satisfaction, the total distance traveled in the system is a measure of the efficiency/effectiveness of the system. Depending on the working principle of FAPS, the time customers wait to get their vehicles back is longer than the time they wait for the parking process (Debnath & Serpen, 2015). The waiting time for each customer *(i)* for the parking operation is the time elapsed between the time the customer enters the system/queue (arrival time) $ta_{(i)}$ and the moment he parks his vehicle in the transfer cabin (parking time) $tp_{(i)}$ and $tp_{(i)}$-$ta_{(i)}$. Therefore, it can be calculated by *(i)*. The waiting time of the customer waiting to get his vehicle back is the time elapsed between the time he enters the

system/queue (departure time) $td_{(i)}$ and the time he takes his vehicle from the cabin (retrieval time) $tr_{(i)}$, ($tr_{(i)}$-$td_{(i)}$). This period includes the time of the carrier to reach the vehicle (empty transport) $te_{(i)}$, the loading of the vehicle to the carrier l, the transportation to the entrance-exit cabin of the vehicle (loaded transport) $tl_{(i)}$, and the transferring from the elevator to the cabin (unloading). Accordingly, in a FAPS where the total number of customers is *N*, the "average waiting time" for customers to receive their vehicles can be calculated with the following Equation (6.1).

$$\sum Wr(i) \,/\, N \;=\; \sum(te(i) \;+\; l \;+\; tl(i) \;+\; u) \,/\, N \quad (1 \le i \le N) \qquad (6.1)$$

Considering that the transfer times of the vehicles from their location to the carrier *(l)* and from the carrier to the cabin *(u)* are constant, it is understood that the most important factor affecting the waiting times is the transfer time of the vehicles. Therefore, the transfer times required for a rollback operation that starts at *"t"* time can be calculated as follows: (x_t,y_t,z_t) coordinates of the carrier at that moment; $(x_{(i)},y_{(i)},z_{(i)})$ the parking lot coordinates of the vehicle; (x_0,y_0,z_0) coordinates of the transfer cabin; and let V_x, V_y, V_z represent the velocities of the carrier in the x-y-z axes, respectively. In this case, the time taken for the carrier to reach the vehicle *(te)* and deliver the vehicle to the cabin *(tl)* can be calculated with the Eq. (6.2) and (6.3).

$$te_{(i)} = |x_{(i)} - x_t| \,/\, V_x + |y_{(i)} - y_t| \,/\, V_y + |z_{(i)} - z_t| \,/\, V_z \qquad (6.2)$$

$$tl_{(i)} = |x_{(i)} - x_0| \,/\, V_x + |y_{(i)} - y_0| \,/\, V_y + |z_{(i)} - z_0| \,/\, V_z \qquad (6.3)$$

It is seen that the transfer times depend on the distance traveled by the carrier, namely the initial position of the carrier (x_t,y_t,z_t) and the location where the vehicle is placed $(x_{(i)},y_{(i)},z_{(i)})$. The starting position of the carrier depends on where the previous operation ended. However, since the order of operations is performed according to certain rules, it is assumed that the order does not change. For this reason, it can be said that the only factor determining the transfer times and thus the customers' waiting times is the location of the vehicles. In addition, if there is a pending transaction in the queue, the transfer times of all previous operations will affect the waiting time. In this context, the *"total distance traveled in the system"* will be considered an objective

function when making optimal vehicle placement decisions during vehicle allocation and retrieval.

GRASP was first proposed by Feo & Resende (1995). This algorithm's solution vector is primarily shown as the empty set. The solution vector mentioned shows the vehicles to be handled in our proposed approach. All the variables (empty cells) that can be selected for the solution are in the candidate list (candidate list). This method is based on considering the individual contributions of each variable to the total performance. First, the variables are sorted in ascending or descending order according to these individual contributions (by minimization or maximization purpose). Then, a subset of variables that are thought to contribute more than a problem-specific function (greedy function) is created. This subset is called the restricted candidate list. Finally, the variable that will form the solution vector is randomly selected from this subset, and the selected variable is removed from the candidate list and subset and added to the solution vector. Then, the best contributing element from the candidate list is added to the subset, and a new random element is selected from the subset and added to the solution vector. These steps are continued until there are no elements in the candidate list. Based on this construction, the steps of the proposed simulation-based algorithm and GRASP algorithm that utilize a simulator module for optimization are given in the following pseudo-code in Figure 6.3.

It is thought that the GRASP algorithm will be effective in solving the optimization problem aimed to be solved in the proposed approach. The most important reason for this is that regardless of the number/state of the variable pool or the instantaneous state of the system, a GRASP-based constructive approach can quickly provide adaptation due to its nature. In other words, the problem encountered at that moment will be solved by considering the current situation without the need to resolve the problem in case of a change of location. This approach is a more intelligent and learning-oriented adaptation of simple heuristic dispatching rules. Another essential feature of GRASP is that it is multi-start. In this way, the algorithm will not be affected by the previous problem environment, the following environments will not affect each other, and thus different alternative solutions can be obtained.

Algorithm 1.

```
E{}= Boş yerlerin kümesi;
F{} = Dolu yerlerin kümesi;
      if n(E) >=2
           p = Tahmin (park süresi)|     !(fonksiyon)
           T = t+p;
        Na{} =Tahmin ("t-T" periyoduna gelecek araçlar);
        Nd{} =Tahmin ("t-T" periyoduna ayrılacak araçlar);
→ Optimization Module (GRASP);
            toplam_mesafe=BM;  !(çok büyük bir sayı)

                for n<=iterasyon_sayısı
                      Çözüm={};
                          While n(E) >0 & n(Na)>0
                                RE{} = boş yerlerin daraltılmış kümesi (kural #); RE⊆ E
                                s = seçilen boş yer; s ∈ RE
                                çözüm = çözüm ∪ s;
                                n(E) = n(E) -1;
                                n(Na) = n(Na) -1;
                           end

→ Simulation Module;
                                    sim_time=t;
                                    sim_mesafe=0;

                                        while t_sim<=T
                                              sırala_geliş zamanı(ta(i));        i ∈ Na,
                                              sırala_ayrılma zamanı(td(j));    j ∈ Nd;
                                              bul (sıradaki_işlem);         !(fonksiyon)

                                                  if işlem==park
                                                      sim_time =ta(i);
                                                      sim_konum(i)=çözüm(i);
                                                      hesapla(mesafe,süre);     !(fonksiyon)
                                                      sim_mesafe=sim_mesafe+mesafe;
                                                      sim_time=sim_t+süre;
                                                   end

                                                   if işlem==geri alma
                                                       sim_time =td(j)
                                                       sim_konum(j)=boş;
                                                       hesapla(mesafe,süre);
                                                       sim_mesafe=sim_mesafe+mesafe;
                                                       sim_time=sim_time+süre;
                                                    end

                                          end

                                    if sim_mesafe<=toplam_mesafe
                                        toplam_mesafe=sim_mesafe;
                                        konum(i)=sim_konum(i);
                                    end

                          end
        end
```

Figure 6.3 Pseudo code of the allocation-optimization algorithm

The *"Tahmin"* function to be developed will integrate with the system's database and use the statistical distributions created about general customer behavior. Thus, the parking time of the arriving vehicle at a time $p = T\text{-}t$, the set of future vehicles *Na* and the set of vehicles to leave *Nd* within the time window *(t-T)* will be estimated by the system based on previous data as illustrated in Figure 6.4. Figure (a) represents roughly a vehicle whose arrival and departure time are 10:00 and 14:30, respectively, while Figure (b) represents roughly 13:30 and 20:15. The time window *(t-T)* that will be forecasted is 10:00-14:30 for the first vehicle and 13:30-20:15 for the second vehicle.

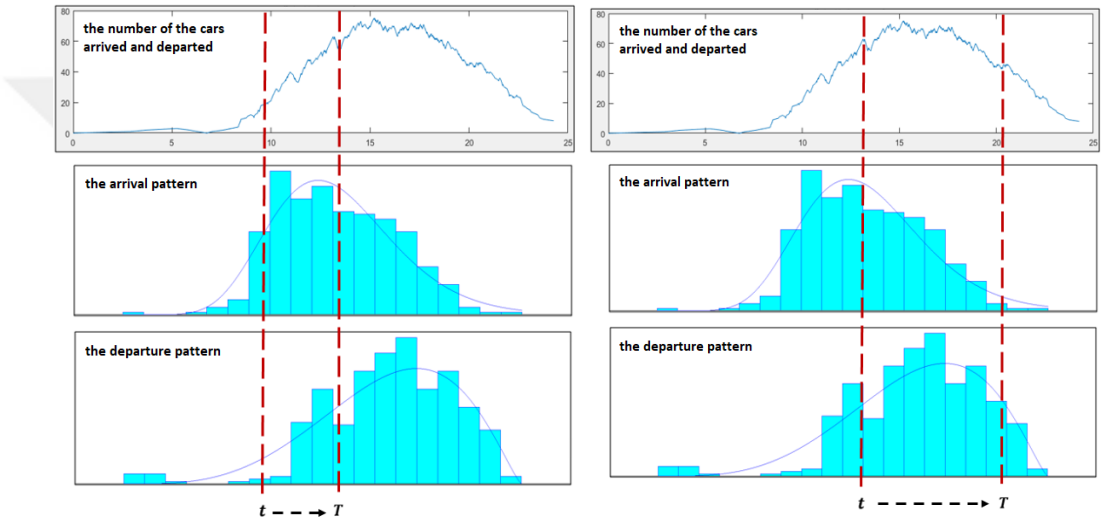


Figure 6.4 Two examples for the time window *(t-T)* that will be forecasted

With the optimization module, a slot will be allocated according to specific rules for the vehicle to be placed and the vehicles planned to arrive; With the simulation module, vehicle entries and exits will be simulated in the *(t-T)* time window. The objective function value obtained will be recalculated with different allocation decisions (solution vector), and the solution minimizing the distance to be covered within the specified time window will be transmitted to the real system as the vehicle's location.

6.2.3 The Main Vectors and Matrices of the Algorithm

The proposed algorithm for planning and controlling FAPS's operations consists of several vectors, including a lot of important information about the system. The first and one of the most important vectors is the *"customer"* vector, where all information about the customers, such as arrival time, departure time, location in the system, and waiting time, is kept. When all"customer" vectors get together, we obtain a *"customer_matrix"*; an example of this matrix is given below.

information →	Arrival time(h)	Departure time(h)	Parking duration(h)	Slot information (no)	Distance to/from I/O point(sec)	Waiting time for parking(sec)	Waiting time for retrieval(sec)	The car in system or not
Cust. No ↓	1	2	3	4	5	6	7	8
1	13.36556	16.12487	2.71204	10	49	170.2047	0.0000	1
2	10.45009	12.41432	1.92587	2	25	138.1028	580.6616	0
3	16.28619	BM	3.02494	0	0	0.0000	0.0000	0
...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...
nb_customers	...	...	...	...	...	...	...	...

Figure 6.5 An example of a customer matrix constituted by customer vectors that include information

As shown in Figure 6.5, a customer matrix is constituted by *"nb_customer"* numbers (rows) and keeps eight information (columns) about each customer. In the given example matrix, the system time is 14:00, and "customer 1" arrived but did not depart the system; "customer 2" arrived and departed the system. On the other hand, "Customer 3" does not arrive yet. Thus, departure time and other information are null/zero for now. Since the proposed simulation model works event-based, once an event occurs in the system customer matrix is appropriately updated for each customer.

The other important vector keeps physical and states information of the FAPS's slot in a *"slot"* vector, which all constitute the location matrix below.

information →	Floor no	Position on x axis	Position on y axis	Status of the slot	The allocated customer
Slot No ↓	1	2	3	4	5
1	1	1	1	1	35
2	1	1	2	0	0
3	1	2	1	0	0
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...
nb_slot	...	...	...	...	...

Figure 6.6 An example of a location matrix constituted by slot vectors

According to Figure 6.6, the matrix consists of nb_slot (rows) and five slot information which helps us to determine the coordinate of the slot and, consequently location/coordinate of the allocated car. For example, “slot 1” is on the first floor, the first slot is on the right of the lift/aisle, and the car of “customer 35” is allocated to this slot. Correspondingly position and coordinates of the robot and each car are kept on a “coordinate” vector with the distance to the input/output point of the garage.

In addition to the customer matrix, we define a que_wait matrix for customers waiting in the queue to park or take their cars. This matrix, or vector of the customer wait in the queue, is used to classify and prioritize customers. This way, different strategies, and policies can be applied when executing the operations. The critical information in this matrix is customer no, operation type, arrival time of the request (parking or departure), the distance (if the car is in the system), and finally the estimated waiting time for each customer waiting in the queue.

information →	Cust. no	Type of the request	Arrival time of the request	The distance to I/O point	Est. waiting time (min)
Order of the request ↓	1	2	3	4	5
1	35	2	14.365	17.500	2.734
2	42	2	15.926	22.500	5.651
3	13	1	18.235	0.000	8.233
...	...	...	...	...	...
...	...	...	...	...	...
...	...	...	...	...	...
nb_waiting	...	...	...	...	...

Figure 6.7 An example of que_wait matrix constituted by vectors of customers waiting in the queue

An example of the que_waiting matrix is given above in Figure 6.7. The customers in the queue are ordered according to the requested arrival time, which means FIFO (First In, First Out). However, different prioritizing and ordering strategies can be applied to improve performance criteria, as discussed extensively in Chapter 5.

Finally, the last presented vector is the solution vector that is used in the optimization algorithm GRASP. Figure 6.8 shows an example of a solution vector where slots are assigned to the forecasted allocation requests. For example, suppose that a vehicle arrives at time *"t"* and leaves the system at a time *"T."* Then, the GRASP algorithm uses the following solution vector to allocate the vehicle at issue and other forecasted arrivals and departures within the time window *(t-T)*.

	Forecated Allocation requests	Allocated_1	Allocated_2	Allocated_3	...	Allocated_n
Cust. No	The vehicle to be allocated (real one)	Forecated_3	Forecated_26	Forecated_43	...	Forecated_215
Slot no	16	65	32	15	...	11

Figure 6.8 An example of a solution vector where slots are assigned

The simulation module will simulate vehicle entries and exits in the *(t-T)* time window. The objective function value obtained will be recalculated with different allocation decisions (solution vector), and the solution minimizing the distance to be covered within the specified time window will be transmitted to the real system as the vehicle's location.

6.3 The Simulation Study

A simulation model of FAPS will be created to test the cognitive intelligence algorithm that aims to be developed within the scope of the thesis. In order to develop the simulation model of the system, first of all, it is necessary to collect the physical and technical data about the system. The most critical point at this stage is the process of analyzing data about customers. Besides being an important input to the simulation model, these data are the cornerstone of the proposed new planning approach.

Furthermore, proactive planning will be possible thanks to the optimization module that works integrated with the database to be created about the customers.

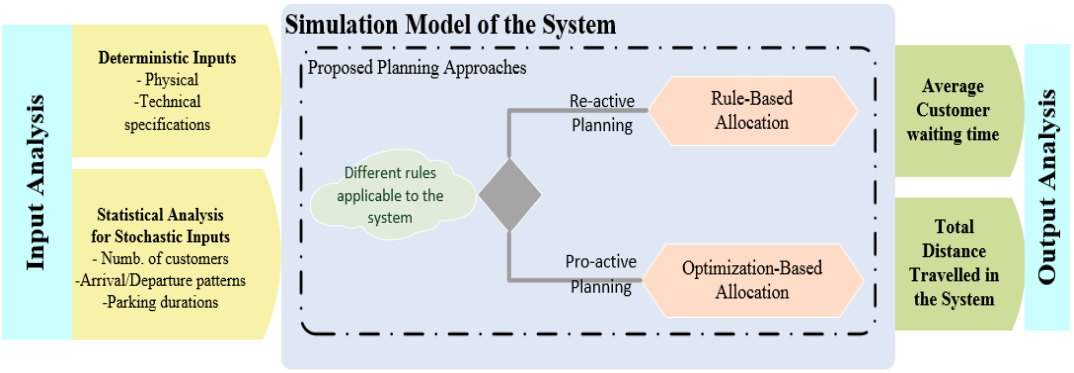


Figure 6.9 The main components of the developed simulation model

The simulation model to be developed will be used to test the validity of the cognitive intelligence algorithm and evaluate the performance of the proposed new planning approach. With the simulation study, the optimization-based vehicle placement approach proposed in the thesis and the rule-based vehicle placement approach used in practice will be compared in terms of performance criteria (system outputs). In this context, the important components of the simulation study are shown in Figure 6.9.

At this stage, the operational efficiency of classical and new planning approaches will be compared. When comparing the two methods, the simulation length of the system is planned to be 6-12 months to save the results from the effects of initial conditions and random parameters and to obtain healthier results. However, a simulation study will represent a single result and will not be reliable enough (Chung, 2003). For this reason, 10 replications will be made for specified periods to increase the results' quality and reliability. Finally, it is planned to create the simulation model in the MATLAB© environment so that it can work faster and be more compatible with the developed algorithms.

6.4 Results and Discussion

This section will examine the efficiency of the new planning approach and proposed novel allocation procedure in terms of solution quality and computational efficiency. The performance criteria were analyzed in 3 main groups as performances related to (i) capacity utilization (customer numbers), (ii) customer satisfaction (waiting times), and (iii) system utilization (transfer distances and times). First, the rule-based and optimization-based allocation performance will be compared for the main performance measurements. After that, the efficiency of the novel allocation procedure and the proposed algorithm will be discussed if it is sufficient to apply a real system in terms of solution quality and time. Finally, the impact of an execution strategy, such as providing additional information to the system, will be analyzed in the last section of the results and discussion.

6.4.1 Efficiency of the Proposed Approach

The effect of the new allocation procedure is examined in this section. The simulation study is also carried out for the optimization-based planning approach. In order to evaluate the improvement or effect of the new approach, it will be compared with the rule-based approach. According to Chapter 5, the most efficient rule combinations are selected and compared with the optimization-based planning, in which details are introduced before. The simulation study was carried out for a rule-based and optimization-based allocation approach precisely with the same parameters in Chapters 4 and 5. However, additional eight separate cases were examined to measure the performances of both approaches depending on customer density for 3 months, 90 days. The obtained results are summarized and illustrated in Table 6.2.

