INTEGRATION OF FACILITY LOCATION AND LAYOUT OF INTERMODAL TRANSPORTATION SYSTEM WITH SCHEDULING

by

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This is to certify that I have examined this copy of a master's thesis by

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To my parents

ABSTRACT

The idea of intermodal freight transportation is to combine two or more different modes of transportation without changing the packaging of the freight transported with the aim of minimizing the cost. One of the most popular intermodal transportation schemes is Ro-La which is the railway transport line carrying vehicles on wheels, rather than on roads. In this thesis, the goal is to provide an integrated model for facility location and layout problems together with scheduling problems arising in Ro-La transportation. To achieve this goal, first, several initial layouts were developed according to different objective functions and final layouts were obtained with the station layout improvement algorithm, to find the best sub-optimal station layout. Next, using the number of platforms from the facility layout model, train scheduling model was developed as an integer programming model to find the minimum number of platforms in a station, the number of trains and the departures with carried trucks/trailers, while scheduling train operations, with the objective of minimizing operating costs. Consequently, facility layout and train scheduling models were combined to form the integrated model. The model was solved with different Ro-La transportation system data as instances for Marmaray Project, which will be operated in Istanbul crossing the Bosphorus. As a result, we suggested how to locate the elements of the system, how to plan the facility layout and how to schedule the intermodal freight transportation in that system.

ÖZETÇE

Çok modlu yük taşımacılığının felsefesi bir veya daha fazla değişik taşıma modunun taşınan yükün ambalajlarının değiştirilmeden maliyeti enazlamak amacıyla birleştirilmesidir. Ro-La taşımacılığı, kamyon ve TIR'ların karayolu yerine, demiryolu ile taşınmasıdır. Bu tezde, Ro-La taşımacılığında ortaya çıkan tesis yerleşimi ve tasarımı problemlerini çizelgeleme problemleri ile bütünleştirecek bir eniyileme modeli geliştirilmiştir. Farklı amaç fonksiyonlarına göre başlangıç istasyon tasarımları elde edilmiş, optimale en yakın istasyon tasarımını bulabilmek için, istasyon tasarımı geliştirme algoritması uygulanarak, sonuç tasarımları elde edilmiştir. Tesis tasarımı modelinden elde edilen platform sayısı kullanılarak, tamsayılı programlama modeli olarak tren çizelgeleme modeli geliştirilmiştir. Amacı operasyon maliyetlerinin enazlanması olan bu model ile tren operasyonlarının çizelgesi hazırlanarak, bir istasyondaki platform sayısı, tren sayısı, sefer sayısı ve taşınan kamyon/TIR sayısı sonuçları elde edilmiştir. Sonuç olarak, tren çizelgeleme modeli ve istasyon tasarım modelinin oluşturduğu entegre model, farklı Ro-La taşımacılığı sistemlerinin datalarına göre oluşturulan İstanbul'da uygulanmakta olan Marmaray Projesi durumlarına uygulanarak, sistemin nasıl yerleştirileceği, tesis tasarımının nasıl planlanacağı, ve bu sistemdeki Ro-La taşımacılığının nasıl çizelgelenmesi gerektiği açıklanmıştır.

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NOMENCLATURE

IMT	Intermodal Transportation
Ro-La	Rollande Lanstraße, Rolling Highway
TIR	Transports Internationaux Routiers, International Road Transport heavy long vehicle
HGV	Heavy goods vehicle
OE	Oekombi, Austrian Ro-La system
MO	Modalohr, French Ro-La system
EU	Eurotunnel, EWS-English and SNCF-French Ro-La system
MTTR	Ministry for Transportation of Turkish Republic
MMI	Metropolitan Municipality of Istanbul
IMPL	Istanbul Metropolitan Planning-Department of Logistics
SRTR	State Railroads of Turkish Republic
GDHTR	General Directorate of Highways of Turkish Republic
TRMI	Turkish Railway Machines Industry Inc.
TLEI	Turkish Locomotive and Engine Industry Inc.
LP	Linear Programming
MIP	Mixed Integer Programming
IP	Integer Programming
MINLP	Mixed Integer Nonlinear Programming
BB	Branch and Bound Algorithm

AHP	Analytical Hierarchical Process
CORELAP	Computerized Relationship Layout Planning
REL Chart	Activity Relationship Chart
CRAFT	Computerized Relative Allocation of Facilities Technique
COFAD	Computerized Facilities Design
ALDEP	Automated Layout Design Problem
SLP	Systematic Layout Planning Approach
ARC	Activity Relationship Chart
SRD	Space Relationship Diagram

Chapter 1

INTRODUCTION

Intermodal Transportation (IMT) is the use and combination of two or more different modes of transportation (road, rail, sea or air) in one transportation chain to move goods / passengers with the aim of minimizing the total cost and without changing the packaging type of the freight. The benefits of intermodal transportation are economical, environmental and operational. Because of these great benefits of IMT, in today's transportation planning purposes, IMT is preferred to take place of road transportation in the countries, where massive freight transportation traffic exist, in especially European countries such as Austria, France and Germany. In IMT, each transportation mode seeks to exploit its own advantages in terms of cost, service, reliability and safety. Customers have the chance to purchase the service to ship their products from door to door by service provider around the world. The companies could offer low rates by integrating rail services and local vehicle pick up and delivery in a seamless network. Requirements for a manageable and cost-effective IMT system are infrastructures and understanding the system behaviour through quantitative analysis. From environmental point of view, some transportation modes cause less carbon emission and noise pollution for transported unit load. On the other hand, with the integration of intermodal transportation, operational efficiency is obtained with decreasing handling in the transfer of goods. This can indirectly decrease risk used in insurance cost calculations by reducing harm to goods. The importance of IMT rises in the logistics applications which involve international and interurban transportation problems.

The most well-known IMT type is Rolling Highway (Ro-La). Ro-La, acronym of Rollande Lanstrae (walking road), is a special train system that carries highway vehicles in railway cars. Ro-La is used to transport trucks/TIRs and carries freight on railroad rather than on highway with or without escorting. In the transportation sector, the term TIR is commonly used instead of the term heavy goods vehicle (HGV). Therefore, in the remainder of this thesis, the term TIR will be used. The goal of Ro-La transportation is to transfer heavy traffic, which gets through a congested area, from highway into railroad. With the combination of cost advantage of rail transportation over road transportation and economies of scale, with Ro-La, great cost savings can occur in freight movement. It is possible to reduce variable operating costs per passenger and per kilometer. Railroad results in much less carbon emission rates when compared to highway, so Ro-La also has environmental benefits. Last important benefit can be expressed as operational, because management and scheduling of trucks/TIRs can be organized more easily and effectively in Ro-La, rather than in highway, where each truck/TIR travels individually. Also, with the use of Ro-La, it is possible to overcome disadvantages of city life, such as traffic intensity on highways and noise pollution.

Istanbul, which is a bridge between Asia and Europe, is in the center of international, national and regional freight movement, because of its geopolitical position. According to the statistics of Fatih Sultan Mehmet Bridge, every day, 12,000 trucks/TIRs pass Istanbul only in one direction. So, Istanbul is one of the major cities in Turkey and in the world where high density traffic flow occurs. 93% of this flow is performed on highways [15]. This movement causes serious transportation intensity in İstanbul Metropolitan Region, so it also causes social, economic and environmental problems. Because of the previously mentioned benefits of Ro-La system, Ministry for Transportation of Turkish Republic (MTTR) and Istanbul Metropolitan Municipality (IMP) plans to apply Ro-La transportation in Istanbul. The goal is to transfer trucks/TIRs traffic, which get through İstanbul, into railroad with the use of Ro-La. The Marmaray Project presents necessary infrastructure to achieve that purpose [16]. Currently, Marmaray Project is an ongoing project and it is the development of commuter rail system in Istanbul, connecting Halkalı on the European side with Gebze on the Asian side with a continuous, modern, technological, high-capacity commuter rail system. Marmaray operates efficiently during the period of 06:00-24:00 with sufficient demand. However, it becomes idle because of inadequate passenger demand for the remaining times. In order to use this idle capacity effectively and to meet heavy freight transportation demand as much as possible, Ro-La transportation is planned between 24:00-06:00 by the coordination of MTTR, State Railroads of Turkish Republic (SRTR) and MMI. With the operation of Ro-La trains in Marmaray, Ro-La system will be used for the first time in Turkey. The aim is to carry goods with Ro-La system between Çerkezköy (in Tekirdağ) and Köseköy (in Kocaeli) on a 231 km route. So, the railway line connecting Çerkezköy with Köseköy is extensively studied from the facility layout and train scheduling perspectives in this thesis. Railroad tracks in both sides of Istanbul Strait will be connected to each other through a tunnel connection under the Bosphorus. This 14 km Marmaray sea tunnel line is the critical part in the entire railway line in Marmaray system, because, only one line is allowed for each direction in tunnel, while additional one line can be served in other segments of the railway, in terms of meeting excess capacity more effectively if required. Currently, Marmaray Project is the largest transportation infrastructure project in terms of budget in Turkey and one of the major transportation infrastructure projects in the world.

The most important operational problem of a Ro-La transport system is the scheduling Ro-La of trips. The most strategically important problem about the administration of Ro-La systems is the determination of the numbers of loading/unloading platforms and the required space, thus leading to facility layout planning. In order to obtain a successful Ro-La enterprise, integration of these two problems is essential. The aim in this thesis is, based on strategic and operational problems in Marmaray Ro-La system, to develop integrated models and solution methods for facility layout planning and train scheduling problems, occurring in intermodal transportation systems.

In this thesis, we develop an integer programming model for train scheduling problem to construct timetable of train operations, which are loading, unloading, transfer and travel. The questions of how to schedule the train operations, of how many platforms are required and of how many vehicles are carried with the trains are also addressed. With the solution of train scheduling model, capacity usage and required number of platforms are determined for different modes. In addition, methods for facility planning are developed by determining the factors, with the analysis of intermodal transportation systems. At the last step, models and solution methods prepared in the thesis are applied to several instances in Marmaray system, the system MMI has, and how to schedule the intermodal freight transportation in that system will be suggested.

The remainder of this thesis is organized as follows. In Chapter 2, an overview of the previous studies about intermodal transportation, facility layout planning and train scheduling is given. Chapter 3 explains preliminary studies about the structure of platforms and also the properties and the requirements of the facility layout problem with the facility layout improvement algorithm. Chapter 4 gives the data obtained to be used for constructing mathematical model and addresses the integer programming model for train scheduling purposes. Results for facility layout, train scheduling, cost of train operations and integrated model are given in Chapter 5. The thesis concludes in Chapter 6. Additional results of facility layout, train scheduling and other analyses about environmental aspects of Marmaray system are given in Appendix A, B and C, respectively.

Chapter 2

LITERATURE REVIEW

In this thesis, intermodal transportation and train scheduling with facility layout problems are studied. This chapter presents the literature survey about railroad network modelling, facility capacity evaluation, systematic layout planning, heuristic algorithms.

2.1 Intermodal Transportation

Intermodal Transportation (IMT) is first defined as “use of more than one mode for freight/passenger transportation in a continuous and one travel” [28]. Since the industrial revolution, as the necessity to transport materials and goods rises, intercontinental, international and interregional transportation became the crucial and the inevitable part of industrial supply chain. As a result of massive freight movement, major investments are required at the terminals, where the processes such as landing and repackaging according to the next transportation mode are applied. In order to control all of these operations effectively, standardization of containers were introduced and in 1970’s, the transportation philosophy changed as carrying containers from one place to another, while transferring from one mode to other occurs. With this standardization, at the beginning of 21st century, 95% of continental transportation happened to be done with containers [12].

As a conclusion of intensive circulation of containers, the following two important problems arise:

1. determination of modes to be used for freight carried by containers and modification of the required substructure,

2. minimization of time and cost for transport of containers from one transportation mode to another.

Since the industrial revolution, until 1970's, main principle in transportation is focused on delivering freight from one place to another [37]. For this purpose, the two above-mentioned problems need to be solved. The research about intermodal transportation systems focuses on solution of problems encountered in two levels, strategic and operational.

Today, it is estimated that the percentage use of highways is the largest in all of the transportation modes: it constitutes 80% of passenger transportation and 50% of freight transportation. While, the role of railroads was 21% in 1970, it was reduced to 8.4% in 1998 and currently, its share in passenger transportation is only 6% [1]. The amount of freight transportation in Europe rises more than 10% in the last decade of the 20th century when compared to the previous decade [4]. Between 1970 and 2000, the number of automobile ownership was tripled (total number was increased from 62 million to 175 million). It is expected that until 2010, freight transportation will increase by 50%. Although, these percentages are applicable to European Union countries, these are estimated to be worse in Turkey. In the last years, the percentage of highways increased to 92% in freight transportation and to 95% in passenger transportation. Therefore, the problems based on transportation are expected to get worse in terms of environment and health [52]. Zografos and Regan [54] addressed open research issues and challenges in IMT and stated that as congestional and environmental impacts worsen, IMT systems will increase its importance.

2.2 Facility Layout Problem

Strategic level problems of IMT focus on facility layout and location, and determination of the fleet size [36]. In order to determine the fleet size, it is required to find travel schedules. Considering complexity of the problem, solution methods should be developed from simplified models. An important problem that can be classified at strategic level is facility layout. The goal in facility layout is to designate the suitable places that are efficient for the activities and operations performed in the facility [40].

Taylor et al. [47] studied the determination of the best facility layout where total distance run by empty trucks/TIRs is minimized. IMT terminals are of critical importance because they are the exchange points between road and rail modes. With the dynamic assignment problem based on uncertain parameters, such as the type and the number of equipments used in platforms, layout of departments and warehousing capacity, operational strategies can be developed and it is possible to increase efficiency in the operations applied to the freight and the containers [10].

Bazaraa [5] showed that, in facility layout planning problem, optimal and sub-optimal results can be found by using branch and bound approach which optimizes the layout from the solution of quadratic set covering problem. In intermodal container transportation problem, the design and the properties of siding construction affect the system economically [21]. Taniguchi et al. [46] implemented a mathematical model that uses queuing theory and non-linear programming techniques to determine the size and the location of logistics terminals. The service quality in IMT terminals depends on loading and unloading operations applied to trains with minimum delays. In addition, transferring freight between road and rail modes affects delay significantly. To study delays in trains that have various service configurations, an analytical simulation model was developed [31]. An iterative search algorithm using genetic algorithm, tabu search and hybrid heuristics was developed to optimally implement storage strategy and scheduling of operations in the container operations at terminals [32].

It is possible to reduce traffic congestion, environmental damage, energy consumption and employment costs with general logistics terminals (multi-company distribution centers). Rotter [44] studied connecting freight transportation in less congested cities to IMT system existing between rural industrial zones and the city center. Based on a novel approach as city center concept, freight transportation between several railroad networks will have continuity with short dwell times at terminals and switching goods between block trains.

The capacity in IMT stations was also evaluated with an IP model, which determines optimal arrival speed of trains to terminals, where this speed affects the design of platforms in the station [42]. The problem about locating departments in a facility, depending on relative locations of each other has a combinatorial complexity, because the number of solutions is exponential in terms of the number of departments. Therefore, in the literature, instead of starting from scratch for a facility layout, an initial layout is determined and with several algorithms, it is tried to be modified to converge to the optimal solution. The heuristic method developed by Armour and Buffa [2] switches locations of adjacent or same-sized departments in a loop and evaluates the new layout with their relative allocations to find a sub-optimal facility layout. CORELAP (Computerized Relationship Layout Planning) is a heuristic method which is used to determine facility layouts based on interrelationship types and levels between activities and area of activities [33]. CORELAP method uses Activity Relationship Chart (REL Chart) for interrelationship types and levels. REL Chart was first introduced by Muther in 1961 [39]. It shows the type and the importance level of reasons and definitions between departments and, in the literature, it is accepted as one of the most important analytical methods in facility layout problems. The most impressive heuristic method is CRAFT (Computerized Relative Allocation of Facilities Technique), which is developed by Armour et al. [3]. CRAFT method has been inspired by several algorithms in the literature, which are quite effective in finding sub-optimal solutions. CRAFT method is only applicable to layout problems inside an existing facility structure. In a new facility design, it is recommended to develop facility plan based on the layout. Therefore, CRAFT method can be inadequate in these situations [33]. Tompkins and Reed [48, 49] developed COFAD (Computerized Facilities Design) to solve facilities desing problem. COFAD tries to minimize total material control system cost while solving joint plant layout and materials handling system selection problems at the same time. COFAD method was developed by analyzing CRAFT method. ALDEP (Automated Layout Design Problem), developed by Seehof and Evans [45], was used to investigate facility layout problem for combinatorial and computation time purposes. This method takes preference criteria inputs such as, area, organizational requirements, location preference in organization, evaluates layout options, scores and produces sub-optimal block and graphical layouts.

CORELAP, CRAFT, COFAD and ALDEP are the most effective heuristic facility layout methods in the literature. Although it was stated that these algorithms could be used for research purposes, because these algorithms were developed in 1970's, it is not possible to find these algorithms. In our study, by analyzing inputs, functions, results in these algorithms, we developed a new facility layout improvement algorithm.

2.3 Train Scheduling Problem

In IMT system, where railroads and highways are used, it is best to travel the farthest possible route with railroads and other remaining start and end link routes should be travelled by highways [36], in order to maximize the usage of railroads while meeting capacity constraints, for fully benefiting from railroad's advantages over highways. Railroad is accepted as the most economic mode for freight transportation on land, when long distances are considered, especially for raw materials.

Newman and Yano [41] studied to determine the timetable of travels at the operational level problems of IMT. In the situations where there exist more than one terminal, economic advantages are seen if one of these terminals is evaluated as central positioned terminal. Besides the operational level, economic losses of possible equipment constraints are investigated. These equipment constraints can occur at vehicle load/unload platforms [30].

In a single line railroad system, an integer programming model with the goal of the number of conflicts and the cost minimization was developed. Also, with this method, the schedule of railroad operations and infrastructure can be developed and the operator can decide on the variations in real-time [22]. Burdett and Kozan [6, 7] explained that the capacity of railroad line depends on train (locomotive and wagon) types, direction of departure, length of rail line, dwell times and passing priorities on intersections. In a single line railway, with adding new rail line parts, operational efficiency can be increased with minimum cost. In these systems, the amount and the location of additional rail line parts are the critical topics. Applying decomposition methods in a mixed integer nonlinear programming model (MINLP) for this type of problems, the solution can be found in short times with quick convergence [23].

Lindner and Zimmermann [35] developed MINLP model for the train scheduling problem with the aim of minimizing total operational cost of all train types with different speed and costs. Usually, it is not possible to solve this type of scheduling problems in reasonable time. Hence they developed an integrated algorithm, which solves the model first with only train constraints, then controls the train types and at last, uses a decomposition method with cutting planes and branch & bound (BB) algorithm. In the literature, maximizing the number of passengers carried / amount of freight transported and minimizing cost are the examples of multi-objective (multi-criteria, multi-attribute) optimization in train scheduling problems. Ghoseiri et al. [20] developed a multi-criteria optimization model with minimizing fuel consumption and time of travel objectives and used pareto analysis in a single and/or two line railroads and various capacitated platforms. Train scheduling problems can be solved according to real-time updated data. A novel constraint programming model, developed by Rodriguez [43], can solve routing and scheduling problems in a railroad network. The model is run by time data found by simulation and from the requests of the operators to prevent delays and conflicts.