Table 6.2 Performance comparision of rule-based allocation and optimization-based allocation

	# of customers (avg. per day)			customers waits			system utilization							
Simulation of 3 months	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (km)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	Decision Time (sec.)	Elapsed Time for sim. (sec.)
Direction of performance	**(+)**	**(-)**	**(-)**	**(-)**	**(-)**	**(-)**	**(-)**	**(-)**	**(-)**	**(-)**	**(-)**	**(-)**	**(-)**	(-)
Average RB-1	83.64	0.00	0.00	0.15	1.32	0.73	62.83	2.36	5362.47	201.05	482.62	301.58	0.00	1.56094
Average RB-2	166.15	0.08	0.18	1.75	2.79	2.27	73.24	2.71	12445.60	459.16	1120.10	688.74	0.00	3.35313
Average RB-3	226.87	7.23	14.39	12.88	12.72	12.80	79.52	2.92	18344.81	671.99	1651.03	1007.99	0.00	5.07969
Average RB-4	254.48	25.98	55.91	18.86	18.50	18.68	82.34	3.01	21174.92	773.69	1905.74	1160.54	0.00	6.76563
Average RB-5	273.32	46.46	105.31	20.76	19.86	20.31	83.59	3.05	23004.60	839.71	2070.41	1259.56	0.00	7.85000
Average RB-6	288.72	66.83	156.00	22.34	20.94	21.64	84.62	3.09	24513.10	894.09	2206.18	1341.14	0.00	8.88438
Average RB-7	297.24	91.55	214.91	23.23	21.63	22.43	85.36	3.11	25502.77	929.36	2295.25	1394.03	0.00	9.80625
Average RB-8	309.90	106.67	284.84	24.15	22.29	23.22	85.90	3.13	26612.16	969.71	2395.09	1454.57	0.00	10.97969
Average of 8 cases	237.54	43.10	103.94	15.51	15.01	15.26	79.68	2.92	19620.06	717.35	1765.80	1076.02	0.00	6.78496
Average OB-1	81.91	0.00	0.00	0.18	1.26	0.72	60.04	2.27	5022.83	189.27	452.05	283.91	0.01	78.38438
Average OB-2	162.40	0.02	0.00	1.04	1.95	1.50	67.07	2.50	11124.23	414.11	1001.18	621.17	0.01	171.05938
Average OB-3	234.73	4.98	4.20	7.01	6.53	6.77	70.02	2.60	16697.00	619.16	1502.73	928.74	0.01	181.43438
Average OB-4	276.36	29.18	22.23	11.91	10.25	11.08	71.17	2.64	19833.47	734.81	1785.01	1102.22	0.01	167.40625
Average OB-5	288.42	72.48	65.15	17.02	15.40	16.21	77.84	2.86	22555.74	828.77	2030.02	1243.15	0.01	184.34063
Average OB-6	304.49	104.38	103.29	18.34	16.42	17.38	78.20	2.87	23879.45	877.18	2149.15	1315.77	0.01	212.07344
Average OB-7	317.75	145.42	141.93	19.21	16.92	18.06	78.61	2.89	24988.80	917.69	2248.99	1376.54	0.01	186.66406
Average OB-8	328.43	181.00	186.21	19.71	17.22	18.46	78.99	2.90	25920.91	951.61	2332.88	1427.42	0.01	190.08125
Average of 8 cases	249.31	67.18	65.38	11.80	10.74	11.27	72.74	2.69	18752.80	691.58	1687.75	1037.36	0.01	171.43047
Improvement ratio	**0.05**	**-0.56**	**0.37**	**0.24**	**0.28**	**0.26**	**0.09**	**0.08**	**0.04**	**0.04**	**0.04**	**0.04**	**-392.84**	**-24.27**

Case_no	**case1**	**case2**	**case3**	**case4**	**case5**	**case6**	**case7**	**case8**
# of cust.	80	160	240	330	420	510	600	700

The performance of the rule-based and optimization-based allocation approaches are tested on 8 cases with different customers' densities. Daily customer arrivals are varied from 80 to 700 for cases listed in the table above. The results presented in Table 6.2 consist of each approach's average performance obtained after 10 replications. The same table demonstrates the mean performance of classic and novel planning approaches on 8 cases. The details of simulation runs are given in Appendix A.2.

It can be seen in the results table the superiority of the proposed new planning approach. However, the significance of the difference between the two pairs should be investigated statistically. In the next step, we will investigate if there is a statistically significant difference between these two planning and control approaches. Thus, in the next step, we will investigate if there is a statistically significant difference between the rule-based planning approach and the optimization-based planning approach in order to prove the superiority of the proposed allocation procedure. For this purpose, the two main performance metrics, average waiting time per operation and average transfer distance per operation, are analyzed.

First, the distribution of the data to be used in the analysis should be determined. Because the tests to be used during the analysis vary according to the data distribution. Methods such as t-test, ANOVA test, and Z-test, which are the most used in the analysis, can be used in case of normal distribution of data. However, the fact that the series does not show normal distribution makes these tests invalid. Therefore, non-parametric tests, also known as "distribution-independent" tests, were used in this study. The data containing 80 instances (for each planning approach) is tested in SPSS for normality, and the results are presented in Table 6.3.

Table 6.3 The normality test for performance criteria (proposed approach)

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
rule based	,251	80	,000	,790	80	,000
opt based	,245	80	,000	,826	80	,000
fark_wait	,163	80	,000	,735	80	,000
rule_based_dist	,255	80	,000	,577	80	,000
opt_base_dist	,256	80	,000	,837	80	,000
fark_dist	,322	80	,000	,273	80	,000

a. Lilliefors Significance Correction

The sample size for both of these examples is 80, so the Shapiro-Wilk test should be used. For all variables, the significance level ($p < 0.05$) suggests strong evidence of non-normality. For this reason, a non-parametric correlation analysis like *Mann-Whitney* or *Wilcoxon* two related samples test should be used when examining the research question: "*Is there a statistically significant difference between the performance of rule-based and optimization-based planning approaches?*" (Eymen, 2007; Neuhauser, 2012).

Table 6.4 The results of the two related samples test (proposed approach)

	Null Hypothesis	Test	Sig.	Decision
1	The median of differences between rule based and opt based equals 0.	Related-Samples Wilcoxon Signed Rank Test	,000	Reject the null hypothesis.

	Null Hypothesis	Test	Sig.	Decision
1	The median of differences between rule_based_dist and opt_base_dist equals 0.	Related-Samples Wilcoxon Signed Rank Test	,000	Reject the null hypothesis.

Asymptotic significances are displayed. The significance level is ,05.

In cases where parametric test assumptions (normal distribution) cannot be fulfilled, Wilcoxon is used to testing whether there is a significant difference between variable measurements at two different times or situations (Neuhauser, 2012). Thus, the differences between performance metrics are investigated by mentioned statistical methods in SPSS. The results of the Wilcoxon two related samples test are given in Table 6.4. As described in the table, the null hypothesis *"the median difference between two approaches is significant"* is rejected since ($p > 0.05$) for both performance metrics, which means both average waiting and traveled distance per operation show statistically meaningful differences.

According to the results, the optimization-based allocation approach outperforms the rule-based allocation approach in all cases except for the time spent on decisions. Still, the time spent deciding on allocation is less than 0.01 seconds, which is acceptable for application to the real system.

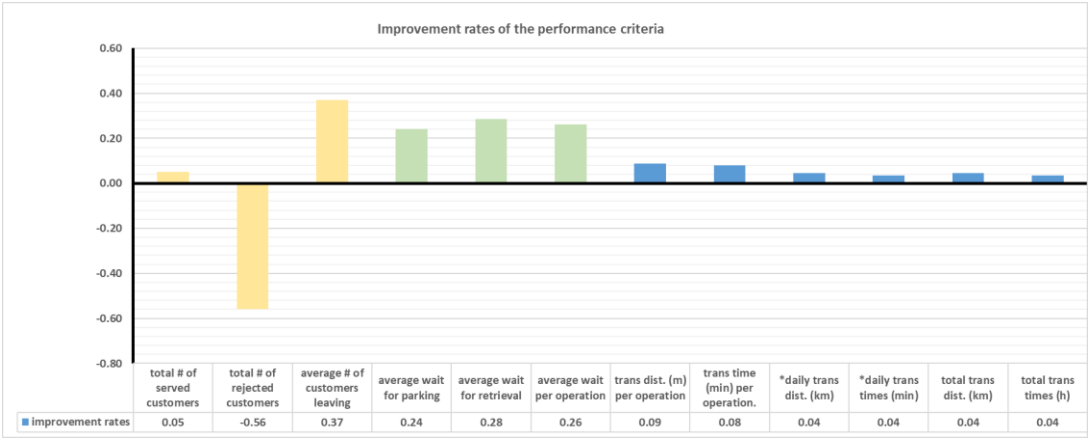


Figure 6.10 Performance improvements by optimization-based approach

Figure 6.10 demonstrates the improvement rates provided by the proposed approach. The primary indicator for capacity utilization (yellow bars), customer satisfaction (green bars), and system utilization (blue bars) are the number of served customers, waiting time and transfer distance per operation, respectively. The difference between the two approaches can be seen better in Table 6.5.

Table 6.5 The improvement provided by the proposed approach to the main performance criteria

	Served_cust	**Avg_wait**	**Traveled dist.**
Rule-based	237.54	15.26	79.68
Opt.-based	249.31	11.27	72.74
Imp. (%)	**0.05**	**0.26**	**0.09**

A detailed analysis shows that the number of served customers daily increases by 5% by utilizing the proposed allocation procedure since the proposed approach leads to the use of the capacity more efficiently. The performance criteria related to customer numbers (served, rejected, leaving)are given in Figure 6.11.



Figure 6.11 Performance comparison in terms of capacity utilization

The performance of the novel approach is better than the classic approach in terms of the number of served customers and customers leaving the system, and the difference between the performances increases as the customer density increases. Although the number of rejected customers seems to increase in the proposed approach, this is an expected outcome. The customers bored and leave the system are decreased, and the capacity is used more efficiently. Thus, the number of rejected customers is increased due to the fullness of the capacity.

With the proposed new method, the most considerable improvement rate was achieved in customer satisfaction with 26%, which is pretty high. (Table 6.3). These results are coherent with the statistical analysis conducted in Section 4.2, which approves the linear relation between operational efficiency and average waiting time. According to the results, one unit improvement in transfer distance leads to almost three units in customers' waiting time.



Figure 6.12 Performance comparison in terms of customer satisfaction

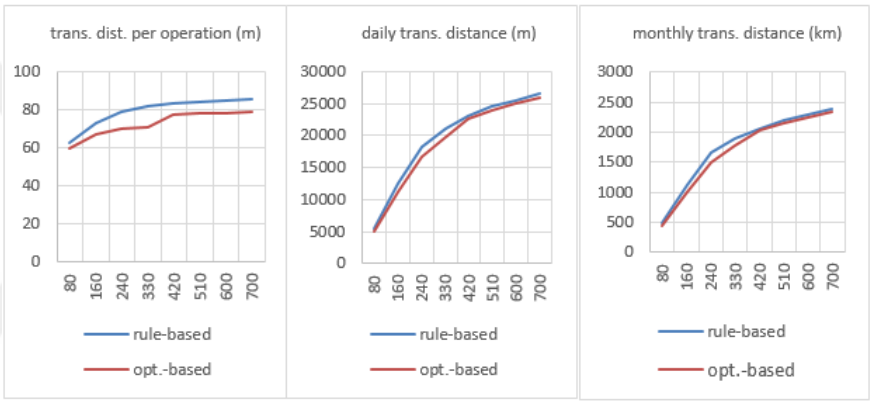


Figure 6.13 Performance comparison in terms of system utilization

Figure 6.12 shows that the improvements in the customer waiting times increase as the customer density increases. In other words, the efficiency of the proposed approach is increased as the capacity utilization rate increases. Figure 6.13 shows that the proposed approach provides better results than the classic approach in system utilization rate, but it seems that the improvements are not affected by the customer density. The results show that the new allocation procedure can considerably improve capacity utilization, customer satisfaction, and system efficiency compared with the classic allocation approach.

6.4.2 Efficiency of the Proposed Algorithm

In the previous section, the performance of the optimization-based planning and control approach using a novel allocation procedure is investigated by comparing the commonly used rule-based planning and control approach. After providing convincing results about the superiority of the proposed approach, the efficiency and effectiveness of the algorithm used in the proposed approach will be analyzed in this section. Because it is seen that even though the new approach has better performance in most of the criteria, the time-consuming of the algorithm should be investigated if it can apply to real systems and software. Thus the performance of the proposed algorithm will be analyzed in terms of solution quality and time consumed for the solution. Finally, it will be discussed if the algorithm provides good solutions in a reasonable time by changing the main parameter of the optimization algorithm.

The solution quality and computational time of the allocation algorithm are investigated depending on the iteration numbers of the GRASP algorithm. In addition, the impact of searching for a better solution on customers' waiting time transfer distance is examined. The transfer distance traveled per operation and average customer waiting per operation are recorded for iteration numbers from 1 to 200 iterations. For this purpose, we simulated the same FAPS with the same parameters, but just for one week (7 days) to be able to test the algorithm with different iteration numbers. The results of the 10 replication for each iteration number is given in Appendix A.2.

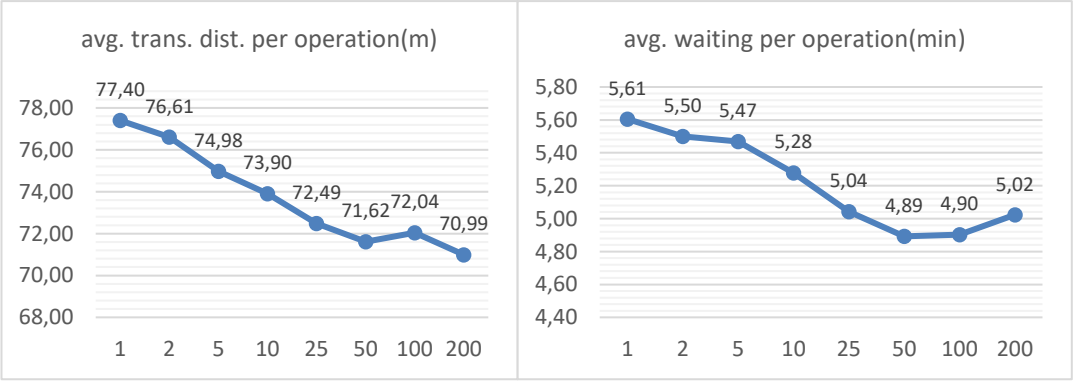


Figure 6.14 Solution quality depending on iteration number

According to the average results of 10 replication shown in Figure 6.14, transfer distance constantly decreases as the iteration number increases, except for 100 iterations. However, it is not possible to mention the same situation for the waiting time. There is a decrease until 50 iterations, but then waiting time increases, contrary to transfer distance. The main reason for the results is the stochastic nature of the system parameters. As discussed in the previous sections, more simulation runs are needed to avoid the environmental impact and provide a more reliable comparison.

On the other hand, the computational efficiency of the proposed algorithm is tested based on different iteration numbers, which is an important parameter responsible for the allocation decision in the GRASP algorithm. Therefore, for each iteration, number 10 replication was taken, and the results table is given in Appendix A.3.

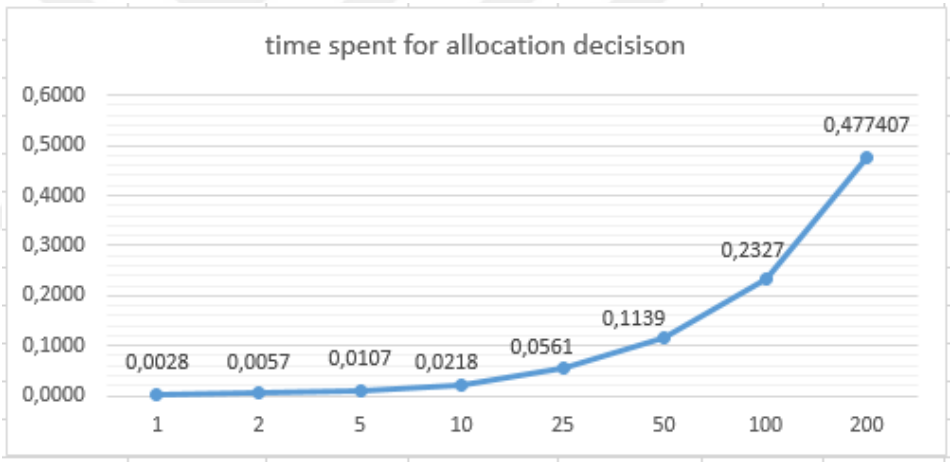


Figure 6.15 Computational time depending on iteration number

Figure 6.15 illustrates the average computation time of the algorithm depending on the iteration number setting in the GRASP algorithm. Although the computational time increases exponentially, the GRASP algorithm having 100 iterations determines a location in 0.23 seconds. In FAPS, drivers leave their vehicles in the parking room. After this point, customers do not need to wait for the transaction to finish. Thus, the system will have time to decide where the vehicle should be located until the car is loaded into the elevator, up to 3-5 seconds. The results presented in Table 6.2 are obtained using 5 iterations in the GRASP algorithm. In other words, each allocation decision is given 0.01 seconds which is quite acceptable for the real system.

6.4.3 Impact of Additional Information

One of the most discussed issues of FAPS is asking for parking durations for customers after leaving their cars. The idea of learning from customers how long they will stay and making an allocation depending on this time. However, when this idea was tried to be implemented in practice, it could not very efficient for various reasons. One reason is that customers mostly forget or ignore to enter the required information into the system. The other reason is that the customers write an indiscriminate time or can not adjust their departure time.

In this section, we investigate the impact of providing additional information to the system in case customers declare how long they park their car with a particular standard deviation. We tried to understand whether the system works better by making predictions based on historical data or getting customer information. For this purpose, we simulated the same FAPS with the same parameters, but just for one week (7 days) to be able to test the algorithm with different iteration numbers. The average results obtained from 10 replication for each case are illustrated in Figure 6.16.