At the terminals, the train planning or scheduling problem was proven to be complex, so it is required to be solved by combinatorial search and integer programming methods. There must be no conflict in train movements and all of the departure, transfer, dwell, loading, unloading, etc. operations must be planned for each train. Also, in an environment where more than one train operator group exists, one cannot address an exact and single objective function. Therefore, instead of manual methods applied by many operator groups, the single heuristic scheduling model can find a satisfying result, subject to all of the constraints-requests of all of the operator groups [8, 9]. Greedy travel advance strategy method is a heuristic model developed by Dorfman and Medanic [13]. This method is constructed considering requirements of railroad operator groups and the method runs in short times with several computing advantages. Also, using capacity control methods, schedule in railroad network is implemented and possible conflicts are minimized.

Gercek et al. [19] analyzed three alternative railroad network projects for Istanbul with Analytical Hierarchical Process (AHP). In multi-criteria decision analysis, AHP is a structured technique to help decision making process by considering perception, experience, knowledge, judgement, goal, scenario, criteria and options. An analytical railroad access pricing methodology was developed to evaluate capacity and pricing, based on type of locomotive and wagons, weight and length, direction of travel, acceleration and deceleration, dwell protocols of trains, locations and length of switchs, signs, lenght of railroad parts and travel times in railroad parts. Also, Eurotunnel system is economically analyzed in terms of the carried passenger number, the amount of freight transported, construction costs, profits/losses of operator groups, travel times, prices, transportation costs and financial status [1].

Although the literature of freight transportation studied single mode transportation problems extensively, a few works on intermodal freight transportation indicate that there is a need for new models. Also, the literature considers different problems arising in intermodal freight transportation separately. As a requirement of the purpose of intermodal transportation, these two problems need to be integrated and to be solved in this way. Moreover, there are no model and solution methods found in the literature that studies these problems in an integrated way which forms the main motivation of this thesis.

Chapter 3

FACILITY LAYOUT PROBLEM AND IMPROVEMENT ALGORITHM

The purpose in the thesis is to develop integrated models and solution methods for facility layout and train scheduling problems, occurring in intermodal transportation systems. Facility layout can be explained with various definitions. The facility layout problem involves allocation of available space to a variety of activities that have different inter-relationships [24]. Layout problems are related to the location of facilities (e.g., machines, departments) in a plant [14]. These problems greatly affect the system performance. A better placement of facilities contributes to the overall efficiency of operations and can decrease 50% of the total operating costs [50]. Facility layout involves the allocation of activities to space in order to satisfy a set of criteria (e.g. area requirements), and/or an objective (e.g. measure of communication costs) [34]. In the literature, layout problems were proven to be complex and generally NP-Hard [18]. Francis et al. [17] explained that the process of developing facility layouts contains elements of both art and science, i.e., creativity, synthesis, style and analysis are very evident and essential in designing layouts. The facility layout is fundamentally different from an optimization problem because it is in fact a design problem. In addition, solutions to facility layout problem depend heavily on the use of synthesis compared to analysis [50]. Facility layout planning problem deals with the determination of best relative arrangement of departments with respect to different layout patterns on a planar site.

3.1 Preliminary Analysis of Platforms

3.1.1 Introduction

For train scheduling and facility layout problems, one of the most important parameters is the design of loading/unloading platforms.

In this preliminary analysis, we proposed two different loading/unloading platforms structures and studied them in terms of the required space and cost per unit space. We designed two different platform siding structures. Figure 3.1 shows the linear platform structure. It has a switch and after the train arrives at the station, without requiring U curve, it covers the minimum required distance after the curve, uses the other locomotive, starts to go in the other direction, passes the curve and enters the convenient platform for unloading/loading processes. Figure 3.2 is called as circular platform and opposite to all of the properties of a linear platform, the train goes in the same direction with a U curve, then enters empty platform.

One of the major differences between two platform structures is that in the linear platform, two locomotives must exist on the train since the train needs to move in both directions, while in the circular platform, one locomotive per train is enough. In the case where two locomotives are used, it is a fact that both the locomotive and the operator cost will be higher. The other difference is that the area of platforms is the same, but siding rail area of two platform structures is different. Since the types of these platform structures are totally different, linear platform requires only one line railroad area, while in circular platform, the area inside U curve must be considered.

3.1.2 Parameters

The following parameters are used in this study:

L: length of train

B: width of one platform

P: length of one platform

r: minimum curve radius

R: maximum curve radius

w: width of railroad

T: width of siding of leaving part of platforms

I: safety distance

N: number of parallel platforms

The first eight parameters are in terms of meters. Length of one platform (P) is equal to length of train (L) plus 10 m. 10 m is the total of 5 m both in the front and the end of train as safety distances. Minimum curve radius (r) is for one wagon, while maximum curve radius (R) is for the whole train.

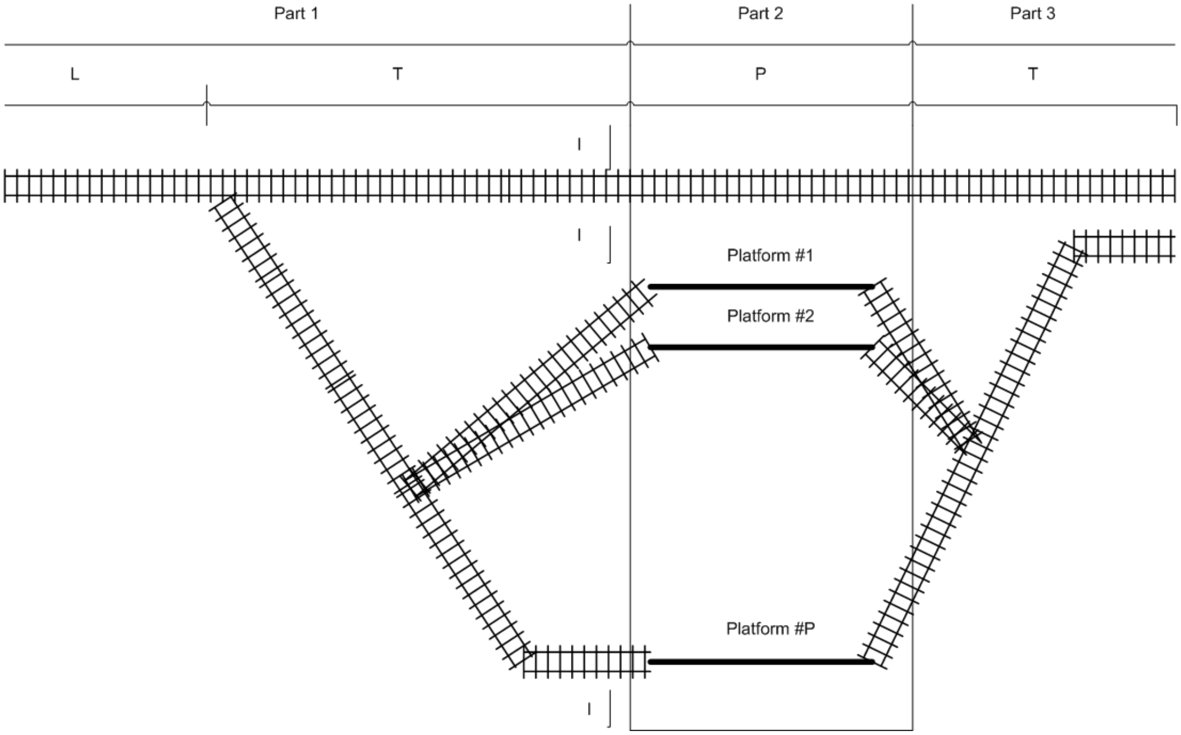

Figure 3.1: Linear Platform Structure

3.1.3 Results

Table 3.1 shows the required space (in m^2) for the main railroad and the siding rails for each system, part of railroads and the platform structure options.

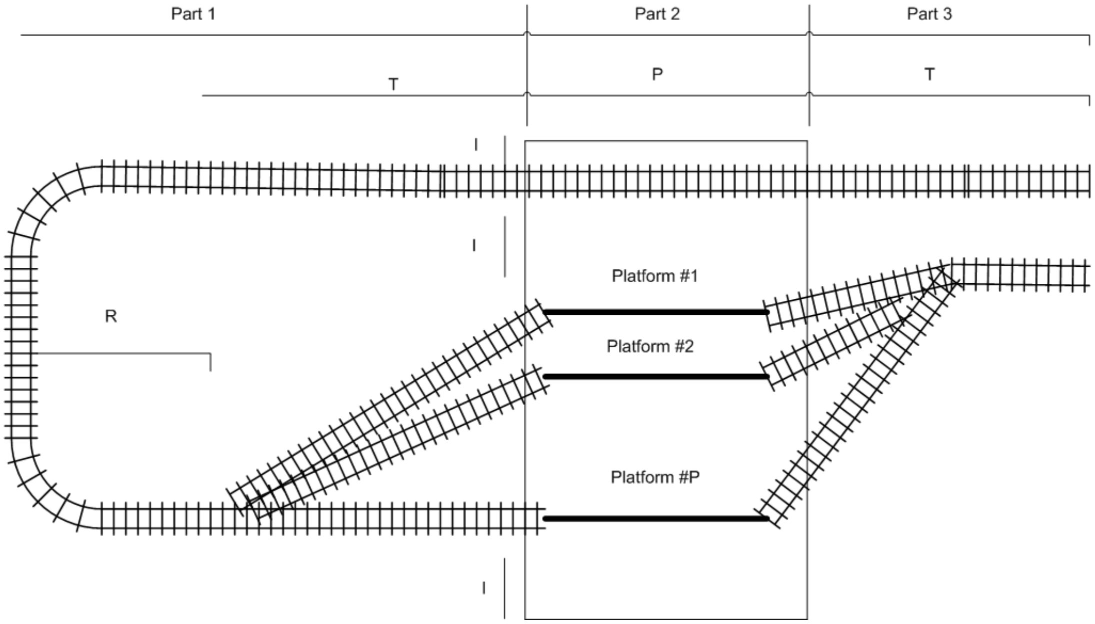

Figure 3.2: Circular Platform Structure

Table 3.1: Space of Railroads in Station

System	Part 1		Part 2	Part 3	Total
	Linear	Circular			
Oekombi	[1240+(600*N)]	[72250+(600*N)]	[8060+(4480*N)]	[375+(600*N)]	[81925+(6280*N)]
Modalohr	[1620+(720*N)]	[72295+(720*N)]	[10940+(6080*N)]	[530+(720*N)]	[85385+(8240*N)]
Eurotunnel	[1520+(680*N)]	[72280+(680*N)]	[10220+(5680*N)]	[505+(680*N)]	[84525+(7720*N)]

The values in Table 3.1 are calculated by computing the length and the width parameters, which are explained in Section 4.1. Three systems; Oekombi (OE), Modalohr (MO) and Eurotunnel (EU) are the current Ro-La transport systems in use. Oekombi is the system in Austria, while Modalohr is in France and Eurotunnel is between England and France. When the area requirements are analyzed for different parts; for Part 1, it is seen that Oekombi system required minimum space with linear platform structure. Also, for Parts 2 and 3, OE system means less area. In order to analyze in terms of systems, it can be seen from total values that, Oekombi system requires minimum area for main railroad and siding rails in a station. This analysis can be very useful in situations where land cost is very important among all cost elements.

3.2 Data for Facility Layout Planning Problem

3.2.1 Systematic Layout Planning Approach

In the literature, the most popular approach in facility layout design has been the systematic layout planning (SLP) approach, which was developed by Muther [39]. Figure 3.3 shows all of the steps in SLP.

All of the steps between "Input Data and Activities" and "5. Space Available" form "Analysis" part, steps between "6. Space Relationship Diagram" and "9. Develop Layout Alternatives" constitute "Search" part, and the last step is for the "Selection" part.

3.2.2 Departments

In this thesis, we studied facility layout problem, based on SLP approach. Therefore, for step 1, we communicated with Istanbul Metropolitan Planning-Department of Logistics (IMPL), and 14 essential departments are determined. Table 3.2 illustrates these departments with their properties.

In the remainder of this thesis, instead of its name, each department will be referred to with its abbreviation, as given in Table 3.2. Some of the dimension values are not entered because these values will be available as the solution of the integrated model with train scheduling problem, so these values will be different for each instance. The available values are assumed to be constant for all instances.

As the second step of SLP approach, the flow between materials should be specified. In our facility layout problem, we evaluated both the physical and the information flows between departments. The physical flows include truck, TIR and car movements. Table 3.3 is organized as two triangles. The diagonal zero values separate these two triangles and the lower triangle shows the flow values, while the upper triangle gives the flow costs (/unit distance, based on flow values). There are no flows between the same departments,

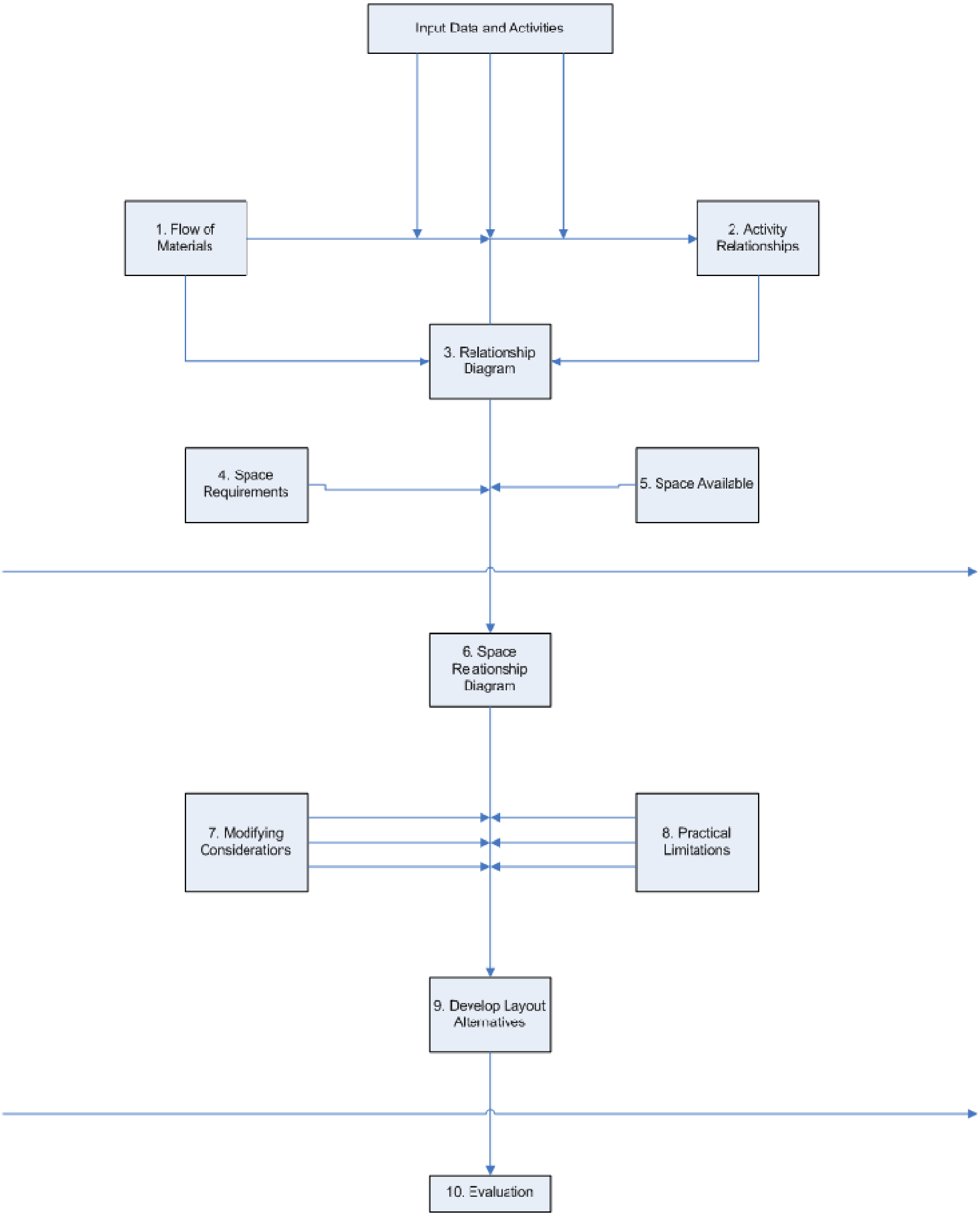

Figure 3.3: Systematic Layout Planning

Table 3.2: Departments and Properties

Code	Name	Abbreviation	Length (m)	Width (m)
1	Platforms	P	-	-
2	Siding	S	-	-
3	Locomotive/Wagon Park Area	L	-	-
4	Locomotive/Wagon Warehouse	A	40	40
5	Shuttle Park Area	K	80	40
6	Shuttle Stop	G	40	40
7	Truck/TIR Park Area	T	-	-
8	Truck/TIR Warehouse	U	40	40
9	Fire Department	F	40	40
10	Social Place	C	200	140
11	Office	O	80	100
12	Infrastructure	I	40	40
13	Gas Station	B	40	40
14	Car Park Area	D	40	200

so the flow values and costs are both shown with 0. Flow values can take 11 different values, between -1 and 9. For instance, flow value between T (Truck/TIR Park Area) and P (Platforms) is decided as 9, because this is the most important and critical activity in the station due to loading of trucks/TIRs to trains on the platforms. Flow value -1 means that there must not be any relation between these departments. On the other hand, flow cost between departments T and P is 8. For example, K (Service Park Area) and S (Siding) departments are totally independent of each other because of their different purposes, so there should not be any physical flow between these departments.

Table 3.4 presents activity relationship chart (ARC), for interrelationships and costs of the connections between departments. This table was prepared in cooperation with IMPL. This table has two triangles; lower triangle shows the relationship definition and the reasons, on the other hand, upper triangle shows the relationship costs. The values “U-0” separates these two triangles. For example, the relationship definition between T (Truck/TIR Park Area) and P (Platforms) is A-“Absolutely necessary”, while the relationship reason is 1-“Flow of materials”. In addition, the relationship cost between departments T and P is 9. The relationship between the same departments are unimportant, and there is no cost, so

Table 3.3: Flow Values and Costs

Flow Costs → Flow Values ↓	P	S	L	A	K	G	T	U	F	C	O	I	B	D
P	0	8	4	2	0	6	8	0	4	8	6	2	4	0
S	9	0	4	2	0	8	0	0	4	0	2	2	2	0
L	6	9	0	8	0	4	0	0	4	0	2	2	4	0
A	4	5	6	0	6	0	0	0	4	2	2	2	4	0
K	4	-1	-1	-1	0	8	4	0	4	0	2	2	6	8
G	3	-1	-1	-1	9	0	4	2	4	0	2	2	6	4
T	9	-1	-1	-1	9	9	0	8	4	6	6	2	8	6
U	2	-1	-1	-1	7	7	9	0	4	2	2	2	6	4
F	2	2	2	2	2	2	2	2	0	4	4	4	4	2
C	5	-1	3	3	2	2	5	7	2	0	8	2	0	4
O	6	2	5	3	4	2	8	6	2	9	0	4	0	8
I	2	2	2	2	2	2	2	2	2	2	2	0	4	2
B	3	1	4	3	6	5	9	8	6	-1	-1	4	0	8
D	-1	-1	-1	-1	7	4	7	5	2	4	9	2	9	0

the diagonal values between same departments are "U-0". For all of the U-"Unimportant" relationship definitions, there does not exist any reason associated, because unimportant relation does not require any reason of activity. The definitions of the activities are given in Table 3.5 and the reasons are explained in Table 3.6 for the values used in Table 3.4.

Figure 3.4 states the space relationship diagram (SRD) for the "Platforms" department. The space relationship diagram is arranged according to Table 3.4. In SRD, the relationship reason corresponding to relation degrees are shown with legend. Relation U states that, there must be no lines between these departments.

3.3 Facility Layout Improvement Algorithm

We developed an improvement algorithm for the facility layout problem in the integrated model. This heuristic algorithm is developed by considering all of the parameters of the departments and the intended consequences.

Table 3.4: Activity Relationship Chart

Relationship Costs → Relationships ↓	P	S	L	A	K	G	T	U	F	C	O	I	B	D
P	U-0	2	3	4	7	7	9	8	3	1	1	2	3	1
S	A/1	U-0	2	3	1	1	1	1	3	1	1	2	1	1
L	E/1	E/1	U-0	9	1	1	1	1	3	1	1	2	6	2
A	I/4	I/5	O/1	U-0	1	1	1	1	3	1	1	2	4	2
K	U	U	U	U	U-0	7	8	9	3	1	1	2	8	8
G	U	U	U	U	A/1	U-0	8	9	3	1	1	2	4	7
T	A/1	U	U	U	I/1	I/3	U-0	8	3	1	1	2	9	8
U	U	U	U	U	I/1	I/4	A/1	U-0	3	1	1	2	8	7
F	O/4	O/4	O/4	O/4	O/4	O/4	O/4	O/4	U-0	3	3	2	4	2
C	I/5	U	O/5	I/5	O/5	I/5	A/5	I/5	O/4	U-0	1	2	4	6
O	E/3	U	I/2	O/2	U	U	I/2	O/2	O/4	A/1	U-0	2	1	9
I	O/5	O/5	O/5	O/5	O/5	O/5	O/5	O/5	O/4	I/4	O/5	U-0	4	1
B	O/4	U	I/1	O/1	E/1	U	A/1	E/1	O/4	U	U	O/4	U-0	9
D	U	U	U	U	I/1	U	E/4	I/4	O/4	E/4	A/1	U	A/1	U-0

Table 3.5: Activity Relationship Chart-Definitions

Rating	Definition
A	Absolutely necessary
E	Especially important
I	Important
O	Ordinary closeness OK
U	Unimportant
X	Undesirable

Table 3.6: Activity Relationship Chart-Reasons

Code	Reason
1	Flow of materials
2	Ease of supervision
3	Common personnel
4	Contact necessary
5	Convenience

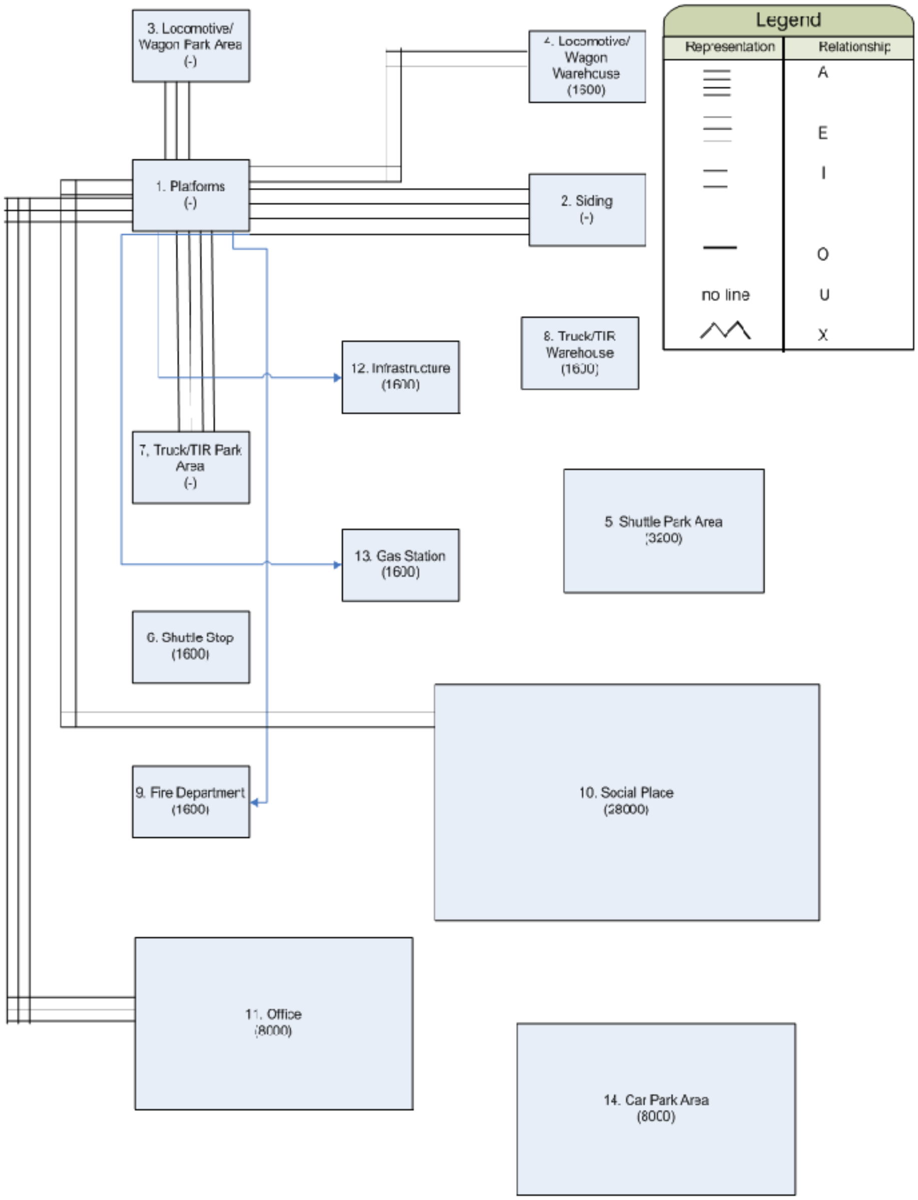

Figure 3.4: Space Relationship Diagram

3.3.1 Pseudocode and Flowchart

In the literature, most of the improvement algorithms permit usually two, or rarely three, activities to be interchanged in the layout, while satisfying all of the conditions and the rules [17]. The basic pseudocode of an algorithm for improving a given layout plan by exchanging the places for two activities is as follows:

```
Method TWODEPARTMENTS
    REPEAT
        CHOOSE a pair of activities
        ESTIMATE the effect of exchanging them
        EXCHANGE if the effect is to reduce total cost
        CHECK to be sure that the new layout is better
    UNTIL no more improvements are possible
END TWODEPARTMENTS
```

In this pseudocode, activities refer to departments. In the step to `CHOOSE` departments, selecting departments depends on the characteristics between these departments. The most important characteristics are, either they have the same area size, or they are adjacent, i.e., share a common boundary. These two properties are the main points for selecting two departments to be exchanged. If the two departments have the same area size, then the point of being adjacent is no more important as the exchange will affect only these two departments. If they do not have the same area size but they are adjacent, then these departments are also swapped. But the resulting shapes of the exchanged departments must satisfy contiguity and connectedness rules. Contiguity rule is defined as follows: if an activity is represented by more than one unit area square, every unit area square representing the activity must share at least one edge with at least one other unit area square representing the activity [17]. According to connectedness rule, the perimeter of an activity must be a single closed loop that is always in contact with some edges of some unit area square representing this activity. In order to satisfy these two rules, departments having different areas must be swapped in a way that the smaller department must have the new place in its symmetric according to the corner point of the smaller department, such that this corner point is the shared point which is located closer to the middle point of the shared common boundary between two departments. This method is explained in detail in Figures 3.5 and

3.6. Figure 3.5 illustrates the true swap operation between two departments having different areas. As seen in this figure, smaller sized department is exchanged to its symmetric place, based on its up-right corner point. This point is chosen as center of symmetry, because this point is closer to the middle of shared boundary than up-left point of department B. Figure 3.6 shows infeasible result of swap operation. This exchange is not allowed, because department A cannot satisfy connectedness rule.

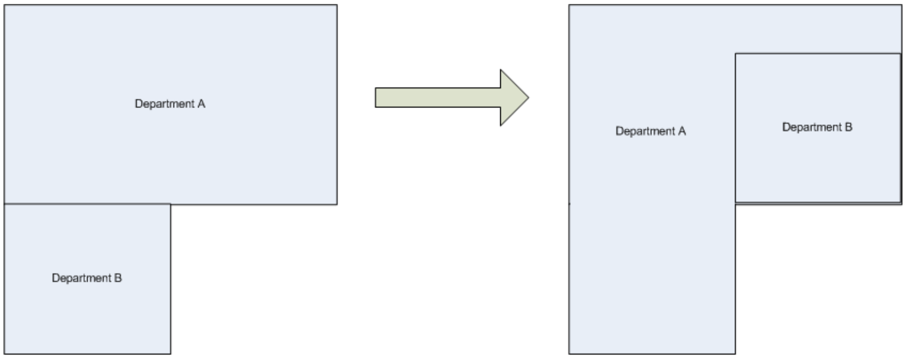

Figure 3.5: Correct swap of different sized departments

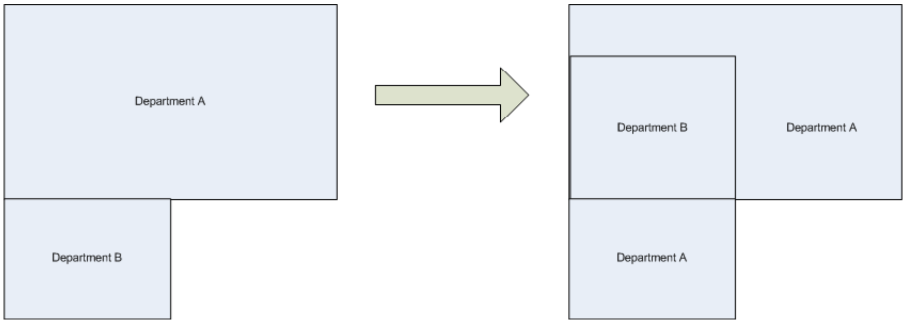

Figure 3.6: Incorrect swap of different sized departments

With `ESTIMATE` step, before updating all departments in the layout, a preliminary study is performed to calculate swapping of the previously selected two departments. This calculation operation requires a scoring function. In our improvement algorithm, seven different scoring functions, based on different aspects, such as relation, cost and distance, are developed. The scoring functions are widely explained in Subsection 3.3.2. If the result of exchanging the departments improves the score of the layout, then the algorithm passes to `EXCHANGE` step, and the place of two departments are swapped. Otherwise, another pair of activities is chosen, until chosen activities improve the score of the layout. With the selection of improving departments, these departments are swapped and the new layout is accepted as the new main layout. In `CHECK` step, the new main layout is again analyzed if it is improving and it is really feasible. The selection of two departments and exchanging are performed in an iterative way, until all of the two-department pairings are evaluated.

This algorithm is run for each initial feasible layout. Several initial layouts are prepared consulting IMPL in order to ensure feasibility. Each initial layout is tried to be improved according to seven different scoring options, and the results, based on each initial layout, and scoring option can be analyzed. Figure 3.7 shows the flowchart of the algorithm.

In the flowchart, all of the shapes are defined for different purposes. Elliptical is for start/stop, rectangular is for process/instruction, paralleogram is for input/output and deltoid is for question/decision operations. Facility layout improvement algorithm is designed in C programming language. The runs for several instances are implemented in Visual C++ 6.0 platform [11]. In the algorithm, there are six input functions (third step in flowchart) which read the data, as their name indicates, from file:

1. ReadInitialLayout
2. ReadDepartmentIndexNameDimension
3. ReadDepartmentFlow
4. ReadDepartmentFlowCostUnitDistance
5. ReadDepartmentCostUnitDistanceUnitLoad
6. ReadDepartmentRelationship

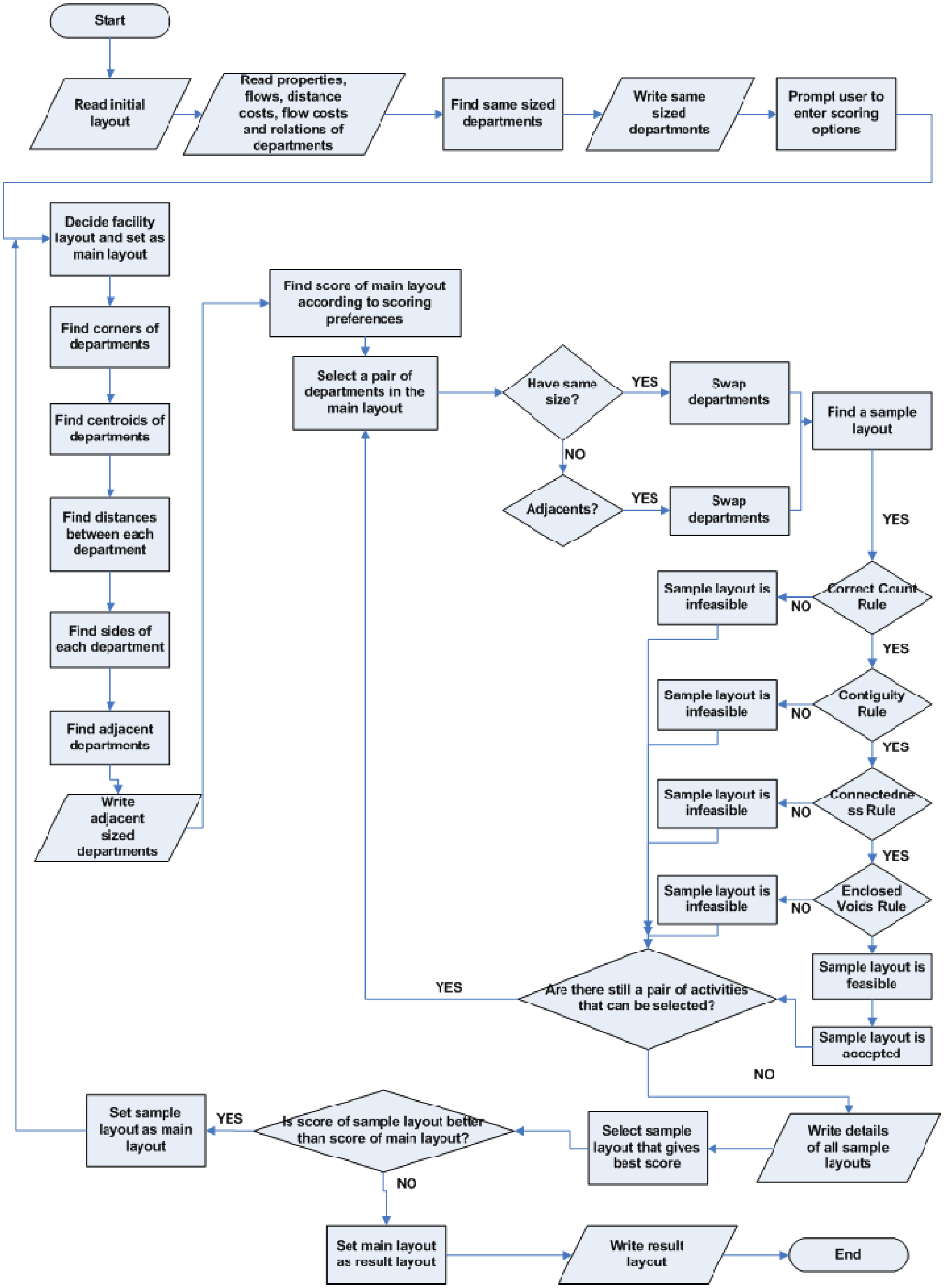

Figure 3.7: Flowchart of Improvement Algorithm

Table 3.7: Relationships and Values

Relation	Value
A	64
E	16
I	4
O	1
U	0
X	-1024

In the ReadDepartmentRelationship function, all of the relationship types are converted to respective scalar values. According to ARC [39], Table 3.7 shows the relationship types and values.

The three output functions all write the data, as their name indicates, to file:

1. WriteOutputLayout
2. WriteSameSizeDepts
3. WriteAdjDepts

Other six functions are coded to analyze the layout and properties, such as corners, sides, etc. of the departments in this layout:

FindSameSizeDepts first calculates the area of each department, then marks the departments that have the same area, then calls WriteSameSizeDepts function to show the user which are the same sized departments.

FindDeptsCorners finds x and y coordinates of each point in each department and keeps these data in struct data type for properties of each department.

FindDeptsCentroids finds x and y coordinates of the centroid of each department. The centroid of a quadrangle is the center of masses of the quadrangle, and it is the point where this quadrangle is stable and in equilibrium. The centroid is a property of volume in space, but, because the layout is defined as planar, it is a property of the area.

FindDistancesbwDepts finds absolute value rectilinear (Manhattan) distance between centroid of departments. In the literature, many algorithms such as CORELAP [33], CRAFT [3], COFAD [48, 49] and ALDEP [45] calculate rectilinear distance. Rectilinear distance is the distance between two points measured along at right axes, i.e., addition of absolute difference of x coordinates and y coordinates of two points.

FindDeptsSides finds x and y coordinates of each side of each department. This function gets help from FindDeptsCorners function because by using each corner point's coordinates, it calculates another coordinate for each side. For instance, for the upside of a quadrangle, x coordinate of side is the x coordinate of left-up corner or right-up corner, and y coordinate of the side is the y coordinate of respective corner points of this side.

FindAdjacentDepts finds if two departments are adjacent by evaluating their sides. Adjacent means that two departments share at least one common boundary. This function invokes WriteAdjDepts function to explain the user which departments are adjacent.

3.3.2 Scoring Options

User can select the desired scoring option from seven alternatives. All of these alternatives are illustrated in Table 3.8 [17].

There does not exist a scoring sub-option for distance-weighted adjacency-based scoring, so it is illustrated as -. For each of the three scoring main-options, functions AdjacencyScore, DistanceScore and DistanceAdjacencyScore are defined in the algorithm.

Table 3.8: Scoring Options

Scoring main-option	**Scoring sub-option**
adjacency-based	by weight, by flow, by normalized flow, by normalized (-)/(+) flow
distance-based	by flow, by cost of flow
distance-weighted adjacency-based	-

Adjacency-based scoring by weight

In this scoring option, the relationship scalar values between 14 departments are added, and algorithm tries to maximize this sum:

Max

$$z = \sum_{i \in S} \sum_{j \in S} r_{i,j} * x_{i,j}, \tag{3.1}$$

where

S: the set of departments in the station,

$x_{i,j}$: 1 if departments i and j are adjacent, 0 otherwise,

$r_{i,j}$: the relationship value between departments i and j.