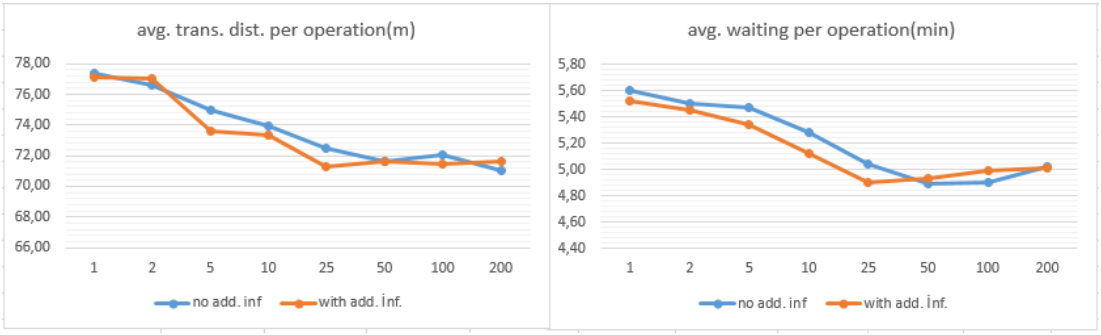


Figure 6.16 The impact of additional information about the parking time on the system

We suppose each customer's input is the mean value of a normal distribution function having a 0.5 h deviation. For example, a customer who will park his/her car enters the system 3 h as parking time. In this case, the system uses the normal distribution function $f(x;\mu,\sigma)$, where $\mu=3$ and $\sigma=0.5$ to predict duration time and allocate the car to an appropriate slot. As seen in Figure 6.16, there is very little difference between the two prediction approaches, even though asking customers

seems more effective. The difference between these two approaches can be neglected since the difference can be derived from the stochastic nature of the system parameters. More and longest simulation runs may avoid the environmental impact and provide a more reliable comparison. After that, it can be understood if there is a significant difference between the two samples using statistical methods. Thus, in the next step, we will investigate if there is a statistically significant difference between asking customers how they will park their cars and not to figure out if such additional information affects the performance of the proposed method. For this purpose, the two main performance metrics, average waiting time per operation and average transfer distance per operation, are analyzed.

Table 6.6 The normality test for performance criteria (additional information)

Tests of Normality

	Kolmogorov-Smirnov[a]			Shapiro-Wilk		
	Statistic	df	Sig.	Statistic	df	Sig.
no add inf	,081	70	,200*	,977	70	,232
with add inf	,080	70	,200*	,984	70	,533
fark_wait	,059	70	,200*	,982	70	,400
no_add_inf_dist	,082	70	,200*	,982	70	,424
with_add_inf_dist	,098	70	,095	,959	70	,023
fark_dist	,061	70	,200*	,993	70	,965

*. This is a lower bound of the true significance.

a. Lilliefors Significance Correction

As discussed in 6.4.1, the tests used during the analysis vary according to the data distribution. Thus, the data distribution used in the analysis should be determined. The samples do not show normal distribution, which makes these tests invalid and should be used as non-parametric tests. The data containing 80 instances (for each planning approach) is tested in SPSS for normality, and the results are presented in Table 6.6. The sample size for both of these examples is 80, so the Shapiro-Wilk test should be used. For all variables, the significance level ($p > 0.05$) suggests strong evidence of normality. For this reason, parametric correlation analyses like *Paired Samples T-test* or *ANOVA* two related samples test should be used when examining the research question: "*Is there a statistically significant difference impact of taking additional information from customers?*" (Eymen, 2007; Neuhauser, 2012).

Table 6.7 The results of the two related samples test (additional information)

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	no_add_inf_wait - with_add_inf_wait	,04600	,52269	,06247	-,07863	,17063	,736	69	,464

		Paired Differences					t	df	Sig. (2-tailed)
		Mean	Std. Deviation	Std. Error Mean	95% Confidence Interval of the Difference Lower	Upper			
Pair 1	no_add_inf_dist - with_add_inf_dist	,36414	2,31575	,27679	-,18803	,91632	1,316	69	,193

In cases where parametric test assumptions (normal distribution) can be fulfilled, Paired Samples T-test is used to test whether there is a significant difference between variable measurements at two different times or situations (Neuhauser, 2012). Thus, the differences between performance metrics are investigated by mentioned statistical methods in SPSS. The results of the Paired Samples T-test of two related samples test are given in Table 6.7. As described in the table, the null hypothesis *"the median difference between two situations is significant"* remains for both performance metrics since ($p>0.05$); which means both average waiting and traveled distance per operation have no statistically meaningful differences.

6.5 Conclusion and Remarks

The findings of the previous chapters implied that the research related to the operational efficiency of FAPSs should mainly focus on assignment/allocation problems as they dramatically affect all system efficiency. Whit this motivation, a novel allocation procedure was developed in the scope of this thesis. On the one hand, the alternative dispatching rules needed to operate the system more efficiently were investigated in detail in previous reports. On the other hand, the proposed planning approach was explained, and the architecture and algorithms of the new intelligent control system were presented. Afterward, the proposed planning approach, which aims to ensure the most appropriate allocation decision, was compared with the classic approach that utilizes a rule for allocation decision. The results showed that the proposed new allocation procedure could significantly improve both customer satisfaction and system utilization efficiency.

Thus the thesis inquires about the difference between two planning approaches (classic rule-based and novel opt.-based). The results of the Wilcoxon test approved a significant difference between the classic planning approach and the proposed planning approach in favor of the latter one. On the other hand, the impact of the additional information is investigated in the proposed planning approach if asking customers how long they park their cars. The results of the Paired Samples T-test show no significant differences between the situation providing additional information or not about the parking duration.

The efficiency of the proposed optimization-based algorithm is also analyzed in terms of the time consumed and the solution quality reflected by system performance measures. The simulation results show that the proposed allocation procedure can be executed in a reasonable time; thus, the novel optimization-based planning approach is implementable in real systems. Besides, the performance criteria improvements prove that the novel approach's capability is quite promising.

Still, there are some deficiencies in the experimental studies. The replication and instance number of cases could be extended to obtain a more reliable comparison. In the next research, it may be designed with more extensive experiments and many more cases to analyze the new approach's performance and performance. Also, the impact of increase and decrease of the standard deviation of the declared parking times by customers can be investigated in the proposed allocation procedure.

Another work planned is performing the proposed planning approach on a different FAPS structure with a multi-depth slot layout. However, it can be concluded that the simultaneous use of technology, data, knowledge, and computational intelligence, especially in the era of Industry 4.0, will increase the operational efficiency and efficiency of FAPS. As a result, it is thought that FAPSs will positively affect economic, socio-cultural, and environmental issues. Also, the scientific research carried out in the scope of this study will contribute to relevant literature.

CHAPTER 7
CONCLUSION

An increase in the number of personal and commercial vehicles related to the rapidly increasing population all over the world reveals parking lot problems, particularly in highly populated cities. Conventional parking lots are inefficient due to insufficient space and insufficient to meet the increasing demand. At this point, especially in the last two decades, Fully Automated Parking Systems (FAPS) offer more efficient and eco-friendly solutions by utilizing new generation technology that employs automatic robots for parking. Although FAPS provides many advantages for the public and citizens, some operational issues should be improved. A limited number of studies deal with planning, scheduling, and control of FSPS's operations. Therefore, academic research is required in order to increase the operational efficiency of FAPS. This thesis aims to develop methods and algorithms that improve the performance of FAPSs by increasing operational efficiency.

The proposed thesis consists of four main phases: motivation and scope determination, problem description, data gathering, solution, and analysis and discussion. In this section, the firstly summary of the thesis is given, then the contribution of this thesis is presented in the following section. Finally, the limitations of this research and future works are discussed in the last section.

7.1 Summary

Fully Automated Parking Systems (FAPSs) are new generation car parking systems where the sensor technology is used, and the parking process is carried out with the help of automated carriers (lifts, conveyors, robots). Especially in recent years, they have offered effective, economical, and environmentally friendly solutions to the car parking problem, which has become a serious problem in crowded cities. Moreover, unlike conventional systems, they use space more efficiently because they can park the cars on top of each other without needing auxiliary structures like ramps and elevators. In addition, the parking process with the help of automatic carriers provides

time, fuel, and energy savings. Owing to all these reasons, FAPSs are seen as the future of the parking systems and becoming more prevalent day by day. However, although many studies have been carried out on the design of FAPSs and the technological equipment to be used in FAPSs, the number of studies on the operational planning and control problems of FAPS is very limited. In this regard, this research area, in which the gains of Industry 4.0 can be utilized, is an emerging subject.

In FAPSs, two operations, car storage (allocation) and retrieval, are carried out in FAPS. As a result, two fundamental decision problems are encountered in the system: (i) in which order the operations will be done (sequencing) and (ii) where the parked cars will be located (allocation). Once the operations and related decisions are not well managed, they may lead to long service times, inefficient energy usage, and high indirect costs in the system. At the point where the design and hardware problems of FAPSs are almost solved, the service time and operational efficiency have become more important issues.

In this context, the problem was discussed, and contributions are highlighted to the gap in the literature. Then, candidate dispatching rules and heuristics were determined and defined. Results of the simulation study and the performance of the dispatching rules/heuristics were presented, and performance analysis of dispatching rules was also investigated. The results demonstrate that the combination of the NAS (Nearest Available Slot) allocation rule and FCFS (First Come First Served) sequencing rule outperforms all other combinations. Additional analyses show that the main differences between the performances originate from assignment/allocation rules. The results clearly show that allocation decision significantly impacts the operational efficiency in FAPSs. Conclusively, the importance of allocation decisions is proven via this study.

The experimental study has shown that the most important factor affecting service time and performance of the system is related to the location of the cars more than the sequence of the operations. In practice, the software used for planning and executing operations in FAPS utilizes simple dispatching/heuristic rules (such as nearest

available lot, first come first served) for such decisions. However, solving these problems as an optimization problem instead of using certain rules will significantly improve system performance, especially in service time. Thus, this thesis aims to develop dynamic and proactive methods for handling and solving the optimal allocation/assignment problem as an optimization problem. For this purpose, the works done within the scope of the thesis can be summarized as follows:

1. Developing a dynamic algorithm that executes the operational planning and control of FAPS
2. Developing a computational intelligence algorithm that uses the previous data and available information for allocating cars proactively to the most appropriate place
3. Collecting the necessary data for the developed proactive method and extracting the statistical information
4. Comparing the performance of computational intelligence (simulation-based optimization) algorithm with classical (rule-based) algorithms via a simulation study and analyzing the results

It was aimed to provide considerable improvements, especially in terms of customer satisfaction and operating costs in the system with the computational intelligence algorithm. When considering the combinatorial and dynamic nature of the problem and the need for a rapid solution for real-time control, heuristic/metaheuristic algorithms are used in this thesis. At this point, when taking into account its success in solving problems, this structure Greedy Randomized Adaptive Search Procedure (GRASP) algorithm is used in the solution approach.

Whit this motivation, a novel allocation procedure was developed in the scope of this thesis. On the one hand, the alternative dispatching rules needed to operate the system more efficiently were investigated in detail in the thesis. On the other hand, the proposed planning approach was explained, and the architecture and algorithms of the new intelligent control system were presented. Afterward, the proposed planning approach, which aims to ensure the most appropriate allocation decision, was

compared with the classic approach that utilizes a rule for allocation decision. The results showed that the proposed new allocation procedure could provide significant improvement in both customer satisfaction and system utilization efficiency.

The thesis also inquires about the correlation between two performance measures (customer waiting time and total distance traveled in the system). The positive correlation revealed by statistical analysis suggests that minimization of the transfer distance can be adequate for the optimization process as a sole objective. On the other hand, the efficiency of the proposed optimization-based algorithm is also analyzed in terms of the time consumed and the quality of the solution reflected by system performance measures. The simulation results show that the proposed allocation procedure can be executed in a reasonable time; thus, the novel optimization-based planning approach is implementable in real systems. Besides, the performance criteria improvements prove that the novel approach's capability is quite promising.

It was aimed to achieve an improvement (decrease) of 5-10% in the average waiting time of the customers and an improvement (decrease) of 2-3% in the total distance traveled in the system. However, compared with the classical rule-based planning&control approach, more than 20% improvement in the average waiting time of the customers and almost 10% improvement in the total distance traveled in the system were achieved with the proposed optimization-based planning approach using a novel allocation procedure. Also, the impact of providing additional information about the parking duration is investigated in the proposed method. Moreover, it was seen that there is no statistically meaningful difference between the two situations. The computational time of the optimization algorithm is much faster than estimated. Although it would have been acceptable to decide in 3-5 seconds the location of the arrived vehicle, the proposed algorithm decides to allocate the vehicle in less than 1 (one) second.

It can be concluded that the simultaneous use of technology, data, knowledge, and computational intelligence, especially in the era of Industry 4.0, will increase the operational efficiency and efficiency of FAPS. As a result, it is thought that FAPSs

will positively affect economic, socio-cultural, and environmental issues. Also, the scientific research carried out in the scope of this thesis will contribute to relevant literature.

7.2 Contribution of the Study

This study reveals the social, economic, and environmental effects of FAPSs, which is one of the motivation sources of the paper. On the other side, this study proves that while the interest in FAPSs is increasing worldwide, the fact that the academic/scientific studies on this subject are still limited indicates a need for work in this area.

Within the scope of this thesis, the proactive/dynamic tool placement/allocation problem will be emphasized. By effectively solving the problem, it aims to improve service times (customer waiting times) and system efficiency (total distance traveled in the system). It is clearly seen that reducing customer waiting times will increase customer satisfaction. On the other hand, it is thought that reducing the total distance covered by the carriers in the system while carrying out the operations will increase the speed of the system and thus customer satisfaction. In addition, the decrease in the total distance traveled will reduce the wear rate of the system, especially while reducing the maintenance and repair costs and extending the system life.

With the proposed approach, the problem in question will be considered an optimization problem, and the necessary solution methods will be developed, contrary to the existing practices and current studies on the subject. When the difficulties arising from the combinatorial nature of the problem are added to the uncertainties regarding the inputs and outputs of the vehicles, it is understood that the problem cannot be solved with exact solution methods and/or it is quite challenging to solve. However, it has been reported in studies (Blum & Roli, 2003; Blum, Puchinger, Raidl, & Roli, 2011) that meta-heuristic methods have yielded very successful results in this regard. In addition, dynamic optimization techniques should be used when planning

operations that take place in a dynamic environment (Baykasoğlu & Ozsoydan, 2017; Baykasoğlu & Ozsoydan, 2018).

In the light of this information, the scientific and technological original value of the thesis can be summarized as follows:

- ✓ Almost all of the existing studies on FAPS have focused on design and hardware issues to improve the performance of parking systems, and operational efficiency/effectiveness has been ignored. This thesis aims to operate the mentioned systems more efficiently by emphasizing the operational problems. Thus, a scientific contribution will be made to the subject.
- ✓ It has been observed that no optimization algorithm is used for decisions such as the placement of vehicles and the sequencing of operations in the scientific literature and the software used. Therefore, within the scope of this thesis, an optimization study will be carried out with an innovative approach, especially to place the vehicles in the correct place in the system.
- ✓ This proposed new approach will also allow proactive placement by taking into account the system's dynamic nature and the customers' stochastic behavior.
- ✓ The cognitive intelligence algorithm, which is planned to be developed, is planned to be designed so that it can be integrated into existing commercial software and can work in harmony with system data.

The proposed approach aims at more environmentally friendly and less energy-consuming FAPSs. At the same time, this study aims to increase customer satisfaction and will contribute to the spread of FAPS. In this context, it is anticipated that the proposed thesis may have positive socio-cultural, economic, and environmental contributions. Additionally, this study will contribute the related literature on the following issues:

- ✓ This study focuses on operational optimization instead of design optimization.
- ✓ Unlike the current literature, the sequencing and optimal allocation decision (only one study is found in the literature) will be conducted for tower-type FAPSs.
- ✓ However, the most significant contribution of this study will be solving these problems from a different perspective by putting daily customer behavior at the center of this research.
- ✓ The core of the study is to optimize operational problems by considering customer behavior.
- ✓ Dynamic and real-time operational planning and control problems of a real structure system are considered, which means the operational planning problems should be handled by taking into account structural and design problems.
- ✓ Problem is considered more general aspects (smart cities and transportation) than a technical issue.

Still, there are some deficiencies in the experimental studies and some points where the research could be extended and enhanced. The limitations of the study and prospective for future research are discussed in the following section.

7.3 Future Works

Regarding the limited number of scientific studies on the subject, there is a need for studies addressing the operational planning and control problems to increase the efficiency and effectiveness of FAPSs. Aftermath, considering these problems as optimization problems and solving them with metaheuristic algorithms instead of using certain rules will significantly improve system performance and service time. In addition, the new planning and control approaches should exploit real data in order to manage uncertainties.

It is clear that, in addition to the complexity of the introduced problem, uncertainty is another challenging issue that affects the quality of real-time decisions. The

mentioned uncertainty indeed stems from various customer profiles, which induce hard-to-predict arrival/retrieval times and parking durations. Remarkably, considering the difference between weekdays and weekends as well as ordinary hours and rush hours, the mentioned problem becomes even more challenging. Thus more detailed analysis and tests can be conducted on the actual system data to provide more detailed information to the system. For example, additional information about the customer or niche classifications and analyses can be conducted. In this way, the proposed system can make more incisive decisions.

On the other hand, the replication and instance number of cases could be extended to obtain a more reliable comparison. In the following research, it may be designed with more extensive experiments and many more cases to analyze the new approach's performance and performance. Also, the impact of increase and decrease of the standard deviation of the declared parking times by customers can be investigated in the proposed allocation procedure.

Another work planned is performing the proposed planning approach on a different FAPS structure with a multi-depth slot layout. However, it can be concluded that the simultaneous use of technology, data, knowledge, and computational intelligence, especially in the era of Industry 4.0, will increase the operational efficiency and efficiency of FAPS. As a result, it is thought that FAPSs will positively affect economic, socio-cultural, and environmental issues. Also, the scientific research carried out in the scope of this study will contribute to relevant literature.