Adjacency-based scoring by flow

In this scoring function, the flows between adjacent departments are added and tried to be maximized:

Max

$$z = \sum_{i \in S} \sum_{j \in S} f_{i,j} * x_{i,j}, \tag{3.2}$$

where

S: the set of departments in the station,

$x_{i,j}$: 1 if departments i and j are adjacent, 0 otherwise,

$f_{i,j}$: the flow value between departments i and j.

Adjacency-based scoring by normalized flow

The flow values between adjacent departments are summed, and it is normalized by dividing this sum by the total flow between all departments:

Max

$$z = \sum_{i \in S} \sum_{j \in S} f_{i,j} * x_{i,j} / \sum_{i \in S} \sum_{j \in S} f_{i,j}, \tag{3.3}$$

where

S: the set of departments in the station,

$x_{i,j}$: 1 if departments i and j are adjacent, 0 otherwise,

$f_{i,j}$: the flow value between departments i and j.

Adjacency-based scoring by normalized (-)/(+) flow

In this scoring preference, first, the positive flow values between adjacent departments are summed, and also, the negative flow values between unadjacent departments are added. The difference between these values is divided to the difference of the total positive flows and the total negative flows:

Max

$$z = \{ \sum_{(i,j) \in F} f_{i,j} * x_{i,j} - \sum_{(i,j) \in F'} f_{i,j} * (1 - x_{i,j}) \} / \{ \sum_{(i,j) \in F} f_{i,j} - \sum_{(i,j) \in F'} f_{i,j} \}, \tag{3.4}$$

where

F: the set of department pairs with positive flow values,

F': the set of department pairs with negative flow values,

$x_{i,j}$: 1 if departments i and j are adjacent, 0 otherwise,

$f_{i,j}$: flow value between departments i and j.

Distance-based scoring by flow

The flow values between adjacent departments are added by multiplying with the distance and the cost/unit distance and the load. In addition, in the distance-based scoring types, minimum score is better:

Min

$$z = \sum_{i \in S} \sum_{j \in S} f_{i,j} * d_{i,j} * c_{i,j}, \tag{3.5}$$

where

S: set of departments in the station,

$f_{i,j}$: flow value between departments i and j,

$d_{i,j}$: distance between departments i and j,

$c_{i,j}$: cost/unit distance and load distance between departments i and j.

Distance-based scoring by cost of flow

The major difference between this scoring option and the distance-based scoring by flow is that in the latter, the distance is multiplied by both the flow and the cost/unit distance and the load, but here, the distance is multiplied by the cost of flow/unit distance only:

Min

$$z = \sum_{i \in S} \sum_{j \in S} fc_{i,j} * d_{i,j}, \tag{3.6}$$

where

S: set of departments in the station,

$fc_{i,j}$: cost of flow/unit distance between departments i and j,

$d_{i,j}$: distance between departments i and j.

Distance-weighted adjacency based scoring

In this scoring function, scalar values of relationships between departments are multiplied by distances:

Min

$$z = \sum_{i \in S} \sum_{j \in S} r_{i,j} * d_{i,j}, \tag{3.7}$$

where

S: set of departments in the station,

$r_{i,j}$: relationship numeric value between departments i and j,

$d_{i,j}$: distance between departments i and j.

SelectPlace function takes two-dimensional array of facility layout, and is defined to partition all of the departments into pairs of two. When partitioning into two groups, two criteria are followed; either the two departments have the same area, or the two departments are adjacent. If both of these criteria are not satisfied, then a pair of departments cannot be considered. This function prepares two sets of department pairings; the first set is for the same sized departments, while the second set is for adjacent departments, although they do not have the same area. After these sets are identified, SwapSameSizeDepts function is called for each pairing in the first set, while the function SwapAdjacentDepts is called for the second set. SwapSameSizeDepts function exchanges the places of two departments that have the same area. For example, let us assume that department A has 4 unit squares of area and is located in up-leftmost section of facility layout, and department B has also 4 unit squares of area and is located in down-rightmost section. SwapSameSizeDepts function changes the location of these departments, resulting in department A to be located in down-rightmost section, while B is located at up-leftmost section, without affecting four unit squares of area that both departments have. The function uses coordinates of corner points of each department for this exchange operation. The 4 unit squared area represents more than one block area, i.e., may be 4 unit blocks. Swapping two departments require exchanging all of the unit blocks at the same time to maintain feasibility after performing the operation. Function SwapAdjacentDepts is constructed for the departments that do not have the same area size, but that are adjacent. Since the two departments do not have the same size, the new location of the small sized department is a location in the innerside of the other department that has a larger area, while the new location of the large-sized department fills the old location of the small-sized department. The correct exchange operation should maintain the feasibility after applying this operation, so the swap operation must be performed as shown previously in Figure 3.5. The two departments must be still connected and satisfy contiguity after swapping. The final layout from these two functions is accepted as the new layout.

After pairing of two departments are selected and swapped as explained, all of the new layouts are subject to four different control rules, to satisfy the feasibility of the new layout. The new layout is first subject to correct count rule function. This function checks if the area of all of the departments are still the same with the area values, calculated in FindSameSizeDepts function, before the exchange operation. If this rule is satisfied, then the layout is controlled by contiguity rule. Contiguity rule is satisfied if for all of the departments, every unit area square representing each department shares at least one edge with at least one another unit area square representing this department. For instance, if a department has five unit blocks, and four unit blocks share edge with each other, while one unit block is far away from them, so as it does not share any edge, then this rule is violated. If contiguity rule is satisfied, then the next rule is connectedness rule. The connectedness rule is defined as the perimeter of each department must be a single closed loop that is always in contact with some edge of some unit area square representing the departments. Contiguity and connectedness rules are very close to each other in terms of definitions, but a department can satisfy contiguity rule, while violating connectedness rule. For example, a department with four unit blocks satisfies the contiguity rule, if two blocks share one edge with each other and other two blocks share one edge with each other, i.e., two separate pair of blocks do not share any edge. But this status violates connectedness rule. Hence, connectedness rule is required for feasibility. Last rule is enclosed voids. In this rule, no department shape can contain an enclosed void, i.e., cannot contain any space inside that is not a unit block. If one of these four rules is not satisfied, then this new layout is not feasible, and cannot be accepted as a sample layout, i.e., to be feasible, all rules must be satisfied. The sample departments A, B and C for three rules are shown in Figure 3.8. Each department has several unit blocks. Department A violates contiguity rule, because one block does not share any edge with others. Department B satisfies the contiguity rule, but violates connectedness rule. Department C violates enclosed voids rule because it has a middle blank unit block that is not part of the department.

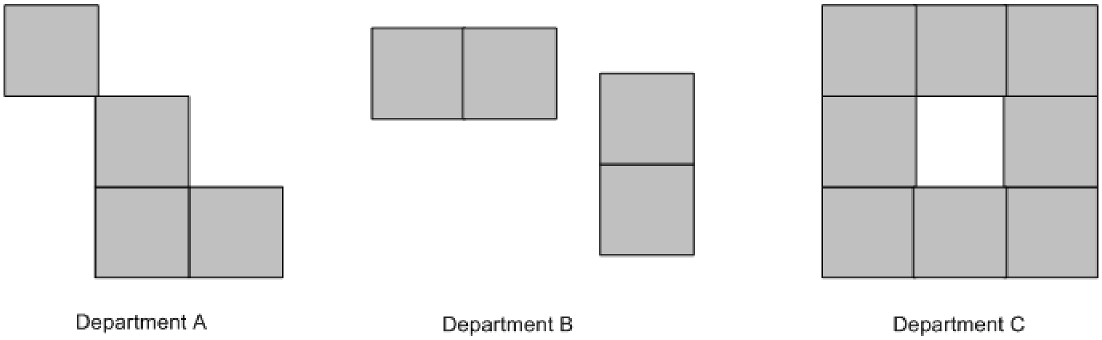

Figure 3.8: Schemas for contiguity, connectedness and enclosed voids rules

The feasible sample layout's score is calculated according to the user preference. In SelectPlace function, from all of the sample layouts, the layout giving the best score (minimum in distance-based and maximum in adjacency-based scoring) is saved with the layout structure and its score. If this score is better than that of the main layout (layout in the previous loop, initial layout for loop 1), this sample layout is accepted as the new main layout, and the algorithm will start a new loop, with FindDeptsCorners function. The loop continues until a sample layout is not better than the main layout. At this point, the run ends, and the main layout, that is the layout of the previous loop, is selected as the final layout. The score of the final layout is calculated, and the layout is written on to the file with WriteOutputLayout function. The results will be explained in Sections 5.2 and 5.6.

Chapter 4

TRAIN SCHEDULING PROBLEM AND MATHEMATICAL MODEL

4.1 Data for Train Scheduling Problem

In this thesis, with the help of Istanbul Metropolitan Planning-Department of Logistics (IMPL), we obtained data about facility layout planning and train scheduling problems applicable according to Ro-La and Marmaray systems. For train scheduling problem, we studied currently used most common three different Ro-La systems in a detailed way. These are; Oekombi (OE), Modalohr (MO) and Eurotunnel (EU). The parameters such as safety time interval between two consecutive departures, start/finish/clearance time of daily operations, platform structures, railroad distance, railroad width and technical life/cost/gauge of locomotive were set since they are not specific to each system. For the trains in each system, train speed, maximum number of wagons in a train, wagon dimensions/capacity, train length and maximum number of trucks/TIRs in a train data were obtained. On the other hand, for stations, transfer duration for a train and loading/unloading time of a train data were gathered. As operational (variable) costs, data about transportation/haulage/maintenance and environmental costs were obtained from systems. As fixed costs, data about locomotive, wagon and land costs were gathered. These data were obtained from IMPL, General Directorate of Highways of Turkish Republic (GDHTR), SRTR, Turkish Railway Machines Industry Inc. (TRMI), Turkish Locomotive and Engine Industry Inc. (TLEI), OE, MO and EU.

The three systems, OE, MO and EU, have fixed parameters and parameters specific to each system. The fixed parameters are shown in Table 4.1. In this table, safety time interval is the required minimum time between two consecutive departures of trains. In rail transportation, this time is the mandatory time gap between two trains to create a safe distance between two trains. For this parameter, 5, 6, ..., 12 minutes are used in the current train systems and all of these seven time intervals are taken into account. For instance, if safety time interval is 5 minutes, then if the first train departs at 00:00, then the second train must depart exactly at 00:05. The second train cannot depart earlier than 00:05 and also, it is not desired to depart after 00:05, because in Marmaray system, the greater the number of departures gets, the greater the number of trucks/TIRs transported is to meet excess demand with a limited capacity as much as possible. Marmaray is planned for passenger transportation for 18 hours/day and at other times, that is between 00:00-06:00, it is planned for freight transportation. Therefore, in Marmaray system, earliest possible departure time is 00:00 and the latest arrival time of any train must be 06:00 at the latest. The clearance time is the interval, at the end of total operation time, when all of the processes such as loading/unloading are not permitted at the station. During the clearance time, required controls, investigations, etc. can be performed. Since, in Marmaray system, the goal is to meet excess demand as much as possible, in order to depart more trains, the clearance time should be short. So, we did not consider clearance time and took its duration as 0. Two platform structures are considered, linear and circular, as explained in Section 3.1. The distance of Ro-La transportation in Marmaray system is 231 km, between Tekirdağ (Çerkezköy) on the European side and Kocaeli (Köseköy) on the Asian side. According to the information from SRTR, the required locomotives and wagons in Marmaray system will be provided by MMI. The type of locomotives will be DE 33000, with diesel engine, having a life of 35 years and it will cost 4,000,000 YTL.

Although EU system is similar to OE system in terms of transfer, loading/unloading times, it is different in many aspects, such as loading/unloading type, speed of train (locomotive). Generally, each one of the three systems is different in terms of train speed, transfer/unloading/loading durations, number/type/capacity of wagons, number of trucks/TIRs and variable costs. In Table 4.2, all of the parameters varying according to the system used (with their units) are explained. These parameters are specific to each system, OE, MO and EU. Transfer duration depends on the platform structure and the length of train. For instance, we can consider the linear platform and OE system. Train length is 550 m and

Table 4.1: Fixed Parameters in Marmaray System

Definition	**Value**
Safety time interval	5, 6, 7, 8, 9, 10, 12 mins
System operation start time	00:00
Clearance time at end of system operation	not applied
System operation end time	06:00
Platform structures	linear, circular
Railroad length	231 km
Railroad width	1,453 mm
Technical life of locomotive	35 years
Cost of locomotive	4,000,000 YTL
Dimensions of locomotive	260*1200*300 cm (width*length*height)
Cost of land Kocaeli, Köseköy	158 YTL / m^2
Cost of land Tekirdağ, Çerkezköy	200 YTL / m^2

the total length of C+Y+A in Figure 3.1 is 1,650 m, because each part, C, Y or A, equals the train length. Also, the length of siding railways and the platform must be at least as a train length. In total, the distance a train requires until its arrival to the platform for operations is 5*550=2,750 m, approximately 3,000 m. The speed of the train inside the station is 10 km/h, so the transfer duration is 18 mins. All of the transfer durations for other platform structures and systems are calculated in this way. Also, during the transfer, personnel/locomotive/wagon change and documents control/planning operations can be performed. Unloading operation is the transfer of trucks/TIRs from the train wagon to the road. Loading operation is the reverse. Systems OE and MO are very different in types of loading and unloading. In OE, truck is loaded to wagon in a linear way, TIR is loaded with tractor and trailer together. In MO, with special equipments on wagon and rail, TIR goes in a crosswise direction, making an angle, and enters to wagon equipment. When the trailer is locked to this equipment, tractor and trailer detaches, then the hydraulic equipment rotates, reduces the angle to 0, so this wagon will carry only the trailer. Also, the separated tractor will be loaded with an angle on another type of wagon and this wagon carries two tractors. In OE and EU, TIR is loaded without separation, so a wagon can carry two trucks or one TIR. But in MO, tractor and trailer are separated and loaded to

Table 4.2: System Specific Parameters in Marmaray System

System	Oekombi	Modalohr	Eurotunnel
Transfer duration (in linear platform, min)	18	24	21
Transfer duration (in circular platform, min)	15	18	15
Unloading duration (min)	20	40	20
Loading duration (min)	30	40	30
Train speed (km/hour)	100	120	140
Maximum number of wagons pulled by locomotive	22	40	30
Type of wagon	1 type for	1^{st} type for 2 TIR tractors	1 type for
	truck and/or TIR	2^{nd} type for 1 TIR trailer	truck and/or TIR
		3^{rd} type for 2 trucks	
Capacity of wagon (ton)	48.4	1^{st} type, 6	50
		2^{nd} type 38	
		3^{rd} type 40	
Length of train (m)	550	750	700
Maximum number of trucks carried in one train travel	44	40	36
Maximum number of TIRs carried in one train travel	22	26	18
Transportation cost (/km) (YTL)	2	0.3	2
Haulage cost (/km) (YTL)	3	3	3
Maintenance cost (/km) (YTL)	0.5	1.3	0.5

different wagons, so the ratio of two trucks to one TIR cannot be stated. Train length affects the speed, curve properties in the station and the number of trucks/TIRs carried. Transportation and maintenance costs are related to locomotive and wagon, but haulage cost is related to the freight transported.

These fixed and specific parameters are generally used when constructing train scheduling mathematical model, facility layout improvement algorithms and getting results from these two problems.

4.2 Problem Description

In the preliminary analysis of the train scheduling problem, sample plans (schedules) were prepared. As data of these plans, systems OE, MO and EU and values t=5, 6, 7, 8, 9, 10 and 12, for safety time interval between consecutive departures in the same station, were considered.

In order to illustrate the way how the schemas were prepared, let us consider an example with system OE and t=10 min. We can choose Çerkezköy station as S1 and Köseköy as S2. General guidelines in sample plans are as follows; a train departing from S1 can also depart from S2, if time permits. Vice versa is also true, if a train departs from S2, it can also depart from S1. The general constraint is that a train can depart at 00:00 at the earliest and can arrive 06:00 at the latest. The major reason to prepare sample plans for every system, safety time interval and platform structure, is to find out the departure time of trains at S1, which can depart again from S2. Analyzing these arrival times, the number of trains that departs second time can be determined. The value from division of total six hour period (operation time in one day) to safety time interval gives the number of departures from one station per day. Using the number of departures, we can estimate the number of locomotives. In OE, loading duration is 30 min, so with t=10, loading duration becomes three periods. This means that, after three periods of loading operation, such as periods 1-2-3 in S1 at platform(P) 1, the first train departs at period 3. Because the departure time is an instantaneous operation, it does not take any period, so it is equal to the last period of respective loading operation. The last period of loading operation is 3, and the train departs at period 3. At one time, only one train can depart from one station, so the second train, which departs from S1-P2 (station 1, platform 2), is subject to loading operation at periods 2-3-4 and departs at period 4. Period 3 means 00:00 and period 4 means 00:10. The third train performs loading at periods 3-4-5 and departs at 5 from S1-P3. Since period 4 (because the first train departs at period 3 from P1) platform 1 is idle. So, instead of defining P4, the fourth train can be loaded at P1 and departs at period 6 from P1. In the same way, the third train departs from P3 at period 5, then the fourth train departs from P1 at period 6. From these data, it can be stated that, if loading duration is 30 minutes, i.e., three periods, then the station has three platforms. The loading duration (in terms of periods) gives the number of parallel platforms in a station. In the same platform, with an increment of loading duration (in periods), the train with additional number of loading duration (in periods) can start its loading operation. For instance, in P1, the first train starts loading at period 1, the fourth train starts loading at period 4, the seventh train starts loading at period 7, etc. This continues until the time of arrival of a train to S1 from S2. Since the arriving train has the strongest precedence, this train must enter the platform immediately and makes the platform busy. In OE, train speed is 100 km/h, so a train travels 231 km Marmaray railroad line in 138.6 mins (14 periods). In this situation, the first train can depart from S1 at period 3 at the earliest, travels in 14 periods and arrives to S2 at period 17. Vice versa is also true for other direction of travel. So, the time limit of first-time loaded trains can be found as period 17. Other train departing at period 4 arrives other station at period 18. In the same manner, for first-time loaded trains departing from S1 and arriving to S2, the time range is $FirstArrivalT$. For instance, after the earliest train departs from S1, it arrives to S2 at period 17 and it is subject to transfer (2 periods), unloading (2 periods) and loading (3 periods) operations successively at S2. Then, if this train can arrive to S1 until 06:00, it is allowed to depart from S2 at period 24 (17+2+2+3).

When a train reaches to a platform, first unloading, then loading operation is performed. So, the train stays at the platform for the duration of unloading+loading durations (2+3=5 periods) and during this time, this platform is busy, i.e., no other train can enter this platform. The most important operational purpose of Marmaray project is to carry the most possible number of trucks/TIRs. In order to achieve this, the most possible number of departures must occur, so, at each period, a train must depart from the station. Because, total occupation time (5 periods) of a train in a platform is longer than only loading time (3 periods), additional platforms (except original platforms) have to be introduced into the station. There are two different sets of trains performed in the station at the same time; one set consists of all the trains which are subject to only loading operation and the other set consists of the trains which are subject to both unloading and loading operations. In order to let these two sets to operate successfully, additional platforms have to exist, otherwise, there would be conflicts. For example, if a train is loaded at the first time for 3 periods, the other arriving train can cause conflict because an idle platform cannot be found for it to unload and load for 5 periods. We analyzed that, in all of the sample plans, the number of additional platforms is at least as the number of original platforms in a station. For instance, if there are already three original platforms, then additional three platforms are enough to ensure that there would be no conflict and all of the trains will find an idle platform without any standby in a station. No standby means that a train departs at each period. An additional platform is used only when none of the original platforms is idle. The major difference between original and additional platforms is that a train departs second time in an original platform, while it does not depart second time in an additional platform. Furthermore, the last train in the system must arrive to target station no later than 06:00. If t=10 minutes, 06:00 is the 37^{th} period and the travel time is 14 periods. Then the last train must depart at period 37-14=23 at the latest.

Table 4.3 shows the data prepared for each 3 systems, 9 safety time intervals and 2 platform structures, making different 3*9*2=54 schemas. The explanation of column abbreviations are as follows:

1. S: system
2. P: platform structure; L for linear and C for circular
3. I: instance number
4. t: safety time interval
5. L: loading duration
6. UL: unloading duration
7. V: transfer duration
8. T: travel duration
9. ST: start time of daily operations
10. FT: end time of daily operations
11. OP: number of original platforms
12. AP: number of additional platforms
13. W: number of trains that can depart second time in two stations in a day
14. FAS: start time of $FirstArrivalT$ time range
15. FAE: end time of $FirstArrivalT$ time range
16. SAS: start time of $SecondArrivalT$ time range

17. SAE: end time of $SecondArrivalT$ time range
18. TAS: start time of $ThirdArrivalT$ time range
19. TAE: end time of $ThirdArrivalT$ time range

The data for L, UL, V, T, ST and FT are in terms of periods. All of the duration data in the table are expressed in terms of periods. In order to prevent critical problems, such as conflict, insensibility, etc., ceiling is applied. For instance, in an instance where L=30 and t=4, L is 8 periods. Start time of loading operations is also the start time of time range Ti in mathematical model for train scheduling. In an instance where L=30 and t=3, start time is 23:30 (period 1). Next time is 23:33 (period 2). All of the operation time is expressed in terms of periods in this way. So, ST=00:00 can be shown with period 10. The trains that depart from a station can be partitioned into groups, according to their loading order. The first group of trains is the group which is loaded elementarily in all of the platforms in a station. Other groups are defined in the same manner. It is required to differentiate group of trains as groups, because the first group of trains start unloading operation immediately after arrival and transfer, but the second group of trains cannot start unloading immediately after, because they must wait for the first group of trains to leave the platform. Because, the first group of trains occupy platform for total of unloading and loading duration, the second group must wait for an additional loading duration to enter the platform. In instance 1, the first train of the first group arrives at period 57, and the last train of the first group arrives at period 62. This additional waiting of loading duration is applied to find start and end times of three time ranges. At most the third group of trains exist in all of the instances, so no other group of trains are required to be defined.

Table 4.3: Data of Sample Plans

S	**P**	**I**	**t**	**L**	**UL**	**V**	**T**	**ST**	**FT**	**OP**	**AP**	**W**	**FAS**	**FAE**	**SAS**	**SAE**	**TAS**	**TAE**
OE	L	1	3	10	7	6	47	10	84	10	10	10	57	62	-	-	-	-
OE	L	2	4	8	5	5	35	8	64	8	8	8	43	46	-	-	-	-
OE	L	3	5	6	4	4	28	6	51	6	6	4	34	37	-	-	-	-
OE	L	4	6	5	4	3	24	5	42	5	5	4	29	30	-	-	-	-

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Table 4.3 – continued from previous page

S	P	I	t	L	UL	V	T	ST	FT	OP	AP	W	FAS	FAE	SAS	SAE	TAS	TAE
OE	L	5	7	5	3	3	20	5	37	5	5	4	25	26	-	-	-	-
OE	L	6	8	4	3	3	18	4	32	4	4	2	22	22	-	-	-	-
OE	L	7	9	4	3	2	16	4	29	4	4	2	20	20	-	-	-	-
OE	L	8	10	3	2	2	14	3	26	3	3	6	17	19	-	-	-	-
OE	C	9	12	3	2	2	12	3	22	3	3	2	15	15	-	-	-	-
OE	C	10	3	10	7	5	47	10	84	10	10	12	57	61	-	-	-	-
OE	C	11	4	8	5	4	35	8	64	8	8	10	43	47	-	-	-	-
OE	C	12	5	6	4	3	28	6	51	6	6	10	34	38	-	-	-	-
OE	C	13	6	5	4	3	24	5	42	5	5	4	29	30	-	-	-	-
OE	C	14	7	5	3	3	20	5	37	5	5	4	25	26	-	-	-	-
OE	C	15	8	4	3	2	18	4	32	4	4	4	22	23	-	-	-	-
OE	C	16	9	4	3	2	16	4	29	4	4	2	20	20	-	-	-	-
OE	C	16	10	3	2	2	14	3	26	3	3	6	17	19	-	-	-	-
OE	C	17	10	3	2	2	14	3	26	3	3	6	17	19	-	-	-	-
OE	C	18	12	3	2	2	12	3	22	3	3	2	15	15	-	-	-	-
MO	L	19	3	14	14	8	39	14	96	14	15	16	53	60	-	-	-	-
MO	L	20	4	10	10	6	29	10	72	10	11	16	39	46	-	-	-	-
MO	L	21	5	8	8	5	24	8	57	8	9	6	32	34	-	-	-	-
MO	L	22	6	7	7	4	20	7	48	7	8	8	27	30	-	-	-	-
MO	L	23	7	6	6	4	17	6	41	6	7	6	23	25	-	-	-	-
MO	L	24	8	5	5	3	15	5	36	5	6	8	20	23	-	-	-	-
MO	L	25	9	5	5	3	13	5	33	5	6	6	18	20	-	-	-	-
MO	L	26	10	4	4	3	12	4	29	4	5	6	16	18	-	-	-	-
MO	L	27	12	4	4	2	10	4	25	4	4	4	14	15	-	-	-	-
MO	C	28	3	14	14	6	39	14	96	14	15	20	53	62	-	-	-	-
MO	C	29	4	10	10	5	29	10	72	10	11	18	39	47	-	-	-	-
MO	C	30	5	8	8	4	24	8	57	8	9	8	32	35	-	-	-	-
MO	C	31	6	7	7	3	20	7	48	7	8	10	27	31	-	-	-	-
MO	C	32	7	6	6	3	17	6	41	6	7	8	23	26	-	-	-	-
MO	C	33	8	5	5	3	15	5	36	5	6	8	20	23	-	-	-	-
MO	C	34	9	5	5	2	13	5	33	5	6	8	18	21	-	-	-	-
MO	C	35	10	4	4	2	12	4	29	4	5	8	16	19	-	-	-	-
MO	L	36	12	4	4	2	10	4	25	4	4	4	14	15	-	-	-	-
EU	L	37	3	10	7	7	33	10	98	10	11	40	43	52	53	62	-	-
EU	L	38	4	8	5	6	25	8	74	8	9	32	33	40	41	48	-	-
EU	L	39	5	6	4	5	20	6	59	6	9	24	26	31	32	37	-	-
EU	L	40	6	5	4	4	17	5	49	5	9	20	22	26	27	31	-	-

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Table 4.3 – continued from previous page

S	**P**	**I**	**t**	**L**	**UL**	**V**	**T**	**ST**	**FT**	**OP**	**AP**	**W**	**FAS**	**FAE**	**SAS**	**SAE**	**TAS**	**TAE**
EU	L	41	7	5	3	3	15	5	42	5	7	18	20	24	25	28	-	-
EU	L	42	8	4	3	3	13	4	37	4	7	16	17	20	21	24	-	-
EU	L	43	9	4	3	3	11	4	34	4	7	14	15	18	19	21	-	-
EU	L	44	10	3	2	3	10	3	30	3	5	12	13	15	16	18	-	-
EU	L	45	12	3	2	2	9	3	25	3	3	10	12	14	15	16	-	-
EU	C	46	3	10	7	5	33	10	98	10	13	40	43	52	53	62	-	-
EU	C	47	4	8	5	4	25	8	74	8	9	32	33	40	41	48	-	-
EU	C	48	5	6	4	3	20	6	59	6	8	26	26	31	32	37	38	38
EU	C	49	6	5	4	3	17	5	49	5	9	20	22	26	27	31	-	-
EU	C	50	7	5	3	3	15	5	42	5	7	18	20	24	25	28	-	-
EU	C	51	8	4	3	2	13	4	37	4	7	16	17	20	21	24	-	-
EU	C	52	9	4	3	2	11	4	34	4	8	16	15	18	19	22	-	-
EU	C	53	10	3	2	2	10	3	30	3	4	14	13	15	16	18	19	19
EU	C	54	12	3	2	2	9	3	25	3	3	10	12	14	15	16	-	-

We developed an integer programming model to schedule Ro-La activities of trains in Marmaray system. The model gives detailed start (and end times if exists) for loading, departure, travel, arrival, transfer, unloading, with platform information where this operation occurs. The model also shows the total operational cost on a daily basis. This model prepares operation and time schedules for each train and platform.

In the literature, variable different structured objective functions, such as shortening total passenger travel time [20], minimizing unit cost of flowing block of vehicles in wagons [27], minimizing in-train physical forces [53], maximizing reliability [29] were studied in train scheduling problems. Based on parameters and analysis in Marmaray system and since Marmaray system is a huge investment, it is determined that most beneficial objective function is to minimize total variable operational costs in a day, at least 6 hours of operations. The number of departures is controlled with the constraints.

4.3 Mathematical Model

In the mathematical model, the set $STr1$ includes the train numbers that depart from

S1. In this set, two types of trains exist; trains that go to S2 and do not depart second time from S2, and other trains that depart first from S2, and departs second time from S1. The set $STr2$ can be considered with the same logic. So, $STr1 \bigcap STr2$ gives the set of trains which travel in both directions in a day. This problem is a scheduling problem with large number of variables and constraints. So, in order to prevent exhaustive enumeration, the largest number of redundant variables and constraints should be discarded. Therefore, the set STr is partitioned into two sets to eliminate redundant constraints. The sets $SP1$ and $SP2$ are also introduced by considering redundant constraints, and $SP1 \bigcap SP2 = \emptyset$, because they represent the platforms in different stations. The seven time ranges (last parameters) is very important for preparing feasible schedules without any conflict. The method to find these time ranges were explained in Section 4.2. As explained in Section 4.2, in some instances, there may not be the second or third group of trains. Therefore, there is no need to include parameters such as $SecondArrivalT$ or $ThirdArrivalT$ in the model. The trains that arrive in times of $FirstArrivalT$, $SecondArrivalT$ and $ThirdArrivalT$ ranges, can depart second time. But in $OtherArrivalT$, a train cannot depart and its last operation is unloading. In all of the time ranges, trains are already subject to transfer and unloading operations. Based on each time range, the start time of loading operations changes. Since when a train arrives to a platform, it occupies platform for a duration of unloading+loading operations, the first group of trains does not wait to enter platform, but the second group of trains waits for the first group of trains to leave platform. Also, the third group of trains waits for the second group of trains. Therefore, start time of loading operations for each group cannot be expressed with an equation, but can be analyzed only with initial experiments. This analysis is given in Section 4.2. For $LoadAndDepartureT$, $ArrivalAndTransferT$ and $UnloadAndLoadAndDeparture$, start time of the time range is the latest start time of two intersecting time ranges, and end time is the earliest end time of intersecting time ranges. The model is presented using six different three index decision variables. These binary variables are defined for each operation taking place in both stations and railway line. With these variables, the model can determine which train performed which operation at what time at which platform, and can find schedules for each train and platform in the system.

Sets:

STr={1,...,Tr}, set of trains.

SR={1,2,...,R}, set of stations.

SP={1,2,...,P}, set of all platforms in all stations.

STi={1,2,...,Ti}, set of periods.

$STr1$={1,2,...,$Tr1$}, set of trains departing from station 1.

$STr2$={1,2,...,$Tr2$}, set of trains departing from station 2, $STr1 \bigcup STr2 = STr$.

$SP1$={1,2,...,(P/R)}, set of platforms in station 1.

$SP2$={(P/R),(P/R) + 1,...,(2P/R)}, set of platforms in station 2, $SP1 \bigcup SP2 = SP$.

Parameters:

Tr: Number of trains.

R: Number of stations.

P: Number of platforms in all stations.

Ti: Number of periods in a daily operation.

$Tr1$: Number of trains departing from station 1.

$Tr2$: Number of trains departing from station 2.

S: Speed of train (km/h).

D: Distance between initial and final stations (km).

t: Safety time interval between two consecutive departures from a station (mins).

T: Travel duration, equal to ceil value of [((D/S)*60)/t] (periods).

L: Loading duration (periods).

UL: Unloading duration (periods).

V: Transfer duration (periods).

ST: Start time of daily operations.

FT: End time of daily operations.

CT: Clearance time at the end of daily operations (if required, mins).

CR: Transportation cost of a train ($/km).

CH: Haulage cost of a train ($/km).

CM: Maintenance cost of a train ($/km).

$FirstLoadT$: Time range from 1 to FT-L+1, for the first loading operations to trains.

$LoadT$: Time range from 1 to FT-1, for all of the loading operations to trains, except the first loading operation.

$DepartureT$: Time range from L to FT, for departures of trains from stations.

$TravelT$: Time range from L+1 to FT+T-1, for all of the times when trains are on railroad line.

$ArrivalT$: Time range from L+T to FT+T, for all of the arrivals of trains to stations.

$TransferT$: Time range from L+T+1 to Ft+T+V, for all of the transfers of trains, from arrival to station, to start of unloading operation.

$UnloadT$: Time range from L+T+V+1 to FT+T+V+UL, for all of the unloading operations to trains.

$FirstArrivalT$: Time range for the first group of trains, from arrival time of the first train to arrival time of the last train in the first group.

$SecondArrivalT$: Time range for the second group of trains, from arrival time of the first train to arrival time of the last train in the second group.

$ThirdArrivalT$: Time range for the third group of trains, from arrival time of the first train to arrival time of the last train in the third group.

$OtherArrivalT$: Time range for the group of trains, except the first, the second or the third group. These group of trains are subject to only transfer and unloading operations and they are not loaded again, so they do not depart second time, unlike all of the other trains. FT do not let these trains to depart second time. This time range must be defined in all of the instances, because at least one train makes only one travel and do not depart second time.

$LoadAndDepartureT$: Time range from L to FT-1. This time range is the intersection of time ranges $UnloadT$ and $DepartureT$.

$ArrivalAndTransferT$: Time range from L+T+1 to FT+T and is the intersection of

$ArrivalT$ and $TransferT$.

$UnloadAndLoadAndDepartureT$: Time range from L+T+V+1 to FT-1. This is the intersection of $UnloadT$, $LoadT$ and $DepartureT$.

Decision Variables:

$a_{i,k,t}$: 1 if train i arrives at platform k at period t, 0 otherwise.

$d_{i,k,t}$: 1 if train i departs from platform k at period t, 0 otherwise.

$yl_{i,k,t}$: 1 if loading operation is implemented to train i in platform k at period t, 0 otherwise.

$yul_{i,k,t}$: 1 if unloading operation is implemented to train i in platform k at period t, 0 otherwise.

$yv_{i,k,t}$: 1 if train i is being transferred to platform k at period t, 0 otherwise.

$z_{i,j,t}$: 1 if train i is travelling to station j at period t, 0 otherwise.

Minimize

$$z = \sum_{i \in STr} \sum_{k \in SP} \sum_{t \in Ti} D * (CR + CH + CM) * d_{i,k,t} \tag{4.1}$$

subject to,

$$\sum_{i \in STr} \sum_{k \in SP} d_{i,k,t} = 2, \qquad \forall t \in DepartureT \tag{4.2}$$

$$\sum_{k \in SP} \sum_{t \in DepartureT} d_{i,k,t} \geq 1, \qquad \forall i \in STr \tag{4.3}$$

$$\sum_{i \in STr} a_{i,k,t} \leq 1, \qquad \forall k \in SP, t \in ArrivalT \tag{4.4}$$

$$\sum_{i \in STr} d_{i,k,t} \leq 1, \qquad \forall k \in SP, t \in DepartureT \tag{4.5}$$

$$\sum_{i \in STr} yl_{i,k,t} \leq 1, \qquad \forall k \in SP, t \in LoadT \tag{4.6}$$

$$\sum_{i \in STr} yul_{i,k,t} \leq 1, \qquad \forall k \in SP, t \in UnloadT \tag{4.7}$$

$$\sum_{i \in STr} yv_{i,k,t} \leq 1, \qquad \forall k \in SP, t \in TransferT \tag{4.8}$$

$$\sum_{i \in STr} yl_{i,k,t} + d_{h,k,t} \leq 1, \qquad \forall k \in SP, t \in LoadAndDepartureT \tag{4.9}$$

$$\sum_{i \in STr} yul_{i,k,t} + yl_{i,k,t} + d_{i,k,t} \leq 1, \qquad \forall k \in SP, t \in UnloadAndLoadAndDepartureT \tag{4.10}$$

$$\sum_{i \in STr} a_{i,k,t} + yv_{h,k,t} \leq 1, \qquad \forall k \in SP, t \in ArrivalAndTransferT \tag{4.11}$$

$$\sum_{k2 \in SP2} \sum_{t \in ArrivalT} a_{i1,k2,t} = 1, \qquad \forall i1 \in STr1 \tag{4.12}$$

$$\sum_{k1 \in SP1} \sum_{t \in ArrivalT} a_{i2,k1,t} = 1, \qquad \forall i2 \in STr2 \tag{4.13}$$

$$\sum_{k1 \in SP} \sum_{t \in DepartureT} d_{i1,k1,t} = 1, \qquad \forall i1 \in STr1 \tag{4.14}$$

$$\sum_{k2 \in SP} \sum_{t \in DepartureT} d_{i2,k2,t} = 1, \qquad \forall i2 \in STr2 \tag{4.15}$$

$$\sum_{k1 \in SP1} \sum_{t \in LoadT} yl_{i1,k1,t} = (L-1), \qquad \forall i1 \in STr1 \tag{4.16}$$

$$\sum_{k2 \in SP2} \sum_{t \in LoadT} yl_{i2,k2,t} = (L-1), \qquad \forall i2 \in STr2 \tag{4.17}$$

$$\sum_{k2 \in SP2} \sum_{t \in UnloadT} yul_{i1,k2,t} = UL, \qquad \forall i1 \in STr1 \tag{4.18}$$

$$\sum_{k1 \in SP1} \sum_{t \in UnloadT} yul_{i2,k1,t} = UL, \qquad \forall i2 \in STr2 \tag{4.19}$$

$$\sum_{k2 \in SP2} \sum_{t \in TransferT} yv_{i1,k2,t} = V, \qquad \forall i1 \in STr1 \tag{4.20}$$

$$\sum_{k1 \in SP1} \sum_{t \in TransferT} yv_{i2,k1,t} = V, \qquad \forall i2 \in STr2 \tag{4.21}$$