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APPENDICES

Appendix-A.1

Table A1.1 Results of simulation study with allocation rule Random Available Slot (RAS)

		Cust number			Waits			utilization					
Simulation of the 6-month period		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
FCFS	Run_1	29137	0	162	2.31	3.25	2.78	91.93	3.33	14871.97	538.90	2676.95	97001.67
	Run_2	30154	7	168	2.44	3.33	2.88	91.35	3.31	15318.79	555.30	2757.38	99953.83
	Run_3	29499	5	164	2.28	3.26	2.77	92.08	3.34	15032.61	544.79	2705.87	98062.03
	Run_4	29927	12	166	2.24	3.19	2.72	92.02	3.33	15262.74	553.09	2747.29	99556.97
	Run_5	29402	10	163	2.32	3.21	2.76	91.48	3.32	14974.17	542.70	2695.35	97685.55
	Run_6	29659	0	165	2.19	3.22	2.71	92.40	3.35	15135.09	548.44	2724.32	98719.58
	Run_7	29306	4	163	2.16	3.13	2.64	91.60	3.32	14936.61	541.30	2688.59	97434.62
	Run_8	29910	0	166	2.33	3.30	2.81	91.46	3.32	15201.68	551.03	2736.30	99186.08
	Run_9	29155	0	162	2.29	3.20	2.74	91.80	3.33	14873.95	538.99	2677.31	97018.37
	Run_10	29890	4	166	2.20	3.18	2.69	92.07	3.34	15249.66	552.60	2744.94	99468.60
	average	29603.9	4.2	164.5	2.3	3.2	2.8	91.8	3.3	15085.7	546.7	2715.4	98408.7

		Cust number			Waits			utilization					
Simulation of the 6-month period		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
NRF	Run_1	29093	0	162	3.62	2.41	3.01	93.54	3.38	15117.30	547.01	2721.11	98461.92
	Run_2	29555	6	164	4.17	2.42	3.30	93.19	3.37	15311.45	554.17	2756.06	99750.05
	Run_3	29236	3	162	3.62	2.41	3.01	93.35	3.38	15175.26	549.15	2731.55	98847.80
	Run_4	29437	5	164	4.16	2.44	3.30	93.27	3.38	15260.06	552.28	2746.81	99410.23
	Run_5	29492	0	164	3.95	2.43	3.19	93.34	3.38	15305.44	553.87	2754.98	99697.18
	Run_6	29774	9	165	3.74	2.43	3.09	93.07	3.37	15411.27	557.82	2774.03	100407.33
	Run_7	29404	0	163	3.98	2.45	3.21	93.38	3.38	15274.44	552.71	2749.40	99487.70
	Run_8	29379	0	163	3.79	2.43	3.11	93.21	3.37	15244.59	551.68	2744.03	99301.95
	Run_9	29565	0	164	3.87	2.46	3.16	93.28	3.38	15322.99	554.57	2758.14	99821.93
	Run_10	29543	4	164	3.85	2.41	3.13	93.34	3.38	15309.34	554.08	2755.68	99734.18
	average	29447.8	2.7	163.6	3.9	2.4	3.2	93.3	3.4	15273.2	552.7	2749.2	99492.0

Table A1.1 Continues

		Cust number			Waits			utilization					
Simulation of the 6-month period		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
PRF -> FCFS (retrievals)	Run_1	29417	46	163	1.28	5.18	3.23	92.11	3.34	15070.21	545.92	2712.64	98265.78
	Run_2	29889	92	166	1.34	5.74	3.54	92.02	3.33	15314.59	554.77	2756.63	99857.93
	Run_3	29610	47	165	1.28	5.84	3.56	92.27	3.34	15161.48	549.25	2729.07	99857.93
	Run_4	29846	41	166	1.30	5.46	3.38	92.35	3.35	15270.89	553.25	2748.76	99584.25
	Run_5	29999	37	167	1.31	6.07	6.07	92.45	3.35	15418.76	558.40	2775.38	99584.25
	Run_6	29642	89	165	1.33	5.84	3.58	91.80	3.33	15162.23	549.32	2729.20	98877.93
	Run_7	29845	43	166	1.34	5.34	3.34	92.64	3.35	15326.61	555.10	2758.79	99918.30
	Run_8	30000	48	167	1.35	5.68	3.52	92.14	3.34	15357.99	556.38	2764.44	100147.93
	Run_9	29904	27	166	1.33	5.75	3.54	92.46	3.35	15329.49	555.29	2759.31	99951.33
	Run_10	29203	53	162	1.30	5.33	3.32	91.96	3.33	14987.55	542.85	2697.76	97712.78
	average	29735.5	52.3	165.2	1.3	5.6	3.7	92.2	3.3	15240.0	552.1	2743.2	99375.8

		Cust number			Waits			utilization					
Simulation of the 6-month period		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
PRF -> NOF (retrievals)	Run_1	29359	22	163	1.30	4.81	3.05	92.39	3.35	15061.78	545.55	2711.12	98199.72
	Run_2	29029	34	161	1.30	5.05	3.18	92.19	3.34	14916.02	540.21	2684.88	97237.20
	Run_3	29370	41	163	1.31	4.86	3.09	92.39	3.35	15060.32	545.52	2710.86	98193.93
	Run_4	29357	24	163	1.29	4.54	2.91	92.22	3.34	15074.24	545.97	2713.36	98273.97
	Run_5	29640	24	165	1.30	4.79	3.05	92.62	3.35	15213.64	551.03	2738.46	99185.83
	Run_6	29582	45	164	1.29	4.64	2.96	92.61	3.35	15238.91	551.79	2743.00	99321.97
	Run_7	29749	36	165	1.31	5.11	3.21	92.34	3.34	15253.11	552.51	2745.56	99451.70
	Run_8	29634	20	165	1.30	4.69	2.99	92.15	3.34	15184.93	550.07	2733.29	99011.98
	Run_9	29068	44	161	1.28	5.03	3.16	92.37	3.35	14931.33	540.77	2687.64	97339.47
	Run_10	29463	36	164	1.36	4.89	3.12	92.33	3.34	15131.44	548.03	2723.66	98645.45
	average	29425.1	32.6	163.5	1.3	4.8	3.1	92.4	3.3	15106.6	547.1	2719.2	98486.1

		Cust number			Waits			utilization					
Simulation of the 6-month period		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
PRF -> FOF(retrievals)	Run_1	29682	42	165	1.33	5.67	3.50	91.67	3.32	15186.84	550.20	2733.63	99036.27
	Run_2	29972	51	167	1.27	5.54	3.40	92.50	3.35	15383.14	557.17	2768.97	100291.40
	Run_3	29190	42	162	1.26	4.93	3.10	91.91	3.33	14938.43	541.19	2688.92	97414.58
	Run_4	29510	47	164	1.26	5.55	3.40	92.36	3.35	15121.89	547.78	2721.94	98600.67
	Run_5	29485	43	164	1.32	6.01	3.67	92.31	3.34	15132.84	548.11	2723.91	98659.73
	Run_6	29735	38	165	1.26	5.41	3.34	92.46	3.35	15252.28	552.46	2745.41	99443.03
	Run_7	29910	89	166	1.35	5.83	3.59	92.11	3.34	15302.43	554.39	2754.44	99790.57
	Run_8	30034	46	167	1.32	5.40	3.36	92.13	3.34	15381.38	557.21	2768.65	100297.35
	Run_9	29877	33	166	1.27	5.53	3.40	92.16	3.34	15297.12	554.17	2753.48	99749.90
	Run_10	29672	84	165	1.30	5.88	3.59	91.92	3.33	15178.49	549.91	2732.13	98983.48
	average	29706.7	51.5	165.0	1.3	5.6	3.4	92.2	3.3	15217.5	551.3	2739.1	99226.7

Table A1.1 Continues

Simulation of the 6-month period		Cust number			Waits			utilization					
		total # of served customers	total # of rejected customers	average # of customers	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
RRF -> FCFS (retrievals)	Run_1	29293	0	163	4.31	2.40	3.36	93.22	3.37	15204.46	550.21	2736.80	99038.20
	Run_2	30098	10	167	4.70	2.43	3.57	93.59	3.39	15628.91	565.55	2813.20	101799.57
	Run_3	29621	0	165	4.40	2.40	3.40	93.47	3.38	15383.48	556.67	2769.03	100199.82
	Run_4	29717	0	165	4.05	2.39	3.22	93.19	3.37	15374.59	556.51	2767.43	100172.07
	Run_5	29761	0	165	4.02	2.43	3.23	93.38	3.38	15451.06	559.13	2781.19	100642.62
	Run_6	29529	0	164	4.00	2.41	3.20	92.83	3.36	15317.68	554.34	2757.18	99780.48
	Run_7	30018	0	167	4.43	2.42	3.42	93.24	3.37	15584.20	563.94	2805.16	101510.00
	Run_8	29510	1	164	4.03	2.40	3.21	93.51	3.38	15338.05	554.99	2760.85	99897.65
	Run_9	29599	2	164	4.27	2.42	3.34	93.48	3.38	15377.26	556.43	2767.91	100156.63
	Run_10	30013	0	167	3.88	2.42	3.15	93.56	3.39	15588.16	564.07	2805.87	101532.43
	average	29715.9	1.3	165.1	4.2	2.4	3.3	93.3	3.4	15424.8	558.2	2776.5	100472.9

Simulation of the 6-month period		Cust number			Waits			utilization					
		total # of served customers	total # of rejected customers	average # of customers	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
RRF -> NOF (retrievals)	Run_1	29516	0	164	4.29	2.37	3.33	93.89	3.40	15400.05	557.06	2772.01	100271.25
	Run_2	29571	0	164	4.18	2.39	3.29	93.24	3.37	15368.27	556.08	2766.29	100095.20
	Run_3	28826	0	160	4.34	2.35	3.34	93.49	3.38	14992.79	542.46	2698.70	97643.68
	Run_4	29704	1	165	4.36	2.40	3.38	93.47	3.38	15448.75	558.96	2780.77	100613.55
	Run_5	29819	7	166	3.94	2.37	3.16	93.69	3.39	15503.03	560.94	2790.54	100969.88
	Run_6	29903	2	166	4.29	2.36	3.33	93.38	3.38	15520.60	561.65	2793.71	101097.75
	Run_7	29780	0	165	4.42	2.38	3.40	93.59	3.39	15499.16	560.76	2789.85	100936.27
	Run_8	30056	1	167	4.31	2.37	3.34	93.45	3.38	15602.41	564.61	2808.43	101629.40
	Run_9	29486	0	164	4.30	2.38	3.34	93.32	3.38	15308.78	553.98	2755.58	99715.60
	Run_10	29701	0	165	4.27	2.37	3.32	93.55	3.39	15474.33	559.81	2785.38	100766.23
	average	29636.2	1.1	164.6	4.3	2.4	3.3	93.5	3.4	15411.8	557.6	2774.1	100373.9

Simulation of the 6-month period		Cust number			Waits			utilization					
		total # of served customers	total # of rejected customers	average # of customers	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
RRF -> FOF (retrievals)	Run_1	29521	3	164	3.98	2.46	3.22	93.25	3.37	15312.86	554.16	2756.32	99749.43
	Run_2	29902	0	166	4.15	2.45	3.30	93.03	3.37	15477.11	560.20	2785.88	100836.53
	Run_3	29159	0	162	3.76	2.40	3.08	93.50	3.38	15128.01	547.47	2723.04	98543.82
	Run_4	30014	0	167	4.09	2.45	3.27	93.46	3.38	15571.35	563.51	2802.84	101431.83
	Run_5	29696	0	165	3.71	2.42	3.06	93.24	3.37	15385.56	556.85	2769.40	100232.32
	Run_6	29882	0	166	4.02	2.44	3.23	93.21	3.37	15476.56	560.16	2785.78	100827.90
	Run_7	29950	0	166	4.21	2.44	3.33	93.20	3.37	15549.06	562.67	2798.83	101281.03
	Run_8	29415	0	163	3.98	2.44	3.21	92.64	3.35	15251.91	551.97	2745.34	99355.43
	Run_9	29068	0	161	3.74	2.40	3.07	93.23	3.37	15085.67	545.92	2715.42	98265.47
	Run_10	29763	7	165	3.91	2.44	3.18	93.11	3.37	15439.60	558.75	2779.13	100574.40
	average	29637.0	1.0	164.7	4.0	2.4	3.2	93.2	3.4	15367.8	556.2	2766.2	100109.8

Table A1.2 Results of simulation study with allocation rule Nearest Available Slot (NAS)

		Cust number			Waits			utilization					
Simulation of the 6-month period		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
FCFS	Run_1	29762	3	165	1.25	2.18	1.71	70.61	2.62	11882.48	440.17	2138.85	79231.40
	Run_2	29193	0	162	1.25	2.19	1.72	70.18	2.61	11643.39	431.36	2095.81	77645.12
	Run_3	29165	13	162	1.29	2.16	1.73	70.42	2.61	11651.96	431.61	2097.35	77689.10
	Run_4	29540	0	164	1.24	2.17	1.71	70.25	2.61	11772.68	436.19	2119.08	78513.42
	Run_5	29250	15	163	1.39	2.26	1.82	70.38	2.61	11710.01	433.67	2107.80	78060.08
	Run_6	30129	0	167	1.20	2.17	1.68	71.10	2.64	12079.91	447.30	2174.38	80513.87
	Run_7	29331	0	163	1.15	2.10	1.62	70.14	2.60	11690.30	433.13	2104.25	77963.40
	Run_8	29727	0	165	1.21	2.12	1.67	70.77	2.63	11887.55	440.29	2139.76	79252.52
	Run_9	29920	0	166	1.16	2.09	1.62	70.64	2.62	11951.96	442.72	2151.35	79690.45
	Run_10	29423	5	163	1.22	2.13	1.67	70.31	2.61	11747.75	435.18	2114.60	78332.63
	average	29544.0	3.6	164.1	1.2	2.2	1.7	70.5	2.6	11801.8	437.2	2124.3	78689.2

		Cust number			Waits			utilization					
Simulation of the 6-month period		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
NRF	Run_1	29851	0	166	1.78	1.81	1.79	71.77	2.66	12114.98	448.06	2180.70	80650.12
	Run_2	29792	0	166	1.75	1.81	1.78	71.17	2.64	12078.10	446.74	2174.06	80413.12
	Run_3	29740	0	165	1.77	1.79	1.78	71.16	2.64	12043.93	445.52	2167.91	80194.27
	Run_4	29926	0	166	1.69	1.80	1.75	71.59	2.65	12143.34	449.11	2185.80	80840.33
	Run_5	29388	0	163	1.90	1.77	1.83	71.21	2.64	11892.73	439.96	2140.69	79193.15
	Run_6	29993	5	167	1.83	1.81	1.82	71.56	2.65	12183.56	450.55	2193.04	81099.50
	Run_7	29737	0	165	1.71	1.78	1.74	71.42	2.65	12045.64	445.58	2168.22	80203.70
	Run_8	29442	0	164	1.67	1.78	1.73	71.06	2.64	11903.43	440.40	2142.62	79271.78
	Run_9	30145	0	167	1.88	1.81	1.85	71.74	2.66	12254.50	453.14	2205.81	81565.65
	Run_10	29697	0	165	1.99	1.80	1.90	71.40	2.65	12032.78	445.09	2165.90	80115.87
	average	29771.1	0.5	165.4	1.8	1.8	1.8	71.4	2.6	12069.3	446.4	2172.5	80354.7

Table A1.2 Continues

Simulation of the 6-month period		Cust number			Waits			utilization					
		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
PRF -> FCFS (retrievals)	Run_1	29624	103	165	0.90	4.06	2.48	71.08	2.64	11973.23	443.00	2155.18	79739.12
	Run_2	29394	87	163	0.85	3.98	2.42	71.01	2.63	11842.99	438.31	2131.74	78896.35
	Run_3	28978	127	161	0.98	4.58	2.78	71.04	2.63	11761.89	434.99	2117.14	78298.80
	Run_4	29519	53	164	0.88	3.75	2.32	71.04	2.63	11898.43	440.35	2141.72	79262.28
	Run_5	29408	122	163	0.93	4.11	2.52	70.85	2.63	11881.34	439.61	2138.64	79130.20
	Run_6	29574	87	164	0.89	3.88	2.39	70.75	2.63	11885.82	440.01	2139.45	79201.32
	Run_7	29098	62	162	0.83	3.26	2.05	70.85	2.63	11701.93	433.17	2106.35	77971.03
	Run_8	29673	95	165	0.91	3.90	2.40	71.21	2.64	12002.58	444.05	2160.47	79928.30
	Run_9	29426	63	163	0.87	3.43	2.15	70.86	2.63	11838.24	438.20	2130.88	78876.35
	Run_10	29346	96	163	0.87	3.90	2.38	70.95	2.63	11847.96	438.41	2132.63	78913.35
	average	29404.0	89.5	163.4	0.9	3.9	2.4	71.0	2.6	11863.4	439.0	2135.4	79021.7

Simulation of the 6-month period		Cust number			Waits			utilization					
		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
PRF -> NOF (retrievals)	Run_1	29274	18	163	0.84	3.22	2.03	70.63	2.62	11738.24	434.64	2112.88	78235.83
	Run_2	29218	70	162	0.90	3.67	2.29	70.93	2.63	11810.11	436.96	2125.82	78652.13
	Run_3	28905	94	161	0.98	3.66	2.32	70.78	2.63	11697.28	432.73	2105.51	77891.70
	Run_4	29486	66	164	0.93	3.45	2.19	71.18	2.64	11977.90	442.95	2156.02	79730.35
	Run_5	29602	53	164	0.87	3.38	2.12	71.01	2.63	11958.21	442.46	2152.48	79643.12
	Run_6	29839	54	166	0.88	3.50	2.19	71.42	2.65	12059.25	446.18	2170.67	80312.58
	Run_7	29470	66	164	0.90	3.61	2.26	71.23	2.64	11929.83	441.32	2147.37	79437.67
	Run_8	29606	41	164	0.87	3.53	2.20	71.14	2.64	11978.11	443.13	2156.06	79763.57
	Run_9	29913	82	166	0.94	3.66	2.30	71.18	2.64	12067.89	446.58	2172.22	80384.12
	Run_10	29227	35	162	0.83	3.30	2.07	70.72	2.62	11743.80	434.76	2113.88	78256.67
	average	29454.0	57.9	163.6	0.9	3.5	2.2	71.0	2.6	11896.1	440.2	2141.3	79230.8

Simulation of the 6-month period		Cust number			Waits			utilization					
		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
PRF -> FOF(retrievals)	Run_1	30205	107	168	0.99	4.87	2.93	71.89	2.66	12270.80	453.77	2208.74	81679.48
	Run_2	29459	184	164	0.90	5.27	3.08	71.27	2.64	11900.48	440.33	2142.09	79258.60
	Run_3	29436	158	164	0.96	4.90	2.93	71.44	2.65	11945.44	441.79	2150.18	79522.22
	Run_4	29585	194	164	0.97	5.21	3.09	71.58	2.65	12034.73	444.99	2166.25	80097.72
	Run_5	29688	121	165	0.89	4.60	2.75	70.92	2.63	11976.16	443.19	2155.71	79773.73
	Run_6	29067	74	161	0.88	4.02	2.45	71.39	2.65	11731.03	434.10	2111.59	78137.37
	Run_7	29141	112	162	0.95	4.31	2.63	71.00	2.63	11731.45	434.22	2111.66	78159.62
	Run_8	29345	92	163	0.85	4.25	2.55	71.10	2.64	11843.69	438.26	2131.86	78887.45
	Run_9	29632	131	165	0.93	4.54	2.74	71.61	2.65	12021.44	444.61	2163.86	80030.53
	Run_10	29958	135	166	0.97	5.19	3.08	71.89	2.66	12225.70	451.91	2200.63	81342.98
	average	29551.6	130.8	164.2	0.9	4.7	2.8	71.4	2.6	11968.1	442.7	2154.3	79689.0