$$\sum_{j \in SR} \sum_{t \in TravelT} z_{i,j,t} \leq 2(T-1), \qquad \forall i \in STr \tag{4.22}$$

$$d_{i1,k1,t+(L-1)} - yl_{i1,k1,t+c} \leq 0, \qquad \forall i1 \in STr1, k1 \in SP1, t \in FirstLoadT, c = 0, ..., (L-2) \tag{4.23}$$

$$d_{i2,k2,t+(L-1)} - yl_{i2,k2,t+c} \leq 0, \qquad \forall i2 \in STr2, k2 \in SP2, t \in FirstLoadT, c = 0, ..., (L-2) \tag{4.24}$$

$$\sum_{k1 \in SP1} d_{i1,k1,t} - z_{i1,2,t+c} \leq 0, \qquad \forall i1 \in STr1, t \in DepartureT, c = 1, ..., (T-1) \tag{4.25}$$

$$\sum_{k2 \in SP2} d_{i2,k2,t} - z_{i2,1,t+c} \leq 0, \qquad \forall i2 \in STr2, t \in DepartureT, c = 1, ..., (T-1) \tag{4.26}$$

$$\sum_{k1 \in SP1} d_{i1,k1,t} - \sum_{k2 \in SP2} a_{i1,k2,t+T} = 0, \qquad \forall i1 \in STr1, t \in DepartureT \tag{4.27}$$

$$\sum_{k2 \in SP2} d_{i2,k2,t} - \sum_{k1 \in SP1} a_{i2,k1,t+T} = 0, \qquad \forall i2 \in STr2, t \in DepartureT \tag{4.28}$$

$$a_{i1,k2,t} - yv_{i1,k2,t+c} \leq 0, \qquad \forall i1 \in STr1, k2 \in SP2, t \in ArrivalT, c = 1, ..., V \tag{4.29}$$

$$a_{i2,k1,t} - yv_{i2,k1,t+c} \leq 0, \qquad \forall i2 \in STr2, k1 \in SP1, t \in ArrivalT, c = 1, ..., V \tag{4.30}$$

$$a_{i1,k2,t} - yul_{i1,k2,t+c} \leq 0, \qquad \forall i1 \in STr1, k2 \in SP2, t \in FirstArrivalT, c = V+1, ..., V+UL \tag{4.31}$$

$$a_{i2,k1,t} - yul_{i2,k1,t+c} \leq 0, \qquad \forall i2 \in STr2, k1 \in SP1, t \in FirstArrivalT, c = V+1, ..., V+UL \tag{4.32}$$

$$a_{i1,k2,t} - yul_{i1,k2,t+c} \leq 0, \qquad \forall i1 \in STr1, k2 \in SP2, t \in SecondArrivalT, c = V+UL+1, ..., V+2UL \tag{4.33}$$

$$a_{i2,k1,t} - yul_{i2,k1,t+c} \leq 0, \qquad \forall i2 \in STr2, k1 \in SP1, t \in SecondArrivalT, c = V+UL+1, ..., V+2UL \tag{4.34}$$

$$a_{i1,k2,t} - yul_{i1,k2,t+c} \leq 0, \qquad \forall i1 \in STr1, k2 \in SP2, t \in ThirdArrivalT, c = V+2UL+1, ..., V+3UL \tag{4.35}$$

$$a_{i2,k1,t} - yul_{i2,k1,t+c} \leq 0, \qquad \forall i2 \in STr2, k1 \in SP1, t \in ThirdArrivalT, c = V+2UL+1, ..., V+3UL \tag{4.36}$$

$$a_{i1,k2,t} - yul_{i1,k2,t+c} \leq 0, \qquad \forall i1 \in STr1, k2 \in SP2, t \in OtherArrivalT, c = V+1, ..., V+UL \tag{4.37}$$

$$a_{i2,k1,t} - yul_{i2,k1,t+c} \leq 0, \qquad \forall i2 \in STr2, k1 \in SP1, t \in OtherArrivalT, c = V+1, ..., V+UL \tag{4.38}$$

$$a_{i1,k2,t} - d_{i1,k2,t+(V+UL+L)} = 0, \qquad \forall i1 \in STr1, k2 \in SP2, t \in FirstArrivalT \tag{4.39}$$

$$a_{i2,k1,t} - d_{i2,k1,t+(V+UL+L)} = 0, \qquad \forall i2 \in STr2, k1 \in SP1, t \in FirstArrivalT \tag{4.40}$$

$$a_{i1,k2,t} - d_{i1,k2,t+(V+UL+L+UL)} = 0, \qquad \forall i1 \in STr1, k2 \in SP2, t \in SecondArrivalT \tag{4.41}$$

$$a_{i2,k1,t} - d_{i2,k1,t+(V+UL+L+UL)} = 0, \qquad \forall i2 \in STr2, k1 \in SP1, t \in SecondArrivalT \tag{4.42}$$

$$a_{i1,k2,t} - d_{i1,k2,t+(V+UL+L+2UL)} = 0, \qquad \forall i1 \in STr1, k2 \in SP2, t \in ThirdArrivalT \tag{4.43}$$

$$a_{i2,k1,t} - d_{i2,k1,t+(V+UL+L+2UL)} = 0, \qquad \forall i2 \in STr2, k1 \in SP1, t \in ThirdArrivalT \tag{4.44}$$

The objective function is to minimize the total variable costs in a daily operation. The cost elements are transportation, haulage and maintenance. The constraints starting from (4.2) to (4.22) are the logic constraints. Constraint (4.2) states that, at each period, exactly one train can depart from a station, making two trains in total. Constraint (4.3) ensures that, each train departs at least one time, considering all of the platforms in two stations and all of the departure time periods. Constraint (4.4) denotes that at most one train can arrive to a platform at one time. Constraint (4.5) notes that at most one train can depart from a platform at one time. Constraint (4.6) explains that at one platform and at a time, no more than one train can exist in the loading operation. Constraint (4.7) states that at one platform and at a time, at most one train can be subject to unloading operation. Constraint (4.8) ensures that no more than one train can be transferred to a platform at one time. Constraint (4.9) guarantees that at one platform and one time, at most one train can be subject to loading operation and departure. Constraint (4.10) cites that, at each platform, no more than one train can be subject to unloading, loading and depart. Constraint (4.9) is required to control the trains that are subject to loading operation first, i.e., the trains which is the first group of trains to depart initially in a day. Constraint (4.10) is required to control other types of trains, i.e., the trains that arrive to a station and subject to unloading operation first. Therefore, constraint (4.10) is needed additionally. Therefore, the time ranges, $UnloadAndLoadAndDepartureT$ of constraint (4.9) and $LoadAndDepartureT$ of constraint (4.10) are different, and two different constraints need to be introduced. Constraint (4.11) states that, at most one train arrive and transfer to same platform at the same time. In a daily operation, the latest train can depart at a time such that it will arrive to other station at the latest before 06:00. Regarding this time limit, considering best options such as the fastest trains and minimum transfer, unloading and loading times, even in the instance with these options, the trains can depart only second time, the time limit do not allow them to depart third time. A system's earliest second departure time is equal to total of travel, transfer, unload and load times. In order to find the earliest second departure time, the platform structure giving minimum transfer time is selected for each system. For instance, in EU system, travel duration is 99, loading duration is 30, unloading duration is 20 and transfer duration is 15 mins. So, the second departure time is equal to their total, making 164 mins. In this manner, the earliest second departure times of also OE and MO can be found with 203.6 and 213.5 mins, respectively. For instance, considering EU system with minimum second departure time duration-164 mins, if the first train departs at time 00:00 (at the earliest time) from S1, it arrives to S2 at 02:44. Then departing from S2, it arrives to S1 at 05:28. But, because the latest train can depart at 04:21, to arrive to other station at 06:00, no other train can depart after 04:21 in EU system. So, the train is not allowed to depart from S2, to arrive to S1 at 05:28, allowing the train to make only two departures. Therefore, constraints between (4.12) and (4.22) are defined to control these number of operations, such as two departures. Constraint (4.12) states that a train in the set of trains departing from S1 can arrive to only one time to all of the platforms in S2 in all arrival time periods. Constraint (4.13) is the opposite of constraint (4.12), i.e., considering set of trains departing from S2 and platforms in S1. Constraint (4.14) denotes that a train can only depart one time from all of the platforms in S1. Constraint (4.16) ensures that, the total of binary loading variables of set of trains departing from S1 must be loading duration-1. This minus one is for the departure operation because departure operation is an instantaneous operation, i.e., it does not continue for even one time period. But, in order to show the departure operation in schedules, departure operation is thought as final time period of the loading operation. Constraint (4.18) guarantees that the total of binary unloading variables in S2 is equal to unloading time duration. Constraint (4.20) denotes that total of transfer variables must be exactly transfer time in the selected platform structure in S2. Constraints (4.15), (4.17), (4.19) and (4.21) are the opposite of constraints (4.16), (4.18), (4.20) and (4.22), respectively, in terms of set of trains and station. Constraint (4.22) states that total of binary travel variables can be at most 2(T-1). This -1 is for the departure operation, as explained in constraint (4.16). Multiplication with 2 is due to the fact that at most a train can depart second time, making two travels in total. The constraints from (4.23) to (4.44) are the time constraints. Constraint (4.23) states that, for all of the trains departing from S1, if a train departs at t+(L-1), then each of the previous (L-1) loading binary variables must be 1, i.e., if a train departs, then it must have been subject to a loading operation at all required time periods. Constraint (4.25) guarantees that if a train departs, then all of the following travel variables must be 1, i.e., the train exists on the railroad line, going in a direction at that specific time. Constraint (4.27) defines the equality such that, if a train departs, then it must arrive to other station exactly after travel duration. Constraint (4.29) explains that if a train arrives, then all of the transfer duration amount of the following transfer variables must be 1. Constraint (4.31) states that if a train arrives, then, after transferred to a platform, the train is subject to unloading operation at all different UL times. The situation to start unloading variables after transfer operation is controlled with starting c from V+1, i.e., one time period after transfer duration. c is defined as a counter. It is inserted to control all of the required operational variables and make them 1, if a departure or arrival occurs. Constraints (4.33) and (4.35) are similar to constraint (4.31), with only difference in the range of t and c. Constraints from (4.31) till

(4.36) are defined according to Table 4.3. The data in Table 4.3 represent the start and end of ranges for counter c in these constraints. These constraints must be defined because the second group of arrivals must wait the first group of arrivals in a duration of UL before entering the platform, otherwise conflicts will occur in the schedules. Therefore range of c in constraint (4.33) starts at $V + UL$+1, later than start time (V+1) of range of c in constraint (4.31). Constraint (4.37) is defined for the trains which go in one direction only in a day, i.e., do not depart second time. Since these group of trains which make only one travel use additional platforms, they do not need to wait previous group of trains to enter platform. So, they do not need to wait UL amount of time, and behave like the first group of arrival trains in constraint (4.31), with only difference in set of trains. Constraints from (4.39) to (4.44) are defined to allow the trains to depart second time. The difference in each of these constraints are in the stand time in the station. Stand time is added to the time of arrival, ensuring that after stand time, the train departs second time. First stand time equals to $(V+UL+L)$, and for each of the next stand times, following one is UL more than the previous one. The constraints between (4.23) and (4.38) (except (4.27) and (4.28)) all have $\leq$. Therefore, in an equality with $\leq$, if left variable is 1, then right variable must be 1 to ensure $\leq$, otherwise, right variable can be 0 or 1. The freedom for right variable to be 0 or 1 is important not to cause a conflict. Constraints (4.24), (4.26), (4.27), (4.30), (4.32), (4.34), (4.36), (4.38), (4.40), (4.42) and (4.44) are the opposite constraints of (4.23), (4.25), (4.28), (4.29), (4.31), (4.33), (4.35), (4.37), (4.39), (4.41) and (4.43), respectively, in terms of set of trains and station. As explained in Section 4.2, there may not be the second or the third group of trains in some instances. Therefore, all or some of the constraints (4.33), (4.34), (4.35), (4.36), (4.41), (4.42), (4.43) and (4.44) may not exist in the model according to the instance.

Chapter 5

RESULTS

5.1 Integration of Facility Layout & Train Scheduling Problems

The integration of facility layout with train scheduling problem is required because the layout problem directly affects the scheduling problem. Figure 5.1 illustrates the integration of these two problems.

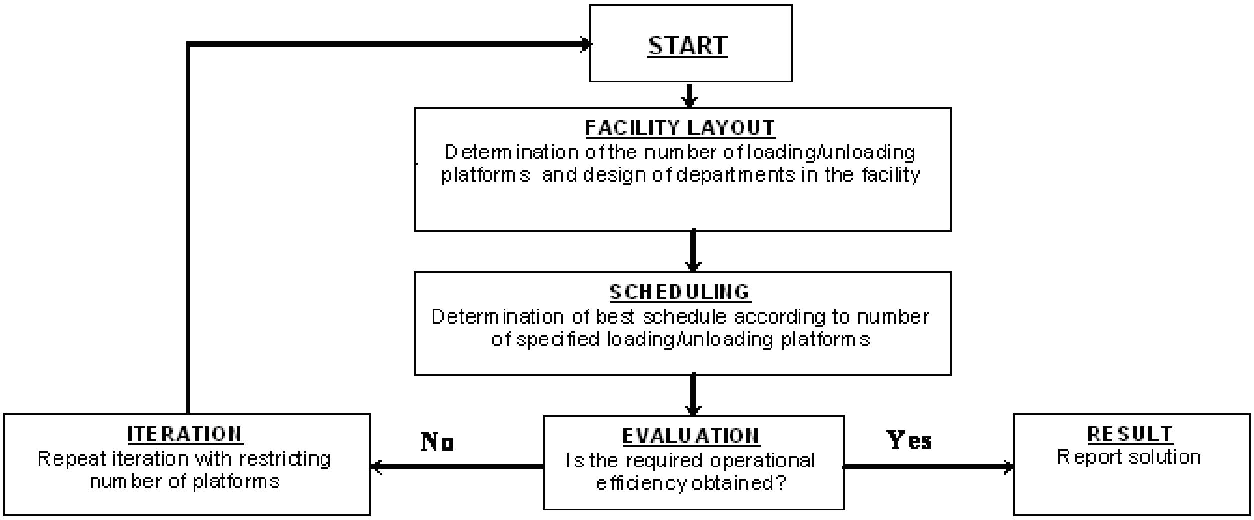


Figure 5.1: Integrated Planning & Scheduling Problem

As seen in Figure 5.1, the number of parallel loading/unloading platforms parameter is very important for two problems. With the preliminary analysis explained in section 4.2, the initial number of parallel platforms can be found. For instance, 12 platforms exist in one station, and according to this number, in the facility layout problem, the required areas of all of the departments are calculated, and the initial layout is tried to be improved with the improvement algorithm. Then, according to 12 platforms, parameters of train scheduling problem are analyzed, and the model is run to find best schedule according to this number of parallel platforms. At evaluation step, operational efficiency is assessed. Examples of operational efficiency can be the status of station layout in the facility layout problem or the total number of trucks and TIRs carried in the train scheduling problem. If the planned operational efficiency is not obtained, then the number of parallel platforms is reduced to 11, and the facility layout and train scheduling problems are again run with different number of platforms. If operational efficiency is determined, then solution of integrated approach can be explained. At one step in the integrated flow, the required minimum number of platforms will be reached, where, below this number, the model in the train scheduling problem will be infeasible.

As can be seen in Table 5.1 in Chapter 5.3, the first three instances are all for Oekombi system, linear platform structure, safety time interval of five minutes, but with different number of total platforms in a station. First, twelve platforms are evaluated, and at last, ten platforms are evaluated. In all of these three instances, feasible solutions are obtained. For this system, the conclusion point is ten platforms, because with nine platforms, the model becomes infeasible, therefore, one does not need to evaluate the remaining number of platforms, which, in fact, prevents the exhaustive enumeration. This is one of the benefits of integrated approach. The number of platforms is the most important parameter in the integrated approach. Another benefit comes from the nature of the Ro-La transportation system. In Ro-La, where rail and road modes are used, in order to obtain a successful enterprise, the facility layout problem (for road mode) and train scheduling problem (for rail mode) should be solved together.

5.2 Facility Layout Problem

When the facility layout and train scheduling problems are solved together, our main goal is to find the best layout in a station according to the number of platforms which will also be used in the train scheduling problem, by assigning this number of platforms to facility layout problem, and by constructing the best layout with this number of platforms.

The facility layout improvement algorithm explained in Section 3.3 is run for three sample initial layouts with seven scoring options. Therefore, for each system, when each initial layout is evaluated, the combination of system-layout is 6*3=18. With also the scoring options, we have 18*7=126 different set of facility layout problem results. In a set of facility layout result, there are four files. File AdjacentDepartments.txt contains the names of departments that share a common boundary. In file SameSizeDepartments.txt, the department names with the same size are written. Also, the most important file is Results.txt. This file shows every operation performed by the algorithm, illustrating such as order, score, names of swapped departments, feasibility for each sample layout in each iteration, and at the end of each iteration, the order, names of two departments giving best score in each iteration. With the best score, it is possible to analyze the improvement in the score at each iteration. If the best score in two successive iterations does not improve (staying same or decreasing in a maximizing objective), then at last, the algorithm writes the best final layout to the file and concludes the run. The last file is ResultLayout.txt, where the two-dimensional array of final layout is shown.

Figure 5.2 shows sample initial layout #1 and Figure 5.3 shows sample initial layout #2, with 14 departments and circular platform structure.

Major difference between Figures 5.2 and 5.3 is that the location of departments other than platforms and siding are totally different. In addition, in Figure 5.2, for siding, the railroad goes from the corner, while in Figure 5.3, for siding, railroad separates from the middle. Today, in real applications, siding like in Figure 5.3 is much more used.

Figure 5.4 shows sample initial layout #3, with linear platform structure. In Figures 5.2 and 5.3, all of the platforms are parallel, but in Figure 5.4, some platforms are serially constructed, making the area of station grow in terms of length, instead of width.

In the facility layout, area size of four departments depend on each instance. These are Platforms, Siding, Truck/TIR Park Area and Locomotive/Wagon Park Area. These area sizes are determined by the decision maker. Also, in this thesis, Tables A.1, A.2 and A.3 in Appendix A shows the dimensions of these four departments. These dimensions are used to obtain facility layout result sets.