Table A1.2 Continues

		Cust number			Waits			utilization					
Simulation of the 6-month period		total # of served customers	total # of rejected customers	average # of customers	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
RRF -> FCFS (retrievals)	Run_1	29115	0	162	1.67	1.77	1.72	71.58	2.65	11804.73	436.62	2124.85	78592.37
	Run_2	30158	0	168	1.88	1.79	1.84	72.06	2.67	12297.79	454.61	2213.60	81828.90
	Run_3	29787	0	165	1.88	1.78	1.83	71.47	2.65	12109.46	447.78	2179.70	80599.98
	Run_4	29773	0	165	1.70	1.76	1.73	71.30	2.64	12037.53	445.36	2166.76	80164.67
	Run_5	29744	3	165	1.95	1.79	1.87	71.85	2.66	12141.39	448.78	2185.45	80780.07
	Run_6	30025	0	167	1.92	1.79	1.85	71.45	2.65	12220.08	451.82	2199.61	81327.13
	Run_7	29568	0	164	1.81	1.76	1.79	71.31	2.64	11983.79	443.26	2157.08	79787.57
	Run_8	29545	0	164	1.68	1.76	1.72	71.26	2.64	11949.01	442.07	2150.82	79572.70
	Run_9	29842	0	166	1.85	1.77	1.81	71.81	2.66	12130.14	448.55	2183.43	80738.70
	Run_10	29665	21	165	2.20	1.80	2.00	71.71	2.66	12102.71	447.37	2178.49	80526.93
	average	29722.2	2.4	165.1	1.9	1.8	1.8	71.6	2.7	12077.7	446.6	2174.0	80391.9

		Cust number			Waits			utilization					
Simulation of the 6-month period		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
RRF -> NOF (retrievals)	Run_1	29749	0	165	1.88	1.77	1.83	72.09	2.67	12132.77	448.50	2183.90	80729.68
	Run_2	29305	0	163	1.84	1.75	1.80	71.06	2.64	11850.95	438.45	2133.17	78920.37
	Run_3	29639	0	165	1.78	1.74	1.76	71.38	2.65	11999.37	443.89	2159.89	79899.97
	Run_4	29791	0	166	1.96	1.76	1.86	71.53	2.65	12087.54	447.05	2175.76	80469.53
	Run_5	29388	0	163	1.72	1.75	1.73	71.15	2.64	11906.78	440.43	2143.22	79277.48
	Run_6	30052	0	167	2.19	1.78	1.98	71.60	2.65	12235.57	452.37	2202.40	81427.30
	Run_7	29916	0	166	1.77	1.75	1.76	71.26	2.64	12119.41	448.30	2181.49	80694.07
	Run_8	29683	0	165	1.72	1.75	1.74	71.34	2.64	12046.93	445.54	2168.45	80197.02
	Run_9	29387	0	163	1.93	1.75	1.84	71.30	2.64	11905.25	440.38	2142.95	79268.03
	Run_10	29867	0	166	1.88	1.77	1.83	71.57	2.65	12159.91	449.58	2188.78	80923.98
	average	29677.7	0.0	164.9	1.9	1.8	1.8	71.4	2.6	12044.4	445.4	2168.0	80180.7

		Cust number			Waits			utilization					
Simulation of the 6-month period		total # of served customers	total # of rejected customers	average # of customers	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
RRF -> FOF (retrievals)	Run_1	30034	0	167	1.88	1.80	1.84	71.34	2.64	12192.89	450.92	2194.72	81166.43
	Run_2	29862	0	166	1.69	1.77	1.73	71.20	2.64	12050.97	445.94	2169.17	80269.00
	Run_3	28851	0	160	1.62	1.76	1.69	71.03	2.63	11680.63	432.10	2102.51	77777.35
	Run_4	29923	0	166	1.80	1.78	1.79	71.02	2.63	12119.28	448.31	2181.47	80695.13
	Run_5	29565	0	164	1.68	1.80	1.74	71.36	2.65	12022.43	444.55	2164.04	80018.57
	Run_6	30066	13	167	1.97	1.82	1.89	71.62	2.65	12224.28	452.02	2200.37	81363.28
	Run_7	29323	0	163	1.74	1.77	1.76	70.75	2.63	11811.75	437.17	2126.12	78689.97
	Run_8	29490	9	164	1.70	1.79	1.74	71.59	2.65	11991.38	443.40	2158.45	79812.28
	Run_9	29631	0	165	1.79	1.78	1.79	71.36	2.65	12015.84	444.43	2162.85	79996.65
	Run_10	29471	0	164	1.63	1.78	1.70	71.55	2.65	11932.51	441.41	2147.85	79454.02
	average	29621.6	2.2	164.6	1.7	1.8	1.8	71.3	2.6	12004.2	444.0	2160.8	79924.3

Table A1.3 Results of simulation study with allocation rule Farest Available Slot (FAS)

Simulation of the 6-month period		Cust number			Waits			utilization					
		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
FCFS	Run_1	29410	4	163	4.10	4.81	4.46	111.98	4.00	17969.33	642.55	3234.48	115658.62
	Run_2	29676	4	165	4.33	5.01	4.67	111.42	3.98	18044.41	645.44	3247.99	116180.07
	Run_3	29172	7	162	3.85	4.52	4.19	111.35	3.98	17785.54	636.07	3201.40	114492.43
	Run_4	29172	7	162	3.85	4.52	4.19	111.35	3.98	17785.54	636.07	3201.40	114492.43
	Run_5	29334	2	163	4.24	4.91	4.58	111.26	3.98	17839.24	638.10	3211.06	114857.83
	Run_6	29925	11	166	4.39	5.05	4.72	111.10	3.97	18200.86	651.03	3276.16	117185.18
	Run_7	29284	11	163	4.20	4.92	4.56	111.95	4.00	17927.10	640.95	3226.88	115371.67
	Run_8	29101	2	162	3.89	4.60	4.25	110.98	3.97	17744.81	634.61	3194.07	114229.10
	Run_9	29624	10	165	4.29	4.97	4.63	111.65	3.99	18077.42	646.47	3253.94	116364.23
	Run_10	29256	6	163	3.78	4.52	4.15	112.22	4.01	17928.84	640.97	3227.19	115374.67
	average	29395.4	6.4	163.3	4.1	4.8	4.4	111.5	4.0	17930.3	641.2	3227.5	115420.6

Simulation of the 6-month period		Cust number			Waits			utilization					
		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
NRF	Run_1	29490	4	164	9.64	3.07	6.35	113.77	4.06	18426.74	657.91	3316.81	118424.42
	Run_2	29810	5	166	8.61	3.04	5.83	113.49	4.05	18553.26	662.60	3339.59	119268.88
	Run_3	29750	8	165	9.22	3.05	6.14	114.06	4.07	18611.61	664.46	3350.09	119603.00
	Run_4	29454	10	164	9.44	3.06	6.25	113.91	4.06	18428.63	657.92	3317.15	118426.17
	Run_5	29853	0	166	9.77	3.05	6.41	113.23	4.04	18579.44	663.54	3344.30	119437.43
	Run_6	29417	9	163	9.33	3.04	6.18	112.90	4.03	18302.45	653.66	3294.44	117659.25
	Run_7	29651	8	165	9.64	3.05	6.34	113.54	4.05	18492.42	660.34	3328.64	118861.45
	Run_8	29627	0	165	9.09	3.06	6.07	114.37	4.08	18571.22	662.93	3342.82	119327.83
	Run_9	29426	0	163	9.25	3.04	6.15	113.76	4.06	18369.57	655.91	3306.52	118064.37
	Run_10	29368	22	163	8.49	3.02	5.75	113.21	4.04	18294.01	653.31	3292.92	117595.52
	average	29584.6	6.6	164.4	9.2	3.0	6.1	113.6	4.1	18462.9	659.3	3323.3	118666.8

Table A1.3 Continues

		Cust number			Waits			utilization					
Simulation of the 6-month period		total # of served customers	total # of rejected customers	average # of customers	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
PRF -> FCFS (retrievals)	Run_1	30080	64	167	1.76	8.85	5.30	110.99	3.97	18326.34	655.44	3298.74	117979.35
	Run_2	29639	25	165	1.74	8.37	5.06	111.42	3.98	18057.54	645.83	3250.36	116249.00
	Run_3	29650	69	165	1.77	9.04	5.41	111.48	3.98	18088.03	646.86	3255.85	116434.85
	Run_4	29166	61	162	1.72	7.94	4.83	112.35	4.01	17889.08	639.51	3220.03	115112.05
	Run_5	30163	51	168	1.77	8.66	5.21	111.43	3.98	18349.86	656.35	3302.97	118142.60
	Run_6	29795	57	166	1.77	9.09	5.43	111.17	3.97	18145.58	648.99	3266.21	116818.83
	Run_7	29795	57	166	1.77	9.09	5.43	111.17	3.97	18145.58	648.99	3266.21	116818.83
	Run_8	29162	36	162	1.78	9.16	5.47	111.65	3.99	17779.72	635.86	3200.35	114454.83
	Run_9	29367	44	163	1.73	8.57	5.15	111.97	4.00	17966.43	642.39	3233.96	115629.78
	Run_10	29220	32	162	1.73	7.85	4.79	111.23	3.97	17852.52	638.37	3213.45	114907.10
	average	29603.7	49.6	164.5	1.8	8.7	5.2	111.5	4.0	18060.1	645.9	3250.8	116254.7

		Cust number			Waits			utilization					
Simulation of the 6-month period		total # of served customers	total # of rejected customers	average # of customers	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
PRF -> NOF (retrievals)	Run_1	29903	31	166	1.82	7.30	4.56	111.76	3.99	18249.70	652.62	3284.95	117472.32
	Run_2	29511	13	164	1.77	7.28	4.52	111.47	3.98	18015.83	644.25	3242.85	115964.57
	Run_3	29927	14	166	1.75	7.26	4.51	111.55	3.98	18244.29	652.48	3283.97	117446.30
	Run_4	29917	16	166	1.75	7.61	4.68	111.68	3.99	18267.22	653.23	3288.10	117581.17
	Run_5	29888	6	166	1.82	7.67	4.75	111.45	3.98	18260.92	652.98	3286.97	117535.65
	Run_6	29507	5	164	1.76	7.55	4.65	111.60	3.99	18023.01	644.48	3244.14	116006.57
	Run_7	30028	28	167	1.82	7.51	4.66	111.29	3.98	18308.28	654.76	3295.49	117857.13
	Run_8	29635	42	165	1.77	7.51	4.64	111.54	3.98	18087.22	646.81	3255.70	116425.97
	Run_9	30075	11	167	1.76	7.68	4.72	111.28	3.98	18265.71	653.41	3287.83	117614.23
	Run_10	29490	8	164	1.69	7.20	4.44	111.59	3.99	18058.34	645.63	3250.50	116214.02
	average	29788.1	17.4	165.5	1.8	7.5	4.6	111.5	4.0	18178.0	650.1	3272.0	117011.8

		Cust number			Waits			utilization					
Simulation of the 6-month period		total # of served customers	total # of rejected customers	average # of customers	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
PRF -> FOF(retrievals)	Run_1	29081	51	162	1.71	8.93	5.32	112.17	4.01	17856.83	638.31	3214.23	114895.88
	Run_2	29400	82	163	1.73	9.17	5.45	111.31	3.98	17987.78	643.15	3237.80	115766.65
	Run_3	30299	61	168	1.79	8.86	5.33	111.30	3.98	18434.94	659.39	3318.29	118689.35
	Run_4	30144	103	167	1.79	10.26	6.02	110.36	3.95	18265.37	653.50	3287.77	117630.63
	Run_5	29628	13	165	1.70	8.86	5.28	111.68	3.99	18120.01	647.89	3261.60	116620.88
	Run_6	29398	60	163	1.76	9.02	5.39	111.36	3.98	17945.83	641.75	3230.25	115514.42
	Run_7	29148	60	162	1.72	9.37	5.54	111.26	3.98	17793.56	636.30	3202.84	114534.17
	Run_8	29642	97	165	1.80	9.95	5.87	111.38	3.98	18125.47	648.10	3262.58	116657.33
	Run_9	30187	95	168	1.78	10.41	6.09	110.97	3.97	18309.90	655.05	3295.78	117909.28
	Run_10	29691	32	165	1.78	9.24	5.51	112.01	4.00	18204.70	650.81	3276.85	117145.80
	average	29661.8	65.4	164.8	1.8	9.4	5.6	111.4	4.0	18104.4	647.4	3258.8	116536.4

Table A1.3 Continues

Simulation of the 6-month period		Cust number			Waits			utilization					
		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
RRF -> FCFS (retrievals)	Run_1	29622	0	165	8.76	3.05	5.90	113.47	4.05	18440.53	658.57	3319.29	118542.35
	Run_2	29507	0	164	9.38	3.05	6.21	113.69	4.06	18414.75	657.54	3314.65	118357.02
	Run_3	29040	0	161	8.26	3.06	5.66	114.59	4.09	18225.61	650.54	3280.61	117097.68
	Run_4	29502	4	164	8.91	3.05	5.98	113.63	4.05	18415.30	657.55	3314.75	118359.02
	Run_5	29772	0	165	8.44	3.04	5.74	113.35	4.04	18535.71	661.96	3336.43	119153.47
	Run_6	29394	2	163	8.94	3.05	5.99	113.78	4.06	18354.65	655.37	3303.84	117966.32
	Run_7	29755	6	165	9.73	3.05	6.39	113.81	4.06	18510.30	661.09	3331.85	118996.48
	Run_8	29895	18	166	8.65	3.01	5.83	112.49	4.02	18563.45	663.07	3341.42	119352.70
	Run_9	28899	0	161	10.62	3.05	6.84	114.28	4.08	18128.91	647.11	3263.20	116479.87
	Run_10	28996	8	161	9.55	3.05	6.30	114.25	4.08	18152.93	648.05	3267.53	116649.87
	average	29438.2	3.8	163.5	9.1	3.0	6.1	113.7	4.1	18374.2	656.1	3307.4	118095.5

Simulation of the 6-month period		Cust number			Waits			utilization					
		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
RRF -> NOF (retrievals)	Run_1	29391	4	163	10.28	2.97	6.63	114.03	4.07	18413.83	657.34	3314.49	118320.60
	Run_2	29722	0	165	10.52	2.98	6.75	113.54	4.05	18507.84	660.96	3331.41	118972.92
	Run_3	28914	4	161	9.20	2.95	6.08	114.44	4.08	18162.21	648.24	3269.20	116683.63
	Run_4	29301	0	163	9.42	2.95	6.19	113.79	4.06	18311.43	653.79	3296.06	117682.15
	Run_5	29280	0	163	8.63	2.97	5.80	114.56	4.09	18426.50	657.59	3316.77	118367.00
	Run_6	29535	1	164	9.74	2.98	6.36	114.63	4.09	18571.70	662.81	3342.91	119306.22
	Run_7	29995	31	167	10.02	2.98	6.50	113.85	4.06	18764.44	669.92	3377.60	120585.33
	Run_8	29747	6	165	9.01	2.99	6.00	113.92	4.06	18599.36	664.05	3347.89	119528.72
	Run_9	29461	0	164	9.77	2.98	6.38	113.89	4.06	18467.68	659.24	3324.18	118662.33
	Run_10	29188	7	162	9.16	3.00	6.08	114.38	4.08	18361.68	655.30	3305.10	117953.53
	average	29453.4	5.3	163.6	9.6	3.0	6.3	114.1	4.1	18458.7	658.9	3322.6	118606.2

Simulation of the 6-month period		Cust number			Waits			utilization					
		total # of served customers	total # of rejected customers	average # of customers per day	average wait for parking	average wait for retrival	average wait per operation	trans dist (m) per opert.	trans time (min) per opert.	*daily trans dist (m)	*daily trans times (min)	total trans dist (km)	total trans times (h)
RRF -> FOF (retrievals)	Run_1	30222	5	168	10.58	3.06	6.82	113.22	4.04	18752.13	669.84	3375.38	120572.00
	Run_2	29984	7	167	11.07	3.06	7.06	113.35	4.04	18677.10	666.99	3361.88	120058.33
	Run_3	29266	0	163	8.28	3.02	5.65	114.05	4.07	18282.61	652.78	3290.87	117499.92
	Run_4	29485	0	164	9.34	3.04	6.19	114.21	4.07	18457.61	658.94	3322.37	118608.30
	Run_5	29218	0	162	10.32	3.05	6.69	113.90	4.06	18211.21	650.33	3278.02	117058.72
	Run_6	29775	4	165	8.97	3.04	6.01	113.52	4.05	18542.36	662.19	3337.62	119194.13
	Run_7	29476	0	164	9.37	3.05	6.21	113.92	4.06	18404.53	657.15	3312.82	118287.43
	Run_8	29876	0	166	9.36	3.07	6.22	113.98	4.07	18665.88	666.46	3359.86	119962.20
	Run_9	29346	26	163	9.32	3.05	6.18	113.80	4.06	18312.70	653.90	3296.29	117701.78
	Run_10	28850	0	160	8.37	3.06	5.72	114.41	4.08	18143.52	647.52	3265.83	116554.45
	average	29549.8	4.2	164.2	9.5	3.1	6.3	113.8	4.1	18445.0	658.6	3320.1	118549.7

Appendix A.2

Table A2.1 Results of the simulation study for Rule-Based Planning Approach

Case-1	# of customers (avg. per day)				customers waits			system utilization							for simulation
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	83.46	83.46	0.00	0.00	0.13	1.31	0.72	63.17	2.37	5339.83	200.25	480.59	300.37	0.000021	2.97
Run2	84.94	84.94	0.00	0.00	0.16	1.33	0.75	62.82	2.36	5453.45	204.43	490.81	306.65	0.000019	1.39
Run 3	83.20	83.20	0.00	0.00	0.15	1.33	0.74	63.05	2.37	5349.18	200.49	481.43	300.74	0.000019	1.48
Run 4	83.16	83.16	0.00	0.00	0.14	1.31	0.73	62.73	2.36	5350.31	200.52	481.53	300.78	0.000019	1.09
Run 5	85.18	85.18	0.00	0.00	0.16	1.33	0.74	63.28	2.38	5488.65	205.67	493.98	308.50	0.000019	1.48
Run 6	82.50	82.50	0.00	0.00	0.13	1.30	0.72	62.11	2.34	5248.26	196.94	472.34	295.41	0.000020	1.77
Run 7	83.56	83.56	0.00	0.00	0.14	1.31	0.72	62.75	2.36	5339.84	200.28	480.59	300.41	0.000020	1.38
Run 8	83.48	83.48	0.00	0.00	0.15	1.30	0.73	62.41	2.35	5318.22	199.53	478.64	299.30	0.000019	1.31
Run 9	81.56	81.56	0.00	0.00	0.14	1.32	0.73	62.84	2.36	5239.29	196.39	471.54	294.59	0.000020	1.41
Run 10	85.42	85.42	0.00	0.00	0.15	1.32	0.74	63.14	2.37	5497.69	206.04	494.79	309.05	0.000019	1.33
Average RB	83.64	83.64	0.00	0.00	0.15	1.32	0.73	62.83	2.36	5362.47	201.05	482.62	301.58	0.000020	1.56