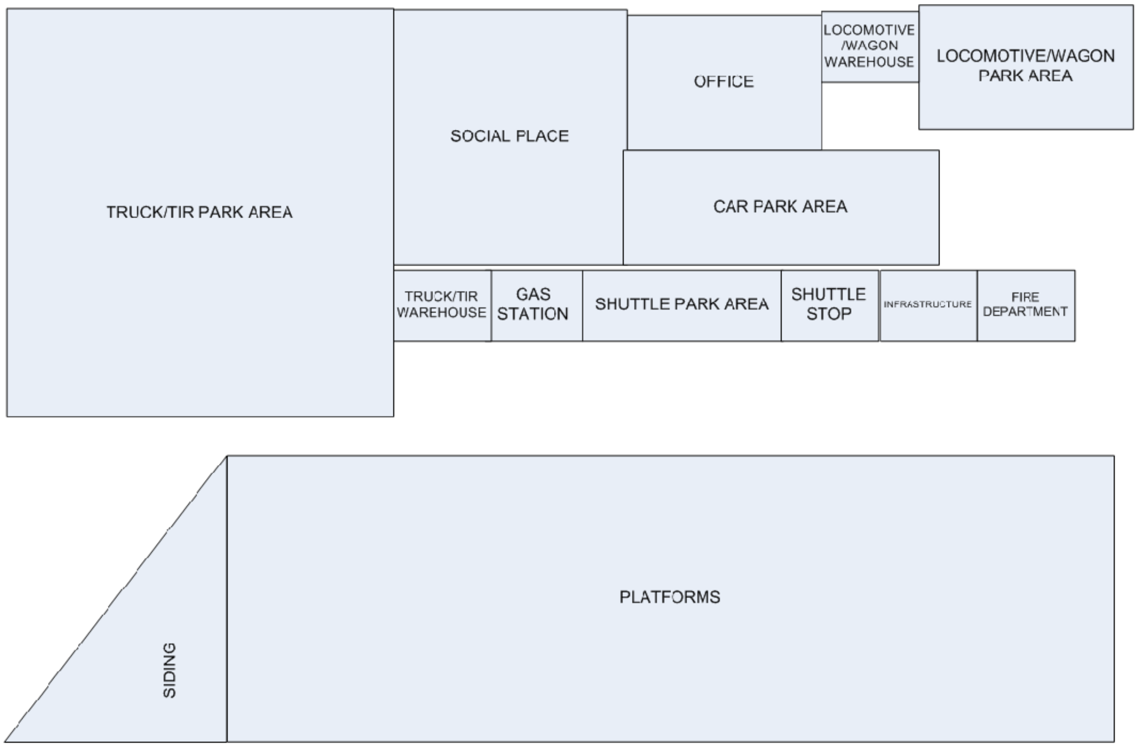


Figure 5.2: Sample initial layout #1

All of the codes for the facility improvement algorithm have been written in ANSI C language, compiled in Visual C++ 6.0 and executed on a PC that has Intel Xeon CPU 5160 with 2 3.00 GHz processors, where each processor is dual core, and with 4.00 GB of RAM.

The results are obtained for each instance of train scheduling model and sample initial layout. For example, let us consider an example (the third instance in train scheduling model) which has Oekombi system, t=5 minutes, linear platform structure and ten platforms in a station. When sample initial layout #1 is selected, dimensions of four departments (Platforms, Siding, Truck/TIR Park Area and Locomotive/Wagon Park Area) are modified for the third instance in train scheduling model and the last status of sample initial layout #1 for the third instance is completed. In the facility layout improvement algorithm, if distance-weighted adjacency-based scoring option is chosen, the operations are applied on the last status of sample initial layout #1 and the final layout is shown in Figure 5.5.

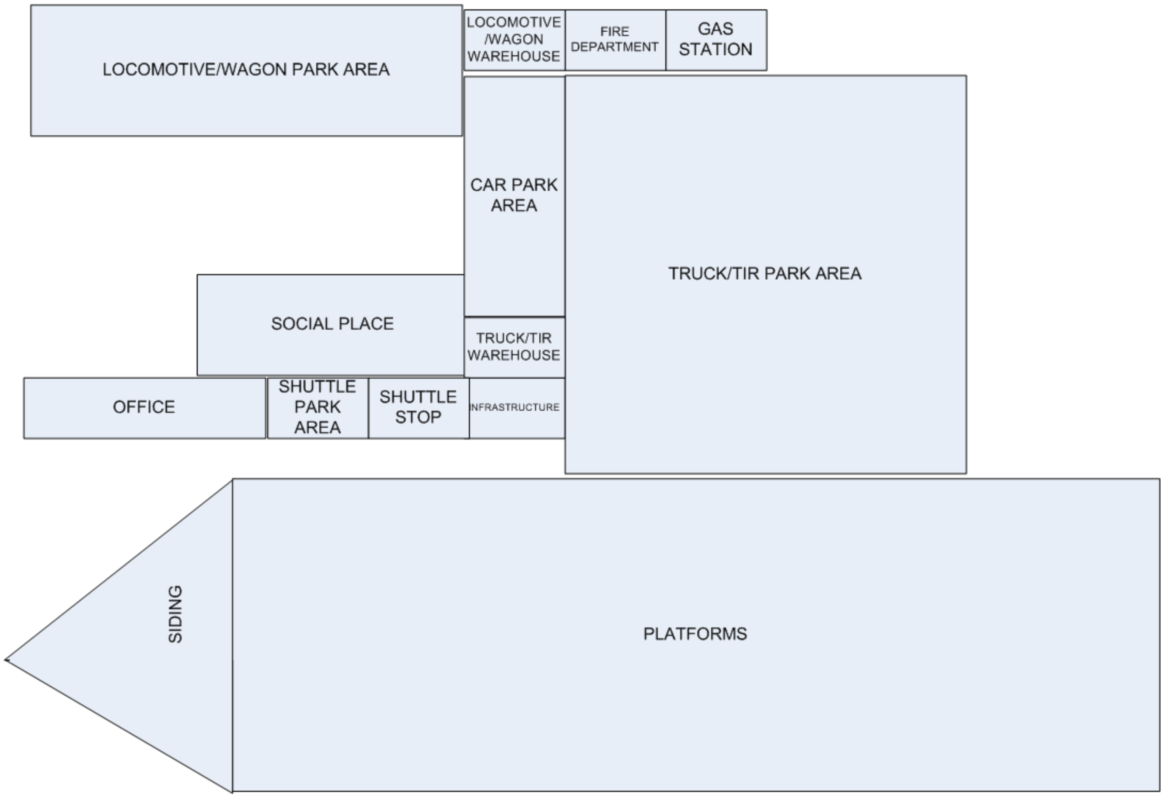


Figure 5.3: Sample initial layout #2

When the initial layout in Figure 5.2 and the final layout in Figure 5.5 are considered, the distance-weighted adjacency-based score of the initial layout is 22,445. The first exchange operation is between departments Gas Station and Social Places. Although these departments do not have the same area size, because they are adjacent and their exchange improve the score, they are swapped, and score of the sample layout is 21,613. The second operation is between departments of Locomotive/Wagon Warehouse and Locomotive/Wagon Park Area, causing a better score of 21,452. The third swap is for departments, Fire Department and Infrastructure. These departments have the same area size, and lowers the score to 21,216. In the fourth loop, minimum score giving the best exchange operation is again swapping Fire Department and Infrastructure, resulting in the same score 21,216. Since there is no improvement, algorithm stops execution, and selects the final layout of the last loop. This final layout is written to ResultOutput.txt. All of the details of these exchange

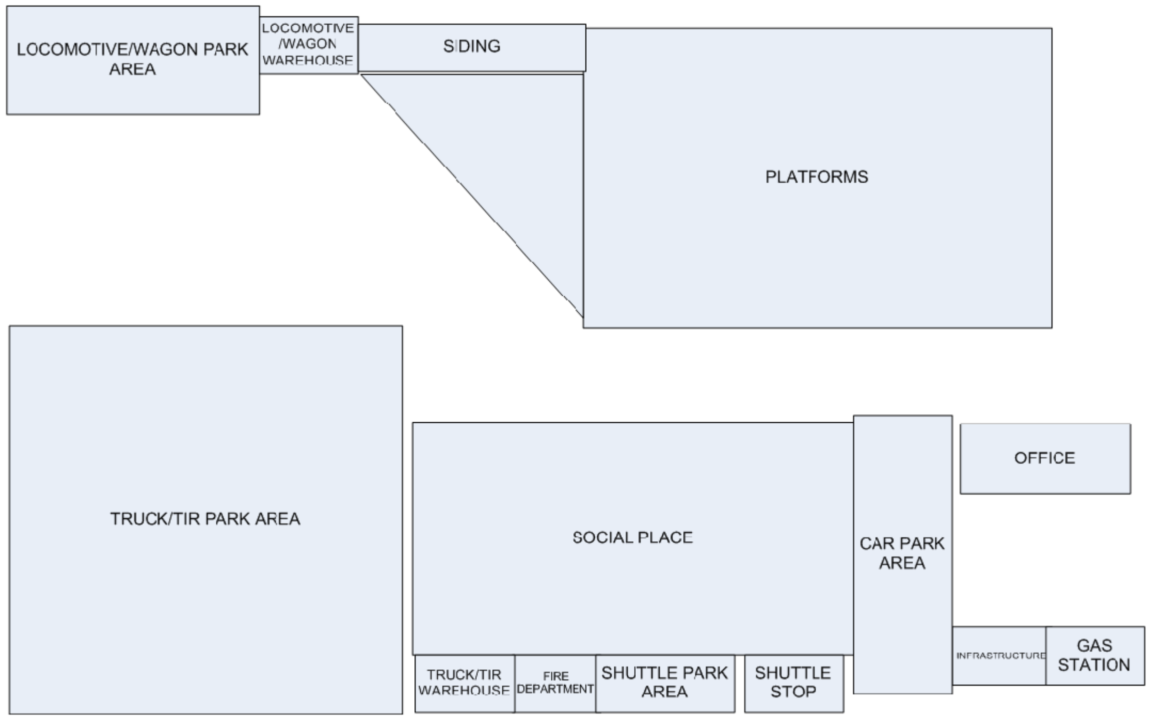


Figure 5.4: Sample initial layout #3

operations are written to Results.txt. Also, the time of each run is calculated in terms of the CPU time. The time of each run is also written to the end of file, Results.txt.

Figure 5.6 shows a sample AdjacentDepartments.txt file. In this file, a two-dimensional array shows 1 for adjacent department pairs. The sentences in the bottom of this file explain this matrix, i.e., which departments are adjacent.

In the algorithm, all of the details of exchange operations in all loops of a run is written to Results.txt file. Figures 5.7, 5.8 and 5.9 all show a sample Results.txt file.

The score of the initial layout is 92, and as the first sample layout, departments Locomotive/Wagon Warehouse and Shuttle Stop are swapped, resulting a feasible sample layout. The selected sample layout, giving the best score can be seen with the result in "order 15", giving a higher (better) score of 99 by swapping departments Infrastructure and Gas Station. The scores of loops 2 and 3 are the same, 100, so the sample layout giving the best score in loop 2 is selected as the final layout, and is written to ResultLayout.txt file. Total

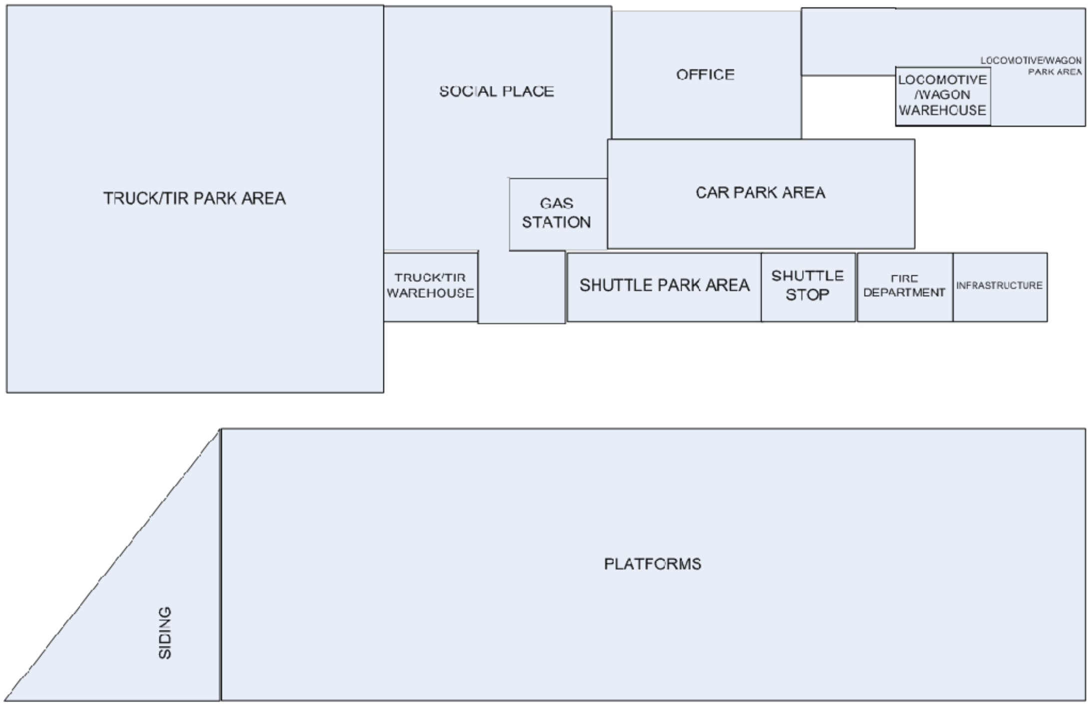


Figure 5.5: Final layout for instance 3

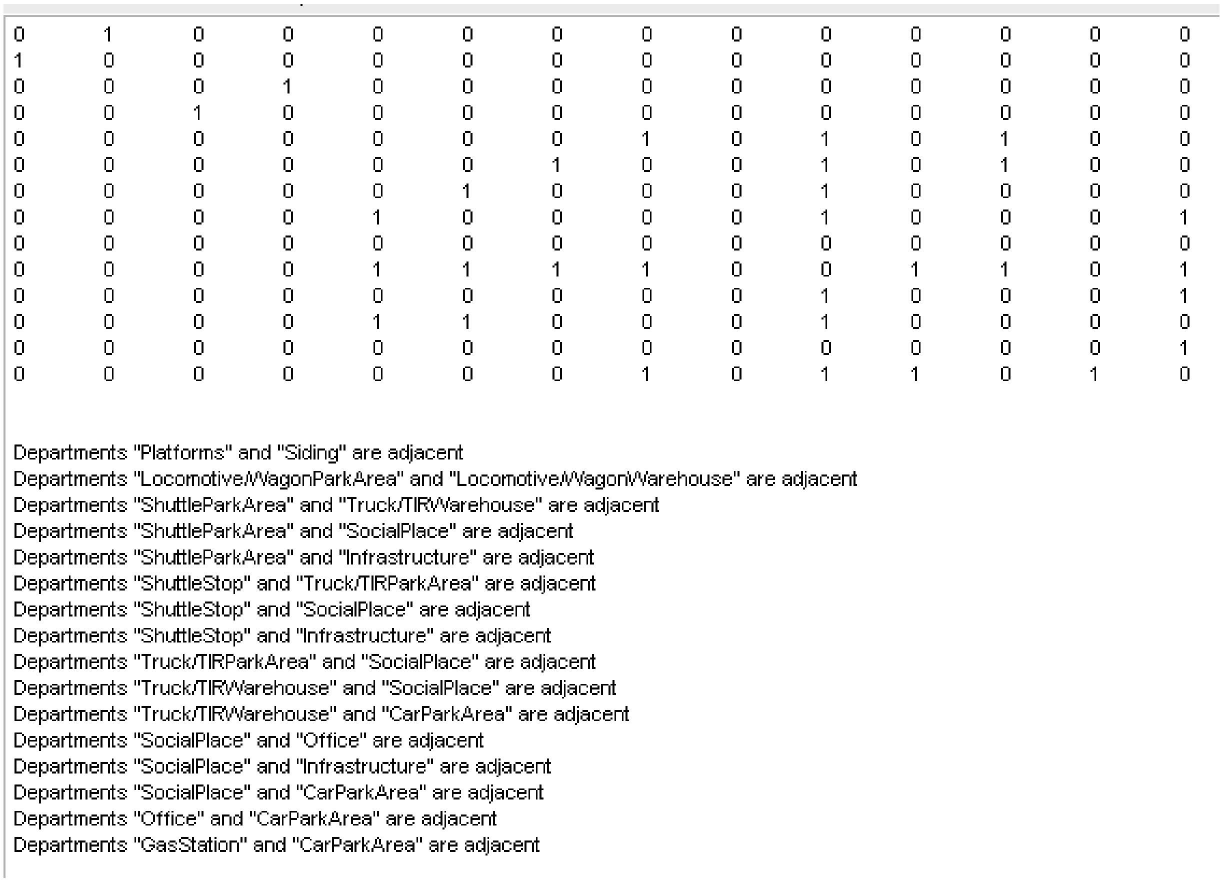
CPU time measured in the algorithm is 3.109 seconds. Each sample layout (order) is also shown with its feasibility. As long as it is infeasible, the score of this sample layout is not required to be calculated. Infeasible sample layout means that one or more of the Correct Count, Contiguity, Connectedness and Enclosed Voids rules is not satisfied.

Figure 5.10 illustrates a sample SameSizeDepartments.txt file, which documents department the pairs that have the same area.

Figure 5.11 is a sample ResultLayout schema, showing abbreviations of each department.