Case-2	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	164.98	164.76	0.08	0.14	1.89	2.80	2.34	73.17	2.71	12324.44	454.75	1109.20	682.12	0.000021	4.98
Run2	164.77	164.46	0.07	0.24	1.74	2.81	2.27	73.28	2.71	12331.68	454.91	1109.85	682.37	0.000020	3.39
Run 3	165.99	165.58	0.21	0.20	2.40	3.37	2.89	74.07	2.74	12525.86	461.68	1127.33	692.52	0.000020	2.89
Run 4	166.14	165.84	0.17	0.13	1.86	2.91	2.39	72.96	2.70	12439.67	458.88	1119.57	688.32	0.000020	3.45
Run 5	165.46	164.92	0.00	0.53	1.58	2.76	2.17	73.21	2.71	12364.67	456.14	1112.82	684.20	0.000020	3.28
Run 6	166.23	166.23	0.00	0.00	1.37	2.49	1.93	72.99	2.70	12388.41	457.28	1114.96	685.91	0.000020	3.28
Run 7	169.36	169.10	0.14	0.11	1.88	2.91	2.40	72.99	2.70	12650.37	466.77	1138.53	700.16	0.000020	3.25
Run 8	168.34	168.09	0.09	0.17	1.98	2.97	2.47	73.19	2.71	12645.31	466.33	1138.08	699.50	0.000020	3.03
Run 9	165.10	165.03	0.00	0.07	1.24	2.34	1.79	72.93	2.70	12269.88	453.01	1104.29	679.51	0.000020	2.83
Run 10	167.73	167.52	0.00	0.21	1.54	2.58	2.06	73.62	2.72	12515.71	461.86	1126.41	692.79	0.000021	3.14
Average RB	166.41	166.15	0.08	0.18	1.75	2.79	2.27	73.24	2.71	12445.60	459.16	1120.10	688.74	0.000020	3.35

Case-1: cust.num*1/4	Case-2: cust.num*2/4	Case-3: cust.num*3/4	*Case-4: cust.num*4/4 (real density)	Case-5: cust.num*5/4	Case-6: cust.num*6/4	Case-7: cust.num*7/4	Case-8: cust.num*8/4

Table A2.1 Continues

Case-3	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	244.89	223.61	6.96	14.32	13.32	13.06	13.19	78.71	2.89	17988.74	659.25	1618.99	988.88	0.000019	5.00
Run2	252.14	229.32	7.72	15.10	13.83	13.38	13.61	80.04	2.93	18587.41	680.73	1672.87	1021.10	0.000019	5.02
Run 3	245.11	226.57	7.13	11.41	12.60	12.33	12.46	79.53	2.92	18323.02	671.19	1649.07	1006.78	0.000019	4.98
Run 4	251.21	230.68	7.84	12.69	11.92	11.51	11.71	79.84	2.93	18624.34	682.33	1676.19	1023.49	0.000020	5.17
Run 5	251.64	225.82	7.28	18.54	13.40	13.21	13.31	79.21	2.91	18229.68	667.88	1640.67	1001.81	0.000019	4.95
Run 6	247.89	225.54	6.01	16.33	12.65	12.55	12.60	78.46	2.88	18083.22	662.92	1627.49	994.38	0.000019	5.08
Run 7	251.43	225.61	7.37	18.46	14.00	13.87	13.94	79.75	2.93	18366.71	672.39	1653.00	1008.58	0.000019	5.09
Run 8	250.93	229.61	8.41	12.91	13.21	13.11	13.16	80.21	2.94	18691.12	684.27	1682.20	1026.40	0.000019	5.28
Run 9	246.72	226.64	7.31	12.77	12.38	12.33	12.35	79.83	2.93	18326.44	671.32	1649.38	1006.98	0.000019	4.97
Run 10	243.02	225.32	6.29	11.41	11.52	11.88	11.70	79.65	2.92	18227.46	667.67	1640.47	1001.50	0.000019	5.25
Average RB	248.50	226.87	7.23	14.39	12.88	12.72	12.80	79.52	2.92	18344.81	671.99	1651.03	1007.99	0.000019	5.08

Case-4	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	333.48	258.17	26.22	49.09	18.72	18.23	18.48	82.47	3.02	21472.12	784.58	1932.49	1176.87	0.000020	8.64
Run2	343.04	258.07	27.57	57.41	18.91	18.75	18.83	82.92	3.03	21582.13	788.22	1942.39	1182.33	0.000019	6.81
Run 3	338.57	253.59	25.34	59.63	18.90	18.82	18.86	82.49	3.02	21174.51	773.44	1905.71	1160.16	0.000019	6.36
Run 4	330.26	250.20	28.36	51.70	18.14	17.59	17.87	82.11	3.00	20803.17	760.16	1872.29	1140.24	0.000019	6.55
Run 5	332.67	254.11	24.47	54.09	18.43	18.32	18.37	82.35	3.01	21090.03	770.76	1898.10	1156.15	0.000019	6.52
Run 6	328.70	251.42	23.56	53.72	18.83	18.45	18.64	81.58	2.99	20819.82	761.04	1873.78	1141.56	0.000019	6.41
Run 7	334.91	253.58	24.21	57.12	18.72	18.04	18.38	82.43	3.01	21092.50	770.70	1898.33	1156.06	0.000019	6.25
Run 8	343.26	256.70	26.36	60.20	19.29	19.32	19.31	82.63	3.02	21370.96	780.82	1923.39	1171.23	0.000019	6.80
Run 9	336.39	255.31	24.73	56.34	19.35	18.90	19.13	82.65	3.02	21263.04	776.85	1913.67	1165.28	0.000019	6.53
Run 10	342.48	253.62	29.02	59.83	19.28	18.60	18.94	81.78	2.99	21080.93	770.33	1897.28	1155.50	0.000019	6.80
Average RB	336.37	254.48	25.98	55.91	18.86	18.50	18.68	82.34	3.01	21174.92	773.69	1905.74	1160.54	0.000019	6.77

Case-1: cust.num*1/4	Case-2: cust.num*2/4	Case-3: cust.num*3/4	*Case-4: cust.num*4/4 (real density)	Case-5: cust.num*5/4	Case-6: cust.num*6/4	Case-7: cust.num*7/4	Case-8: cust.num*8/4

Table A2.1 Continues

Case-5	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	421.40	270.39	46.58	104.43	20.88	19.90	20.39	83.12	3.04	22679.27	828.08	2041.13	1242.12	0.000019	9.33
Run2	432.69	275.52	47.86	109.31	20.30	19.58	19.94	84.12	3.07	23230.96	847.84	2090.79	1271.76	0.000019	7.66
Run 3	442.86	277.73	45.30	119.82	21.81	20.49	21.15	84.04	3.07	23461.82	856.12	2111.56	1284.18	0.000019	7.70
Run 4	405.87	271.49	49.11	85.27	19.74	18.78	19.26	83.28	3.04	22745.63	830.58	2047.11	1245.88	0.000019	7.72
Run 5	417.02	268.82	37.50	110.70	21.16	20.47	20.82	83.55	3.05	22713.26	828.79	2044.19	1243.19	0.000019	7.38
Run 6	430.89	274.23	49.17	107.49	21.40	20.52	20.96	83.40	3.05	23098.52	843.08	2078.87	1264.62	0.000019	7.61
Run 7	419.39	275.66	51.00	92.73	19.91	19.03	19.47	84.10	3.07	23208.28	847.12	2088.75	1270.68	0.000019	7.91
Run 8	432.67	274.04	44.68	113.94	21.05	20.10	20.57	83.74	3.06	23057.69	841.67	2075.19	1262.50	0.000019	7.66
Run 9	417.63	271.56	47.32	98.76	20.24	19.41	19.82	83.04	3.03	22805.61	832.60	2052.51	1248.90	0.000019	7.97
Run 10	430.48	273.74	46.08	110.66	21.14	20.35	20.74	83.50	3.05	23044.98	841.16	2074.05	1261.75	0.000019	7.58
Average RB	425.09	273.32	46.46	105.31	20.76	19.86	20.31	83.59	3.05	23004.60	839.71	2070.41	1259.56	0.000019	7.85

Case-6	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	519.09	287.30	72.50	159.29	22.20	20.76	21.48	84.75	3.09	24401.96	890.01	2196.18	1335.02	0.000019	10.58
Run2	502.96	283.58	59.62	159.76	23.22	21.60	22.41	84.48	3.08	24137.36	880.20	2172.36	1320.30	0.000019	8.31
Run 3	485.93	286.36	62.26	137.32	21.32	20.25	20.78	84.45	3.08	24250.42	884.71	2182.54	1327.06	0.000019	8.27
Run 4	517.98	292.70	64.21	161.07	22.57	21.19	21.88	84.87	3.10	24883.03	907.49	2239.47	1361.23	0.000019	9.11
Run 5	522.57	293.14	66.52	162.90	22.76	21.61	22.19	84.84	3.09	24918.11	908.78	2242.63	1363.16	0.000019	8.69
Run 6	513.56	289.21	77.38	146.97	22.12	20.46	21.29	84.61	3.09	24579.72	896.45	2212.18	1344.67	0.000018	8.73
Run 7	515.89	293.81	65.87	156.21	22.69	21.30	21.99	84.60	3.09	24856.24	906.89	2237.06	1360.34	0.000019	8.98
Run 8	516.40	287.97	72.73	155.70	21.68	20.31	21.00	84.58	3.09	24446.86	891.69	2200.22	1337.53	0.000018	8.73
Run 9	510.19	288.44	56.94	164.80	22.53	21.37	21.95	84.42	3.08	24431.57	891.30	2198.84	1336.96	0.000019	8.58
Run 10	510.96	284.67	70.31	155.98	22.30	20.55	21.43	84.62	3.09	24225.76	883.44	2180.32	1325.15	0.000019	8.86
Average RB	511.55	288.72	66.83	156.00	22.34	20.94	21.64	84.62	3.09	24513.10	894.09	2206.18	1341.14	0.000019	8.88

Case-1: cust.num*1/4	Case-2: cust.num*2/4	Case-3: cust.num*3/4	*Case-4: cust.num*4/4 (real density)	Case-5: cust.num*5/4	Case-6: cust.num*6/4	Case-7: cust.num*7/4	Case-8: cust.num*8/4

Table A2.1 Continues

Case-7	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	593.37	273.10	132.40	187.87	Inf	NaN	NaN	NaN	NaN	24248.95	881.13	2182.41	1321.69	0.000018	12.02
Run2	620.96	303.00	75.79	242.17	24.56	22.94	23.75	85.65	3.12	25979.98	946.80	2338.20	1420.20	0.000018	9.27
Run 3	601.87	296.81	81.10	223.96	23.41	22.07	22.74	85.19	3.11	25349.39	924.13	2281.45	1386.19	0.000018	9.52
Run 4	612.92	295.64	127.27	190.01	20.50	19.42	19.96	86.27	3.14	25589.24	931.81	2303.03	1397.72	0.000018	10.00
Run 5	605.03	302.37	85.39	217.28	23.11	21.72	22.42	84.82	3.09	25735.60	938.48	2316.20	1407.73	0.000019	9.67
Run 6	588.71	302.26	70.34	216.11	23.82	21.95	22.89	85.32	3.11	25774.76	939.76	2319.73	1409.64	0.000019	10.45
Run 7	597.40	301.93	88.74	206.72	22.71	21.15	21.93	85.28	3.11	25744.63	938.67	2317.02	1408.01	0.000019	9.27
Run 8	605.58	300.56	87.01	218.01	23.23	21.53	22.38	85.16	3.11	25650.37	935.16	2308.53	1402.74	0.000019	9.66
Run 9	613.78	297.48	77.02	239.28	24.38	22.51	23.45	85.23	3.11	25409.47	926.31	2286.85	1389.46	0.000019	8.98
Run 10	597.33	299.22	90.40	207.71	23.34	21.39	22.37	85.30	3.11	25545.32	931.30	2299.08	1396.96	0.000018	9.23
Average RB	603.69	297.24	91.55	214.91	23.23	21.63	22.43	85.36	3.11	25502.77	929.36	2295.25	1394.03	0.000019	9.81

Case-8	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	704.67	312.23	105.88	286.56	23.67	21.84	22.75	85.82	3.13	26754.60	975.08	2407.91	1462.62	0.000018	11.94
Run2	712.16	308.84	101.63	301.68	24.76	23.02	23.89	85.81	3.13	26535.92	966.89	2388.23	1450.33	0.000017	10.00
Run 3	693.62	310.22	96.20	287.20	23.99	22.36	23.18	85.82	3.13	26592.23	969.13	2393.30	1453.70	0.000018	10.44
Run 4	700.87	306.37	111.88	282.62	24.32	22.09	23.21	85.76	3.13	26306.48	958.58	2367.58	1437.87	0.000018	10.48
Run 5	692.22	310.78	106.88	274.57	24.44	22.95	23.69	86.27	3.14	26794.13	976.01	2411.47	1464.02	0.000018	10.23
Run 6	704.21	307.14	101.88	295.19	24.44	22.44	23.44	85.79	3.13	26426.97	962.80	2378.43	1444.21	0.000020	12.02
Run 7	704.32	308.66	109.28	286.39	23.65	21.50	22.58	85.94	3.13	26502.90	965.74	2385.26	1448.61	0.000021	11.53
Run 8	697.73	313.11	113.62	271.00	23.84	22.11	22.98	86.16	3.14	26922.63	980.92	2423.04	1471.38	0.000019	10.97
Run 9	711.38	315.42	126.44	269.51	23.82	21.60	22.71	85.77	3.13	27005.79	984.31	2430.52	1476.46	0.000019	11.28
Run 10	692.86	306.23	92.97	293.66	24.52	22.99	23.76	85.83	3.13	26279.92	957.66	2365.19	1436.49	0.000020	10.91
Average RB	701.40	309.90	106.67	284.84	24.15	22.29	23.22	85.90	3.13	26612.16	969.71	2395.09	1454.57	0.000019	10.98

Case-1: cust.num*1/4	Case-2: cust.num*2/4	Case-3: cust.num*3/4	*Case-4: cust.num*4/4 (real density)	Case-5: cust.num*5/4	Case-6: cust.num*6/4	Case-7: cust.num*7/4	Case-8: cust.num*8/4

Table A2.2 Results of the simulation study for Optimization-Based Planning Approach

Case-1	# of customers (avg. per day)				customers waits			system utilization							for simulation
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	80.64	80.64	0.00	0.00	0.17	1.22	0.70	58.48	2.22	4840.91	182.87	435.68	274.30	0.0089	76.70
Run2	82.02	82.02	0.00	0.00	0.19	1.26	0.72	60.62	2.29	5073.43	190.99	456.61	286.48	0.0092	78.11
Run 3	83.70	83.70	0.00	0.00	0.19	1.26	0.72	60.46	2.28	5152.16	194.06	463.69	291.09	0.0089	79.50
Run 4	82.92	82.92	0.00	0.00	0.18	1.26	0.72	60.44	2.28	5090.46	191.79	458.14	287.69	0.0092	80.47
Run 5	82.01	82.01	0.00	0.00	0.18	1.24	0.71	59.69	2.26	4972.64	187.62	447.54	281.44	0.0090	80.78
Run 6	79.81	79.81	0.00	0.00	0.19	1.35	0.77	61.34	2.31	5034.53	189.10	453.11	283.65	0.0093	76.20
Run 7	82.79	82.79	0.00	0.00	0.16	1.25	0.71	59.94	2.26	5064.64	190.90	455.82	286.35	0.0092	79.52
Run 8	82.54	82.54	0.00	0.00	0.19	1.23	0.71	59.27	2.24	5023.41	189.46	452.11	284.19	0.0089	78.11
Run 9	81.29	81.29	0.00	0.00	0.19	1.26	0.73	60.88	2.30	5035.66	189.53	453.21	284.30	0.0087	75.72
Run 10	81.38	81.38	0.00	0.00	0.17	1.23	0.70	59.30	2.24	4940.48	186.38	444.64	279.58	0.0091	78.73
Average RB	81.91	81.91	0.00	0.00	0.18	1.26	0.72	60.04	2.27	5022.83	189.27	452.05	283.91	0.0090	78.38

Case-2	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	162.43	162.43	0.00	0.00	0.92	1.84	1.38	65.71	2.46	10919.23	407.29	982.73	610.94	0.0112	173.27
Run2	162.58	162.58	0.00	0.00	1.07	2.00	1.53	67.85	2.53	11230.20	417.69	1010.72	626.54	0.0107	168.17
Run 3	162.69	162.67	0.00	0.02	1.09	1.96	1.53	68.08	2.54	11257.07	418.61	1013.14	627.92	0.0109	167.73
Run 4	160.11	159.99	0.10	0.02	1.08	2.01	1.55	66.23	2.47	10881.87	405.39	979.37	608.09	0.0108	166.08
Run 5	160.33	160.33	0.00	0.00	1.14	2.03	1.58	67.94	2.53	11122.41	413.50	1001.02	620.25	0.0109	170.05
Run 6	161.51	161.51	0.00	0.00	0.84	1.88	1.36	65.42	2.45	10834.92	404.23	975.14	606.35	0.0115	179.25
Run 7	162.09	162.09	0.00	0.00	1.11	1.99	1.55	66.59	2.49	11085.67	412.75	997.71	619.12	0.0115	174.78
Run 8	165.54	165.54	0.00	0.00	1.08	1.97	1.52	68.92	2.56	11586.26	430.35	1042.76	645.53	0.0107	171.83
Run 9	164.13	164.13	0.00	0.00	0.99	1.88	1.44	65.45	2.45	11008.87	410.73	990.80	616.10	0.0109	172.13
Run 10	162.76	162.70	0.06	0.00	1.10	1.98	1.54	68.49	2.55	11315.78	420.58	1018.42	630.87	0.0108	167.31
Average RB	162.42	162.40	0.02	0.00	1.04	1.95	1.50	67.07	2.50	11124.23	414.11	1001.18	621.17	0.0110	171.06

Case-1: cust.num*1/4	Case-2: cust.num*2/4	Case-3: cust.num*3/4	*Case-4: cust.num*4/4 (real density)	Case-5: cust.num*5/4	Case-6: cust.num*6/4	Case-7: cust.num*7/4	Case-8: cust.num*8/4

Table A2.2 Continues

Case-3	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	248.58	239.48	5.40	3.70	6.74	6.28	6.51	70.31	2.61	17032.78	631.62	1532.95	947.43	0.0089	185.91
Run2	242.60	233.91	3.82	4.87	7.08	6.75	6.91	70.59	2.62	16767.54	621.29	1509.08	931.94	0.0092	181.45
Run 3	240.77	230.80	6.29	3.68	6.63	6.06	6.34	69.35	2.58	16331.74	605.94	1469.86	908.91	0.0087	174.75
Run 4	244.06	235.30	3.80	4.96	7.06	6.81	6.94	70.01	2.60	16740.68	620.77	1506.66	931.15	0.0091	185.70
Run 5	241.46	232.17	5.48	3.81	6.25	5.79	6.02	69.78	2.59	16465.24	610.75	1481.87	916.13	0.0085	171.33
Run 6	246.06	236.73	5.34	3.98	7.93	7.22	7.58	71.01	2.63	17086.57	632.68	1537.79	949.02	0.0089	180.88
Run 7	247.31	239.51	3.81	3.99	7.69	6.86	7.28	69.52	2.58	16811.54	624.25	1513.04	936.38	0.0095	193.56
Run 8	241.72	229.84	6.93	4.94	7.61	7.11	7.36	70.47	2.62	16570.61	613.65	1491.36	920.47	0.0087	173.27
Run 9	240.46	230.59	5.39	4.48	6.09	5.70	5.89	69.75	2.59	16349.38	606.47	1471.44	909.70	0.0093	182.69
Run 10	246.08	238.98	3.49	3.61	6.98	6.74	6.86	69.38	2.58	16813.95	624.19	1513.26	936.29	0.0089	184.81
Average RB	243.91	234.73	4.98	4.20	7.01	6.53	6.77	70.02	2.60	16697.00	619.16	1502.73	928.74	0.0090	181.43

Case-4	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	333.08	279.53	30.89	22.66	11.47	9.80	10.64	70.78	2.63	19979.03	740.51	1798.11	1110.77	0.0071	172.06
Run2	321.40	262.72	35.78	22.90	11.82	10.19	11.01	74.44	2.75	19799.99	730.06	1782.00	1095.09	0.0069	151.22
Run 3	328.61	276.58	31.02	21.01	11.02	9.34	10.18	70.09	2.60	19555.99	725.62	1760.04	1088.43	0.0069	158.91
Run 4	325.53	274.44	29.70	21.39	11.21	10.03	10.62	70.98	2.63	19763.89	731.98	1778.75	1097.97	0.0070	164.98
Run 5	336.88	279.44	32.88	24.56	11.92	10.30	11.11	70.72	2.62	19909.02	738.15	1791.81	1107.23	0.0070	163.39
Run 6	334.77	281.53	33.60	19.63	11.76	10.07	10.91	70.37	2.61	19964.60	740.56	1796.81	1110.84	0.0070	163.33
Run 7	328.74	278.17	25.50	25.08	13.08	11.36	12.22	71.75	2.66	20081.01	743.54	1807.29	1115.32	0.0075	170.00
Run 8	329.19	280.57	24.92	23.70	13.08	11.18	12.13	69.98	2.60	19808.84	735.11	1782.80	1102.67	0.0074	172.36
Run 9	325.56	276.69	26.01	22.86	12.20	10.47	11.33	71.87	2.66	19973.20	739.56	1797.59	1109.34	0.0075	175.64
Run 10	313.98	273.94	21.47	18.57	11.52	9.76	10.64	70.74	2.62	19499.10	723.02	1754.92	1084.53	0.0078	182.17
Average RB	327.77	276.36	29.18	22.23	11.91	10.25	11.08	71.17	2.64	19833.47	734.81	1785.01	1102.22	0.0072	167.41

Case-1: cust.num*1/4	Case-2: cust.num*2/4	Case-3: cust.num*3/4	*Case-4: cust.num*4/4 (real density)	Case-5: cust.num*5/4	Case-6: cust.num*6/4	Case-7: cust.num*7/4	Case-8: cust.num*8/4

Table A2.2 Continues

Case-5	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	430.13	286.93	73.71	69.49	16.91	15.08	16.00	78.10	2.87	22492.87	826.28	2024.36	1239.42	0.0069	198.08
Run2	432.99	288.72	76.53	67.73	16.69	15.31	16.00	77.25	2.84	22499.16	826.96	2024.92	1240.45	0.0062	182.34
Run 3	418.26	287.78	67.53	62.94	16.70	15.10	15.90	78.32	2.88	22578.02	829.34	2032.02	1244.01	0.0063	179.23
Run 4	430.60	289.86	75.71	65.03	16.94	15.29	16.12	77.84	2.86	22667.70	832.88	2040.09	1249.33	0.0062	180.72
Run 5	428.07	286.31	79.78	61.98	17.60	15.83	16.72	77.99	2.87	22504.04	826.48	2025.36	1239.73	0.0060	176.25
Run 6	426.99	287.76	72.73	66.50	16.91	15.24	16.07	77.65	2.86	22470.95	825.77	2022.39	1238.65	0.0064	186.58
Run 7	427.50	290.40	73.91	63.19	17.57	15.82	16.70	77.98	2.87	22710.94	834.47	2043.99	1251.71	0.0065	188.17
Run 8	411.91	287.46	63.31	61.14	16.67	15.22	15.94	77.98	2.87	22458.16	825.26	2021.23	1237.89	0.0065	185.22
Run 9	432.88	293.62	73.36	65.90	17.09	15.47	16.28	77.54	2.85	22861.73	840.36	2057.56	1260.54	0.0062	184.75
Run 10	421.20	285.34	68.23	67.62	17.12	15.62	16.37	77.78	2.86	22313.84	819.89	2008.25	1229.83	0.0063	182.06
Average RB	426.05	288.42	72.48	65.15	17.02	15.40	16.21	77.84	2.86	22555.74	828.77	2030.02	1243.15	0.0064	184.34

Case-6	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	510.38	304.08	106.70	99.60	18.16	16.18	17.17	77.83	2.86	23719.78	871.75	2134.78	1307.62	0.006642	212.23
Run2	505.94	304.86	99.56	101.53	18.50	16.36	17.43	78.34	2.88	23930.88	878.99	2153.78	1318.49	0.007040	216.25
Run 3	516.80	305.21	105.09	106.50	18.14	16.67	17.40	78.55	2.89	23964.62	880.21	2156.82	1320.32	0.006749	207.72
Run 4	519.41	308.69	112.44	98.28	18.67	16.57	17.62	78.45	2.88	24253.13	890.75	2182.78	1336.13	0.007037	219.83
Run 5	514.34	309.24	108.97	96.13	18.10	16.22	17.16	78.26	2.88	24239.01	890.43	2181.51	1335.65	0.006442	209.00
Run 6	512.93	302.23	112.26	98.44	18.71	16.50	17.60	77.98	2.87	23684.57	870.08	2131.61	1305.12	0.006285	197.36
Run 7	515.70	302.83	108.17	104.70	18.14	16.28	17.21	78.01	2.87	23710.66	871.11	2133.96	1306.67	0.006500	204.34
Run 8	514.12	304.17	97.74	112.21	18.14	16.38	17.26	78.28	2.88	23887.79	877.37	2149.90	1316.06	0.006781	210.63
Run 9	516.17	304.78	106.90	104.49	18.85	16.80	17.82	78.10	2.87	23897.26	877.85	2150.75	1316.77	0.007603	234.72
Run 10	495.79	298.78	85.99	111.02	18.02	16.20	17.11	78.17	2.87	23506.81	863.23	2115.61	1294.85	0.006798	208.66
Average RB	512.16	304.49	104.38	103.29	18.34	16.42	17.38	78.20	2.87	23879.45	877.18	2149.15	1315.77	0.006788	212.07

Case-1: cust.num*1/4	Case-2: cust.num*2/4	Case-3: cust.num*3/4	*Case-4: cust.num*4/4 (real density)	Case-5: cust.num*5/4	Case-6: cust.num*6/4	Case-7: cust.num*7/4	Case-8: cust.num*8/4

Table A2.2 Continues

Case-7	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	612.48	321.02	138.28	153.18	19.76	17.45	18.61	79.09	2.90	25352.25	930.68	2281.70	1396.02	0.005730	190.89
Run2	587.02	313.16	149.68	124.19	18.30	16.09	17.20	78.31	2.88	24534.11	901.31	2208.07	1351.97	0.005455	183.41
Run 3	591.17	315.81	141.24	134.11	19.71	17.19	18.45	78.67	2.89	24885.55	913.73	2239.70	1370.60	0.005517	179.59
Run 4	617.08	319.68	155.81	141.59	18.42	16.32	17.37	78.18	2.87	25009.72	918.90	2250.87	1378.36	0.005529	186.75
Run 5	609.42	320.40	135.94	153.08	19.14	17.15	18.14	78.32	2.88	25073.77	921.23	2256.64	1381.85	0.005753	188.33
Run 6	603.44	315.49	146.63	141.32	19.25	16.89	18.07	78.38	2.88	24796.18	910.67	2231.66	1366.00	0.005485	185.75
Run 7	605.20	318.97	142.66	143.58	19.47	17.34	18.41	78.95	2.90	25191.36	924.77	2267.22	1387.15	0.005653	184.52
Run 8	615.18	318.82	157.52	138.83	18.48	16.16	17.32	78.83	2.89	25098.81	921.65	2258.89	1382.47	0.005603	187.06
Run 9	605.48	314.43	133.44	157.60	19.87	17.52	18.70	78.82	2.89	24833.57	911.63	2235.02	1367.45	0.005819	194.09
Run 10	604.56	319.73	153.00	131.82	19.65	17.13	18.39	78.53	2.88	25112.67	922.35	2260.14	1383.53	0.005626	186.25
Average RB	605.10	317.75	145.42	141.93	19.21	16.92	18.06	78.61	2.89	24988.80	917.69	2248.99	1376.54	0.005617	186.66

Case-8	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	707.07	332.19	181.90	192.98	20.66	18.07	19.36	79.48	2.92	26364.25	967.39	2372.78	1451.09	0.0053	191.91
Run2	693.76	325.40	181.19	187.17	19.95	17.37	18.66	78.79	2.89	25686.62	942.99	2311.80	1414.49	0.0055	192.45
Run 3	706.44	330.66	174.46	201.33	20.53	17.85	19.19	79.22	2.91	26150.48	959.86	2353.54	1439.79	0.0054	187.41
Run 4	681.14	328.30	165.50	187.34	19.78	17.41	18.60	79.08	2.90	25912.02	951.28	2332.08	1426.92	0.0056	190.47
Run 5	707.10	332.64	193.40	181.06	20.12	17.60	18.86	78.97	2.90	26246.75	963.60	2362.21	1445.40	0.0054	190.58
Run 6	681.54	321.86	168.53	191.16	19.39	16.92	18.15	78.70	2.89	25358.82	931.12	2282.29	1396.68	0.0056	190.44
Run 7	691.76	331.51	189.08	171.17	18.66	16.27	17.46	78.96	2.90	26113.22	958.84	2350.19	1438.27	0.0054	194.81
Run 8	677.82	324.84	179.94	173.03	18.74	16.49	17.61	78.56	2.89	25509.72	936.95	2295.87	1405.42	0.0054	187.14
Run 9	721.01	331.01	192.84	197.16	19.45	16.95	18.20	79.25	2.91	26176.26	960.81	2355.86	1441.22	0.0053	186.88
Run 10	688.72	325.89	183.11	179.72	19.79	17.28	18.54	78.85	2.90	25690.94	943.27	2312.19	1414.90	0.0055	188.73
Average RB	695.64	328.43	181.00	186.21	19.71	17.22	18.46	78.99	2.90	25920.91	951.61	2332.88	1427.42	0.0054	190.08

Case-1: cust.num*1/4	Case-2: cust.num*2/4	Case-3: cust.num*3/4	*Case-4: cust.num*4/4 (real density)	Case-5: cust.num*5/4	Case-6: cust.num*6/4	Case-7: cust.num*7/4	Case-8: cust.num*8/4

Appendix A.3

Table A3.1 Results of the simulation study for solution quality and computational time (without additional information)

Case-0 (1) without inf	# of customers (avg. per day)				customers waits			system utilization							for simulation
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	344.00	259.14	3.86	81.00	5.29	6.18	5.73	79.21	2.91	20362.43	747.85	142.54	5234.97	0.0030	4.84
Run2	358.71	260.57	0.57	97.57	5.53	6.43	5.98	77.34	2.84	20280.29	745.50	141.96	5218.47	0.0029	4.50
Run 3	335.71	255.71	8.00	72.00	5.25	6.07	5.66	77.59	2.85	19744.00	726.32	138.21	5084.27	0.0027	4.55
Run 4	358.14	264.43	1.00	92.71	5.67	6.37	6.02	79.07	2.90	20805.79	764.04	145.64	5348.28	0.0028	4.50
Run 5	317.86	245.00	0.00	72.86	5.34	6.13	5.73	75.53	2.78	18960.79	697.36	132.73	4881.52	0.0027	4.38
Run 6	312.29	240.57	0.57	71.14	4.28	5.41	4.85	76.59	2.82	18467.21	679.73	129.27	4758.08	0.0028	4.28
Run 7	322.43	247.57	0.00	74.86	4.47	5.47	4.97	74.53	2.75	18721.36	690.06	131.05	4830.45	0.0028	4.77
Run 8	328.14	252.57	3.14	72.43	4.98	6.02	5.50	74.25	2.74	19526.14	718.22	136.68	5027.57	0.0027	4.33
Run 9	344.57	257.57	2.57	84.43	5.72	6.33	6.02	80.27	2.94	20547.57	753.60	143.83	5275.23	0.0029	5.17
Run 10	336.86	258.43	0.00	78.43	5.22	5.95	5.58	79.62	2.92	20339.71	746.90	142.38	5228.33	0.0029	4.48
Average RB	335.87	254.16	1.97	79.74	5.18	6.04	5.61	77.40	2.85	19775.53	726.96	138.43	283.91	0.0028	4.58
Case-1 (2) without inf	# of customers (avg. per day)				customers waits			system utilization							for simulation
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	318.14	241.43	1.14	75.57	4.48	5.32	4.90	74.81	2.76	18436.29	678.92	129.05	4752.47	0.0054	10.39
Run2	314.43	254.29	0.00	60.14	4.84	5.64	5.24	76.76	2.83	19504.21	717.95	136.53	5025.65	0.0056	10.48
Run 3	344.57	245.57	4.29	94.71	5.41	6.58	5.99	76.31	2.81	19351.71	710.54	135.46	4973.80	0.0056	9.95
Run 4	335.57	263.14	2.71	69.71	5.03	5.94	5.49	77.27	2.84	20332.93	747.94	142.33	5235.55	0.0056	10.27
Run 5	348.71	260.71	2.71	85.29	5.60	6.09	5.85	78.52	2.88	20394.29	749.33	142.76	5245.33	0.0054	9.48
Run 6	313.00	249.71	0.00	63.29	5.03	6.06	5.55	76.13	2.80	19052.57	701.68	133.37	4911.73	0.0059	10.33
Run 7	336.29	258.57	2.43	75.29	5.15	5.58	5.36	74.88	2.76	19499.71	718.94	136.50	5032.60	0.0054	9.89
Run 8	349.00	252.86	1.71	94.43	5.64	6.16	5.90	77.46	2.85	19878.14	730.03	139.15	5110.23	0.0058	9.69
Run 9	349.86	271.86	2.71	75.29	5.49	5.96	5.72	78.85	2.90	21283.43	781.94	148.98	5473.60	0.0059	11.28
Run 10	314.86	244.86	0.29	69.71	4.32	5.67	4.99	75.16	2.77	18795.07	691.80	131.57	4842.58	0.0064	10.72
Average RB	332.44	254.30	1.80	76.34	5.10	5.90	5.50	76.61	2.82	19652.84	722.91	137.57	5060.36	0.0057	10.25

Case-0: 1 iter.	Case-1: 2 iter.	Case-2: 5 iter.	Case-3: 10 iter.	Case-4: 25 iter.	Case-5: 50 iter.	Case-6-: 100 iter.

Table A3.1 Continues

Case-2 (5) without inf	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 1 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	364.29	262.57	0.00	101.71	5.61	6.37	5.99	75.76	2.79	20167.36	742.26	141.17	5195.85	0.0107	20.13
Run2	356.00	266.86	2.29	86.86	5.38	5.92	5.65	75.77	2.79	20349.00	749.46	142.44	5246.23	0.0107	20.16
Run 3	331.43	262.57	0.00	68.86	5.35	5.73	5.54	76.27	2.81	20201.14	743.39	141.41	5203.73	0.0100	19.69
Run 4	350.00	268.29	0.29	81.43	5.30	6.00	5.65	76.34	2.81	20455.07	753.38	143.19	5273.65	0.0107	20.20
Run 5	357.29	264.43	0.14	92.71	5.40	6.46	5.93	75.06	2.77	20032.71	738.27	140.23	5167.90	0.0105	20.41
Run 6	334.71	258.00	0.00	76.71	5.38	5.80	5.59	74.34	2.74	19439.14	716.77	136.07	5017.40	0.0104	19.25
Run 7	293.71	255.71	2.14	35.86	4.53	4.61	4.57	73.01	2.70	18660.64	690.21	130.62	4831.48	0.0109	20.17
Run 8	329.57	266.57	0.00	63.00	5.19	5.47	5.33	72.60	2.69	19541.07	722.45	136.79	5057.18	0.0106	20.06
Run 9	314.57	252.14	0.00	62.43	5.02	5.81	5.42	75.40	2.78	19246.29	708.78	134.72	4961.47	0.0108	19.78
Run 10	333.00	266.86	0.00	66.14	4.73	5.32	5.02	75.26	2.78	20014.71	738.32	140.10	5168.23	0.0118	22.53
Average RB	336.46	262.40	0.49	73.57	5.19	5.75	5.47	74.98	2.77	19810.71	730.33	138.68	5112.31	0.0107	20.24

Case-3 (10) without inf	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	355.14	282.71	0.00	72.43	5.00	5.38	5.19	73.18	2.71	20607.29	762.30	144.25	5336.10	0.0238	48.89
Run2	344.71	261.86	0.14	82.71	5.03	5.76	5.39	72.96	2.70	19460.71	718.52	136.23	5029.63	0.0222	41.80
Run 3	344.86	270.29	0.43	74.14	5.14	5.66	5.40	75.14	2.77	20207.00	745.64	141.45	5219.50	0.0219	43.09
Run 4	326.57	269.43	9.43	47.71	4.18	4.59	4.38	72.52	2.68	19438.43	719.80	136.07	5038.57	0.0217	44.41
Run 5	344.71	265.71	0.00	79.00	5.02	5.54	5.28	73.82	2.73	19732.71	728.61	138.13	5100.30	0.0214	41.77
Run 6	346.86	268.43	0.00	78.43	5.13	5.67	5.40	75.08	2.77	20201.14	744.95	141.41	5214.67	0.0206	40.16
Run 7	343.14	273.43	0.00	69.71	4.94	5.71	5.32	75.17	2.77	20446.07	754.45	143.12	5281.15	0.0222	44.56
Run 8	343.86	269.43	0.29	74.14	5.23	5.82	5.53	75.19	2.77	20174.00	744.31	141.22	5210.20	0.0217	42.33
Run 9	325.57	252.57	0.00	73.00	5.33	5.34	5.34	72.20	2.67	18678.36	689.96	130.75	4829.75	0.0210	38.84
Run 10	362.71	268.29	0.14	94.29	5.26	5.83	5.55	73.72	2.72	20026.93	739.11	140.19	5173.75	0.0213	42.44
Average RB	343.81	268.21	1.04	74.56	5.03	5.53	5.28	73.90	2.73	19897.26	734.77	139.28	5143.36	0.0218	42.83

Case-0: 1 iter.	Case-1: 2 iter.	Case-2: 5 iter.	Case-3: 10 iter.	Case-4: 25 iter.	Case-5: 50 iter.	Case-6-: 100 iter.

Table A3.1 Continues

Case-4 (25)without inf	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	342.86	279.14	0.00	63.71	4.68	4.93	4.80	72.96	2.70	20199.71	747.76	141.40	5234.33	0.0545	114.03
Run2	323.43	253.57	0.00	69.86	4.63	4.99	4.81	72.17	2.67	18431.21	681.99	129.02	4773.95	0.0537	105.13
Run 3	357.29	271.43	0.00	85.86	5.26	5.98	5.62	74.09	2.74	20226.00	746.58	141.58	5226.07	0.0547	110.66
Run 4	327.14	270.86	0.00	56.29	4.43	5.25	4.84	72.03	2.67	19359.43	717.54	135.52	5022.80	0.0591	120.94
Run 5	335.71	265.00	0.00	70.71	4.94	5.61	5.27	73.23	2.71	19587.36	723.58	137.11	5065.05	0.0527	105.75
Run 6	349.29	278.86	0.00	70.43	4.88	5.23	5.06	72.18	2.67	20087.43	743.94	140.61	5207.60	0.0570	120.09
Run 7	314.86	257.86	0.00	57.00	4.59	4.99	4.79	71.70	2.66	18630.29	689.77	130.41	4828.40	0.0574	110.66
Run 8	312.71	267.86	0.00	44.86	4.31	5.11	4.71	70.69	2.62	18948.14	703.03	132.64	4921.23	0.0635	125.53
Run 9	332.43	267.57	0.00	64.86	4.98	5.36	5.17	72.71	2.69	19491.07	721.05	136.44	5047.38	0.0525	106.39
Run 10	359.14	279.43	0.00	79.71	5.07	5.63	5.35	73.14	2.70	20385.43	754.03	142.70	5278.20	0.0561	118.63
Average RB	335.49	269.16	0.00	66.33	4.78	5.31	5.04	72.49	2.68	19534.61	722.93	136.74	5060.50	0.0561	113.78

Case-5 (50) without inf	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	331.43	272.86	0.71	57.86	5.00	5.45	5.22	75.95	2.80	20437.29	754.00	143.06	5278.03	0.1190	248.83
Run2	351.43	284.29	0.00	67.14	5.14	5.32	5.23	70.96	2.63	20222.43	749.89	141.56	5249.23	0.1107	236.27
Run 3	345.14	271.29	0.29	73.57	5.00	5.48	5.24	71.83	2.66	19596.71	725.57	137.18	5078.97	0.1013	209.95
Run 4	338.00	264.43	0.00	73.57	4.74	5.25	5.00	70.65	2.62	18823.29	697.96	131.76	4885.70	0.1179	236.31
Run 5	313.57	258.86	0.71	54.00	4.15	4.49	4.32	71.40	2.65	18572.00	688.10	130.00	4816.67	0.1107	219.16
Run 6	364.29	289.86	0.00	74.43	5.38	5.58	5.48	71.66	2.66	20722.93	768.06	145.06	5376.42	0.1132	241.72
Run 7	332.00	271.29	0.00	60.71	4.61	5.04	4.83	70.97	2.63	19341.64	717.06	135.39	5019.45	0.1166	239.36
Run 8	302.29	260.57	0.00	41.71	3.80	4.15	3.98	68.29	2.54	17887.00	665.72	125.21	4660.03	0.1219	240.27
Run 9	324.57	261.14	0.00	63.43	4.39	5.11	4.75	73.79	2.73	19308.36	713.25	135.16	4992.75	0.1083	212.55
Run 10	344.86	276.29	0.00	68.57	4.60	5.18	4.89	70.69	2.62	19518.36	724.29	136.63	5070.02	0.1199	247.94
Average RB	334.76	271.09	0.17	63.50	4.68	5.10	4.89	71.62	2.65	19443.00	720.39	136.10	5042.73	0.1139	233.23

Case-0: 1 iter.	Case-1: 2 iter.	Case-2: 5 iter.	Case-3: 10 iter.	Case-4: 25 iter.	Case-5: 50 iter.	Case-6-: 100 iter.

Table A3.2 Results of the simulation study for solution quality and computational time (with additional information)

Case-0 (1) with add. inf	# of customers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	354.14	272.14	6.57	75.43	5.16	5.84	5.50	77.45	2.85	20998.64	772.53	146.99	5407.68	0.002829	5.47
Run2	341.00	252.00	3.71	85.29	5.44	6.10	5.77	72.45	2.68	18970.57	699.55	132.79	4896.87	0.002949	4.77
Run 3	348.86	261.00	4.00	83.86	5.55	6.20	5.88	78.59	2.89	20428.36	750.55	143.00	5253.82	0.002737	4.78
Run 4	327.43	260.86	2.57	64.00	5.28	5.77	5.53	77.64	2.85	20401.93	749.63	142.81	5247.38	0.002649	4.41
Run 5	356.00	266.86	1.57	87.57	5.71	6.26	5.98	78.40	2.88	20819.86	765.16	145.74	5356.10	0.002862	4.95
Run 6	337.71	261.29	0.57	75.86	5.28	5.72	5.50	78.21	2.87	20401.14	749.71	142.81	5248.00	0.002934	4.95
Run 7	350.43	265.14	2.86	82.43	5.30	6.35	5.82	79.68	2.92	21044.00	772.17	147.31	5405.20	0.002730	4.61
Run 8	325.57	252.86	0.00	72.71	4.96	5.63	5.29	76.19	2.81	19324.50	711.58	135.27	4981.05	0.003206	5.27
Run 9	287.43	241.57	0.71	45.14	4.25	4.91	4.58	74.58	2.75	18102.00	667.82	126.71	4674.73	0.002878	4.58
Run 10	325.86	253.29	5.29	67.29	5.32	5.41	5.36	78.20	2.87	19734.14	725.35	138.14	5077.43	0.002780	4.67
Average RB	335.44	258.70	2.79	73.96	5.22	5.82	5.52	77.14	2.84	20022.51	736.40	140.16	5154.83	0.002855	4.85

Case-1 (2) with add inf	mers (avg. per day)				customers waits			system utilization							
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	311.57	241.00	1.29	69.29	4.91	5.66	5.29	74.00	2.73	18381.00	676.97	128.67	4738.77	0.004982	9.23
Run2	309.43	246.43	1.57	61.43	5.06	5.49	5.28	77.26	2.84	19049.43	700.70	133.35	4904.87	0.004642	8.28
Run 3	347.00	263.86	4.14	79.00	5.17	6.01	5.59	78.25	2.88	20609.00	757.33	144.26	5301.30	0.004598	8.44
Run 4	350.29	272.14	0.14	78.00	5.31	6.03	5.67	78.21	2.87	21303.50	782.69	149.12	5478.82	0.004532	8.80
Run 5	326.86	251.00	0.00	75.86	4.71	5.60	5.15	76.18	2.81	19276.07	709.47	134.93	4966.28	0.004888	8.44
Run 6	370.57	273.43	6.14	91.00	5.34	6.10	5.72	78.56	2.89	21338.71	784.20	149.37	5489.43	0.004264	8.11
Run 7	325.29	250.86	0.43	74.00	4.79	6.07	5.43	77.20	2.84	19452.21	715.30	136.17	5007.12	0.004773	8.63
Run 8	367.86	264.00	1.71	102.14	5.59	6.28	5.94	78.66	2.89	20652.93	758.83	144.57	5311.82	0.004603	7.81
Run 9	320.57	252.57	0.57	67.43	4.62	5.36	4.99	75.35	2.78	19173.29	706.46	134.21	4945.23	0.004836	8.39
Run 10	328.14	252.71	0.29	75.14	5.19	5.79	5.49	76.50	2.82	19588.14	720.33	137.12	5042.30	0.004650	8.17
Average RB	335.76	256.80	1.63	77.33	5.07	5.84	5.45	77.02	2.83	19882.43	731.23	139.18	5118.59	0.004677	8.43

Case-0: 1 iter.	Case-1: 2 iter.	Case-2: 5 iter.	Case-3: 10 iter.	Case-4: 25 iter.	Case-5: 50 iter.	Case-6-: 100 iter.

Table A3.2 Continues

Case-2 (5) with add inf	mers (avg. per day)			customers waits			system utilization								
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
	338.71	257.00	0.00	81.71	5.03	6.09	5.56	73.60	2.72	19372.64	714.29	135.61	5000.02	0.0111	21.67
Run 1	342.57	259.86	9.71	73.00	5.34	5.81	5.57	75.21	2.77	19781.07	728.66	138.47	5100.65	0.0101	19.89
Run2	351.71	263.86	0.00	87.86	5.42	6.13	5.78	74.54	2.75	19918.71	734.32	139.43	5140.23	0.0112	21.94
Run 3	314.71	251.57	0.00	63.14	5.31	5.59	5.45	73.79	2.73	18905.21	697.26	132.34	4880.82	0.0111	20.00
Run 4	344.00	259.29	0.43	84.29	5.38	5.67	5.52	74.41	2.75	19599.43	722.46	137.20	5057.20	0.0122	22.56
Run 5	294.14	244.29	0.00	49.86	4.61	5.44	5.03	73.33	2.71	18221.43	672.52	127.55	4707.67	0.0119	20.98
Run 6	290.43	232.14	0.00	58.29	4.52	5.17	4.85	69.14	2.57	17139.43	633.22	119.98	4432.53	0.0108	18.55
Run 7	321.57	238.43	0.57	82.57	5.46	5.41	5.43	69.81	2.59	17727.79	654.51	124.09	4581.55	0.0124	20.23
Run 8	324.14	258.86	0.00	65.29	4.48	5.20	4.84	75.97	2.80	19534.86	720.19	136.74	5041.33	0.0120	23.34
Run 9	322.14	259.57	1.57	61.00	4.91	5.92	5.42	75.78	2.79	19705.43	726.07	137.94	5082.47	0.0108	21.22
Run 10	324.41	252.49	1.23	70.70	5.05	5.64	5.35	73.56	2.72	18990.60	700.35	132.93	4902.45	0.011346	21.04

Case-3 (10) with add inf	mers (avg. per day)			customers waits			system utilization								
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	349.71	268.14	0.86	80.71	5.10	5.87	5.49	73.68	2.72	19876.93	734.07	139.14	5138.48	0.022174	45.44
Run2	344.43	257.57	0.00	86.86	5.07	6.19	5.63	72.74	2.69	19051.50	703.74	133.36	4926.15	0.021628	41.00
Run 3	303.86	243.29	0.86	59.71	4.45	4.78	4.62	73.36	2.71	18000.57	664.90	126.00	4654.27	0.021314	42.25
Run 4	347.57	274.29	0.14	73.14	5.30	5.60	5.45	75.24	2.77	20625.00	760.64	144.38	5324.50	0.019547	40.36
Run 5	306.57	250.71	0.00	55.86	4.33	4.78	4.56	70.97	2.63	17972.00	665.92	125.80	4661.47	0.023846	43.50
Run 6	322.43	256.00	0.00	66.43	4.78	5.31	5.04	72.33	2.68	18589.29	687.91	130.13	4815.37	0.024110	43.95
Run 7	318.43	256.43	0.86	61.14	4.68	5.29	4.99	74.41	2.75	19145.14	706.55	134.02	4945.87	0.021994	43.98
Run 8	349.57	274.43	0.00	75.14	4.44	5.37	4.91	72.37	2.68	19935.29	737.69	139.55	5163.83	0.025291	52.52
Run 9	336.57	275.57	0.00	61.00	5.19	5.43	5.31	74.77	2.76	20561.57	758.87	143.93	5312.10	0.022467	46.27
Run 10	346.71	271.43	0.00	75.29	4.87	5.67	5.27	73.14	2.70	19764.07	731.18	138.35	5118.28	0.023934	47.19
	332.59	262.79	0.27	69.53	4.82	5.43	5.13	73.30	2.71	19352.14	715.15	135.46	5006.03	0.0226	44.65

Case-0: 1 iter.	Case-1: 2 iter.	Case-2: 5 iter.	Case-3: 10 iter.	Case-4: 25 iter.	Case-5: 50 iter.	Case-6-: 100 iter.

Table A3.2 Continues

Case-4 (25) with add inf	mers (avg. per day)			customers waits			system utilization								
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	341.57	272.71	0.00	68.86	4.98	5.53	5.26	72.32	2.68	19788.71	732.35	138.52	5126.43	0.056444	117.47
Run2	328.71	268.86	0.86	59.00	4.64	5.25	4.95	72.31	2.68	19499.57	721.68	136.50	5051.77	0.055452	113.89
Run 3	334.00	265.71	0.00	68.29	4.89	5.59	5.24	71.87	2.66	19117.79	708.12	133.82	4956.82	0.061497	123.58
Run 4	264.86	232.29	1.00	31.57	3.85	4.19	4.02	68.83	2.56	16343.07	606.71	114.40	4246.98	0.055270	103.56
Run 5	298.29	240.71	0.00	57.57	4.01	4.73	4.37	71.31	2.64	17435.71	645.38	122.05	4517.67	0.058168	106.80
Run 6	322.29	268.29	0.00	54.00	4.12	4.72	4.42	70.57	2.62	18967.57	703.80	132.77	4926.57	0.057077	116.44
Run 7	363.00	265.00	0.00	98.00	5.35	5.98	5.66	71.89	2.66	19486.00	720.20	136.40	5041.40	0.052395	106.94
Run 8	347.29	273.86	0.00	73.43	4.98	5.39	5.18	71.58	2.65	19760.86	731.72	138.33	5122.07	0.054108	113.20
Run 9	326.86	267.14	0.00	59.71	4.86	5.30	5.08	71.27	2.64	19138.57	709.19	133.97	4964.33	0.056168	113.36
Run 10	349.29	278.14	0.00	71.14	4.54	5.05	4.80	71.22	2.64	19929.93	738.50	139.51	5169.52	0.054357	115.45
Average RB	327.61	263.27	0.19	64.16	4.62	5.17	4.90	71.32	2.64	18946.78	701.77	132.63	4912.36	0.056094	113.07

Case-5 (50) with add inf	mers (avg. per day)			customers waits			system utilization								
Simulation of 3 months	total # of customers	total # of served customers	total # of rejected customers	average # of customers leaving	average wait for parking	average wait for retrieval	average wait per operation	trans dist. (m) per operation	trans time (min) per operation.	*daily trans dist. (m)	*daily trans times (min)	total trans dist. (km)	total trans times (h)	**Decision Time (sec.)**	**Elapsed Time (sec.)**
Run 1	356.29	276.43	0.00	79.86	4.84	5.73	5.29	71.59	2.65	19915.93	737.58	139.41	5163.05	0.114164	237.16
Run2	357.57	277.00	0.00	80.57	5.00	5.37	5.18	72.78	2.69	20171.14	746.24	141.20	5223.67	0.117103	246.13
Run 3	335.86	257.14	0.00	78.71	4.36	5.11	4.73	67.63	2.52	17923.50	666.02	125.46	4662.15	0.115685	226.61
Run 4	353.86	277.71	0.00	76.14	5.25	5.71	5.48	74.08	2.74	20428.50	755.01	143.00	5285.05	0.117798	249.80
Run 5	351.29	281.86	0.00	69.43	4.75	5.09	4.92	73.72	2.72	20642.00	763.23	144.49	5342.60	0.118538	256.53
Run 6	308.43	261.71	0.00	46.71	4.56	4.98	4.77	68.17	2.54	18029.00	670.76	126.20	4695.30	0.128643	249.20
Run 7	348.29	281.57	0.00	66.71	5.07	5.50	5.29	73.25	2.71	20487.36	758.00	143.41	5305.98	0.116195	253.55
Run 8	324.29	266.00	0.00	58.29	4.71	5.05	4.88	70.52	2.62	18902.93	701.03	132.32	4907.22	0.109563	226.77
Run 9	311.00	260.57	0.00	50.43	4.80	5.27	5.04	72.19	2.67	18916.71	700.04	132.42	4900.30	0.117835	223.56
Run 10	343.86	271.29	0.00	72.57	5.00	5.42	5.21	70.94	2.63	19575.14	724.85	137.03	5073.93	0.117446	236.95
Average RB	339.07	271.13	0.00	67.94	4.84	5.32	5.08	71.49	2.65	19499.22	722.28	136.49	5055.93	0.117297	240.63

Case-0: 1 iter.	Case-1: 2 iter.	Case-2: 5 iter.	Case-3: 10 iter.	Case-4: 25 iter.	Case-5: 50 iter.	Case-6-: 100 iter.