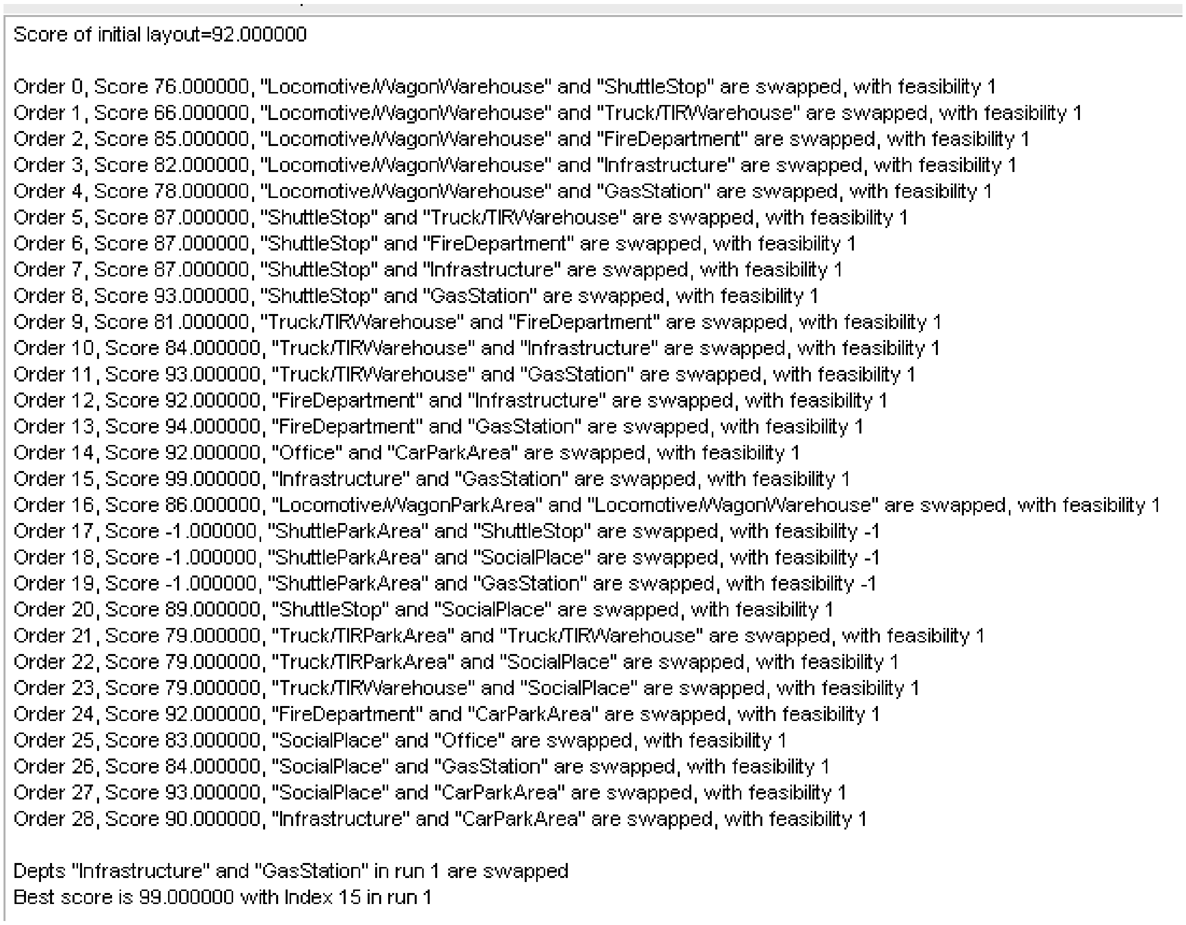
5.3 Train Scheduling Problem

The integer programming model is run for three systems, OE, MO, EU; integer values of 5, 6, 7, 8, 9, 10 and 12 for t, safety time interval and two platform structures, making 42 instances in total. For each of these 42 instances, the number of platforms is different,



```
0    1    0    0    0    0    0    0    0    0    0    0    0    0
1    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    1    0    0    0    0    0    0    0    0    0    0
0    0    1    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    0    0    0    1    0    1    0    1    0    0
0    0    0    0    0    0    1    0    0    1    0    1    0    0
0    0    0    0    0    1    0    0    0    1    0    0    0    0
0    0    0    0    1    0    0    0    0    1    0    0    0    1
0    0    0    0    0    0    0    0    0    0    0    0    0    0
0    0    0    0    1    1    1    1    0    0    1    1    0    1
0    0    0    0    0    0    0    0    0    1    0    0    0    1
0    0    0    0    1    1    0    0    0    1    0    0    0    0
0    0    0    0    0    0    0    0    0    0    0    0    0    1
0    0    0    0    0    0    0    1    0    1    1    0    1    0


Departments "Platforms" and "Siding" are adjacent
Departments "Locomotive/WagonParkArea" and "Locomotive/WagonWarehouse" are adjacent
Departments "ShuttleParkArea" and "Truck/TIRWarehouse" are adjacent
Departments "ShuttleParkArea" and "SocialPlace" are adjacent
Departments "ShuttleParkArea" and "Infrastructure" are adjacent
Departments "ShuttleStop" and "Truck/TIRParkArea" are adjacent
Departments "ShuttleStop" and "SocialPlace" are adjacent
Departments "ShuttleStop" and "Infrastructure" are adjacent
Departments "Truck/TIRParkArea" and "SocialPlace" are adjacent
Departments "Truck/TIRWarehouse" and "SocialPlace" are adjacent
Departments "Truck/TIRWarehouse" and "CarParkArea" are adjacent
Departments "SocialPlace" and "Office" are adjacent
Departments "SocialPlace" and "Infrastructure" are adjacent
Departments "SocialPlace" and "CarParkArea" are adjacent
Departments "Office" and "CarParkArea" are adjacent
Departments "GasStation" and "CarParkArea" are adjacent
```

Figure 5.6: Sample AdjacentDepts.txt

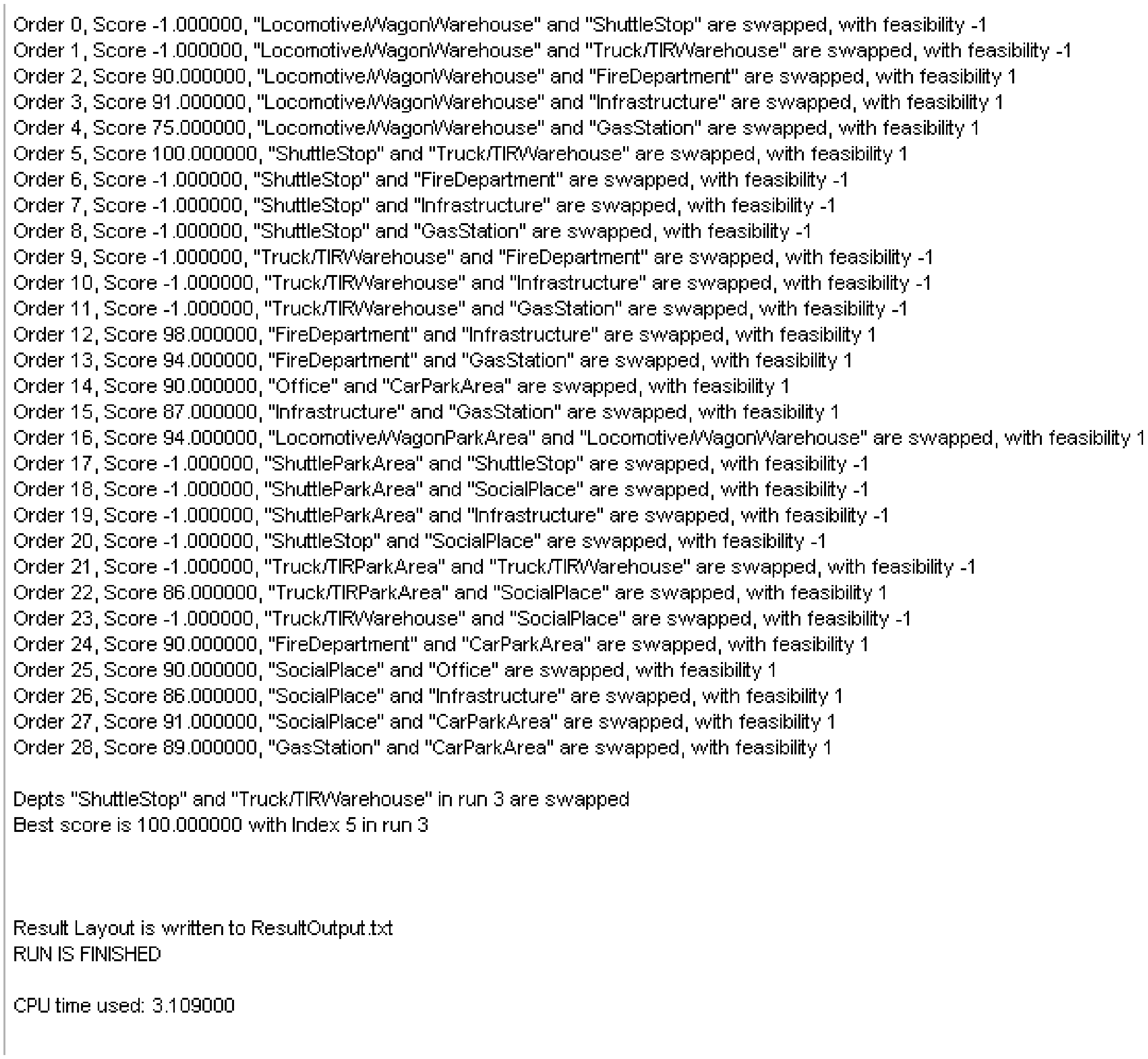


```
Score of initial layout=92.000000

Order 0, Score 76.000000, "Locomotive/WagonWarehouse" and "ShuttleStop" are swapped, with feasibility 1
Order 1, Score 66.000000, "Locomotive/WagonWarehouse" and "Truck/TIRWarehouse" are swapped, with feasibility 1
Order 2, Score 85.000000, "Locomotive/WagonWarehouse" and "FireDepartment" are swapped, with feasibility 1
Order 3, Score 82.000000, "Locomotive/WagonWarehouse" and "Infrastructure" are swapped, with feasibility 1
Order 4, Score 78.000000, "Locomotive/WagonWarehouse" and "GasStation" are swapped, with feasibility 1
Order 5, Score 87.000000, "ShuttleStop" and "Truck/TIRWarehouse" are swapped, with feasibility 1
Order 6, Score 87.000000, "ShuttleStop" and "FireDepartment" are swapped, with feasibility 1
Order 7, Score 87.000000, "ShuttleStop" and "Infrastructure" are swapped, with feasibility 1
Order 8, Score 93.000000, "ShuttleStop" and "GasStation" are swapped, with feasibility 1
Order 9, Score 81.000000, "Truck/TIRWarehouse" and "FireDepartment" are swapped, with feasibility 1
Order 10, Score 84.000000, "Truck/TIRWarehouse" and "Infrastructure" are swapped, with feasibility 1
Order 11, Score 93.000000, "Truck/TIRWarehouse" and "GasStation" are swapped, with feasibility 1
Order 12, Score 92.000000, "FireDepartment" and "Infrastructure" are swapped, with feasibility 1
Order 13, Score 94.000000, "FireDepartment" and "GasStation" are swapped, with feasibility 1
Order 14, Score 92.000000, "Office" and "CarParkArea" are swapped, with feasibility 1
Order 15, Score 99.000000, "Infrastructure" and "GasStation" are swapped, with feasibility 1
Order 16, Score 86.000000, "Locomotive/WagonParkArea" and "Locomotive/WagonWarehouse" are swapped, with feasibility 1
Order 17, Score -1.000000, "ShuttleParkArea" and "ShuttleStop" are swapped, with feasibility -1
Order 18, Score -1.000000, "ShuttleParkArea" and "SocialPlace" are swapped, with feasibility -1
Order 19, Score -1.000000, "ShuttleParkArea" and "GasStation" are swapped, with feasibility -1
Order 20, Score 89.000000, "ShuttleStop" and "SocialPlace" are swapped, with feasibility 1
Order 21, Score 79.000000, "Truck/TIRParkArea" and "Truck/TIRWarehouse" are swapped, with feasibility 1
Order 22, Score 79.000000, "Truck/TIRParkArea" and "SocialPlace" are swapped, with feasibility 1
Order 23, Score 79.000000, "Truck/TIRWarehouse" and "SocialPlace" are swapped, with feasibility 1
Order 24, Score 92.000000, "FireDepartment" and "CarParkArea" are swapped, with feasibility 1
Order 25, Score 83.000000, "SocialPlace" and "Office" are swapped, with feasibility 1
Order 26, Score 84.000000, "SocialPlace" and "GasStation" are swapped, with feasibility 1
Order 27, Score 93.000000, "SocialPlace" and "CarParkArea" are swapped, with feasibility 1
Order 28, Score 90.000000, "Infrastructure" and "CarParkArea" are swapped, with feasibility 1

Depts "Infrastructure" and "GasStation" in run 1 are swapped
Best score is 99.000000 with Index 15 in run 1
```

Figure 5.7: Sample Results.txt - 1

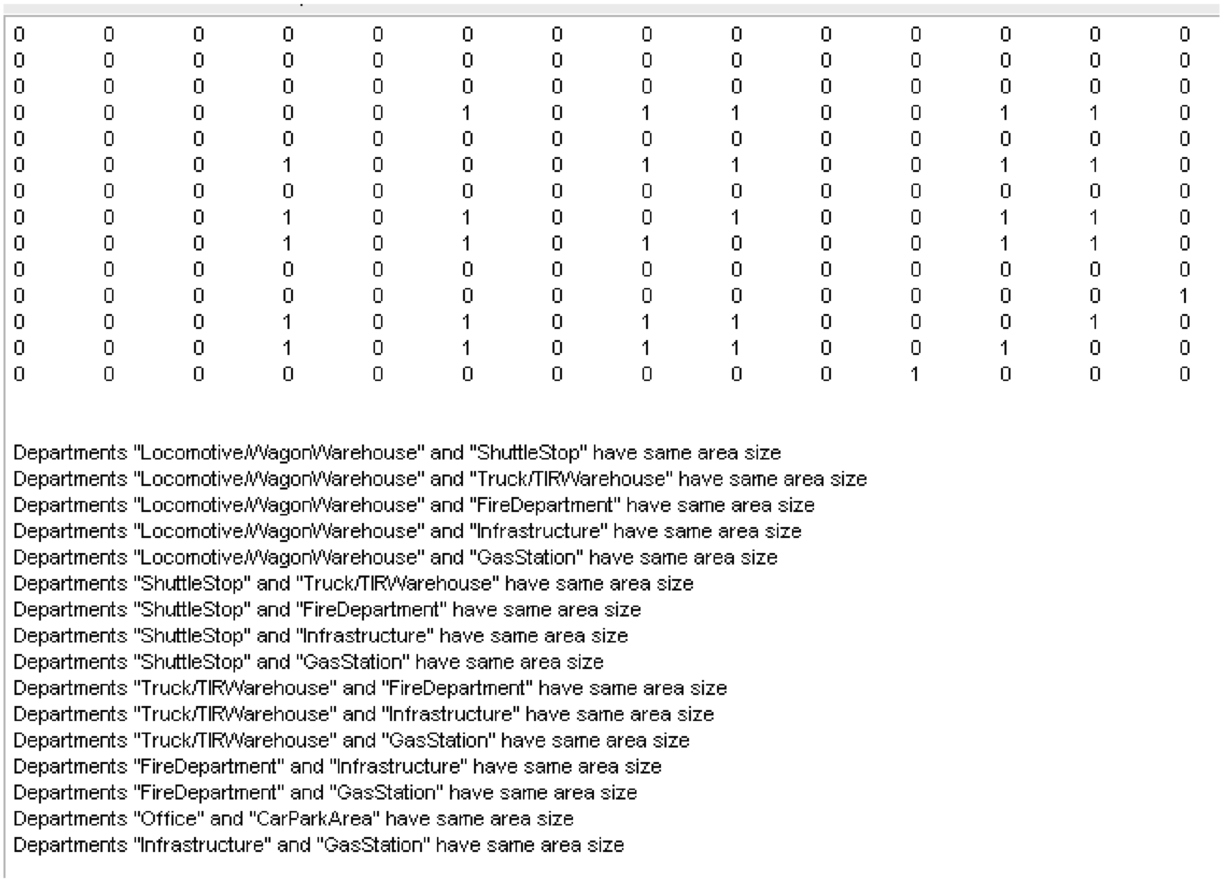
```
Order 0, Score 81.000000, "Locomotive/WagonWarehouse" and "ShuttleStop" are swapped, with feasibility 1
Order 1, Score 78.000000, "Locomotive/WagonWarehouse" and "Truck/TIRWarehouse" are swapped, with feasibility 1
Order 2, Score 89.000000, "Locomotive/WagonWarehouse" and "FireDepartment" are swapped, with feasibility 1
Order 3, Score -1.000000, "Locomotive/WagonWarehouse" and "Infrastructure" are swapped, with feasibility -1
Order 4, Score -1.000000, "Locomotive/WagonWarehouse" and "GasStation" are swapped, with feasibility -1
Order 5, Score 100.000000, "ShuttleStop" and "Truck/TIRWarehouse" are swapped, with feasibility 1
Order 6, Score 94.000000, "ShuttleStop" and "FireDepartment" are swapped, with feasibility 1
Order 7, Score -1.000000, "ShuttleStop" and "Infrastructure" are swapped, with feasibility -1
Order 8, Score -1.000000, "ShuttleStop" and "GasStation" are swapped, with feasibility -1
Order 9, Score 92.000000, "Truck/TIRWarehouse" and "FireDepartment" are swapped, with feasibility 1
Order 10, Score -1.000000, "Truck/TIRWarehouse" and "Infrastructure" are swapped, with feasibility -1
Order 11, Score -1.000000, "Truck/TIRWarehouse" and "GasStation" are swapped, with feasibility -1
Order 12, Score -1.000000, "FireDepartment" and "Infrastructure" are swapped, with feasibility -1
Order 13, Score -1.000000, "FireDepartment" and "GasStation" are swapped, with feasibility -1
Order 14, Score -1.000000, "Office" and "CarParkArea" are swapped, with feasibility -1
Order 15, Score 99.000000, "Infrastructure" and "GasStation" are swapped, with feasibility 1
Order 16, Score 93.000000, "Locomotive/WagonParkArea" and "Locomotive/WagonWarehouse" are swapped, with feasibility 1
Order 17, Score -1.000000, "ShuttleParkArea" and "ShuttleStop" are swapped, with feasibility -1
Order 18, Score -1.000000, "ShuttleParkArea" and "SocialPlace" are swapped, with feasibility -1
Order 19, Score -1.000000, "ShuttleParkArea" and "GasStation" are swapped, with feasibility -1
Order 20, Score 87.000000, "ShuttleStop" and "SocialPlace" are swapped, with feasibility 1
Order 21, Score -1.000000, "ShuttleStop" and "CarParkArea" are swapped, with feasibility -1
Order 22, Score 85.000000, "Truck/TIRParkArea" and "Truck/TIRWarehouse" are swapped, with feasibility 1
Order 23, Score 90.000000, "Truck/TIRParkArea" and "SocialPlace" are swapped, with feasibility 1
Order 24, Score 86.000000, "Truck/TIRWarehouse" and "SocialPlace" are swapped, with feasibility 1
Order 25, Score 90.000000, "SocialPlace" and "Office" are swapped, with feasibility 1
Order 26, Score -1.000000, "SocialPlace" and "GasStation" are swapped, with feasibility -1
Order 27, Score -1.000000, "SocialPlace" and "CarParkArea" are swapped, with feasibility -1
Order 28, Score 99.000000, "Infrastructure" and "CarParkArea" are swapped, with feasibility 1

Depts "ShuttleStop" and "Truck/TIRWarehouse" in run 2 are swapped
Best score is 100.000000 with Index 5 in run 2
```

Figure 5.8: Sample Results.txt - 2



```
Order 0, Score -1.000000, "Locomotive/WagonWarehouse" and "ShuttleStop" are swapped, with feasibility -1
Order 1, Score -1.000000, "Locomotive/WagonWarehouse" and "Truck/TIRWarehouse" are swapped, with feasibility -1
Order 2, Score 90.000000, "Locomotive/WagonWarehouse" and "FireDepartment" are swapped, with feasibility 1
Order 3, Score 91.000000, "Locomotive/WagonWarehouse" and "Infrastructure" are swapped, with feasibility 1
Order 4, Score 75.000000, "Locomotive/WagonWarehouse" and "GasStation" are swapped, with feasibility 1
Order 5, Score 100.000000, "ShuttleStop" and "Truck/TIRWarehouse" are swapped, with feasibility 1
Order 6, Score -1.000000, "ShuttleStop" and "FireDepartment" are swapped, with feasibility -1
Order 7, Score -1.000000, "ShuttleStop" and "Infrastructure" are swapped, with feasibility -1
Order 8, Score -1.000000, "ShuttleStop" and "GasStation" are swapped, with feasibility -1
Order 9, Score -1.000000, "Truck/TIRWarehouse" and "FireDepartment" are swapped, with feasibility -1
Order 10, Score -1.000000, "Truck/TIRWarehouse" and "Infrastructure" are swapped, with feasibility -1
Order 11, Score -1.000000, "Truck/TIRWarehouse" and "GasStation" are swapped, with feasibility -1
Order 12, Score 98.000000, "FireDepartment" and "Infrastructure" are swapped, with feasibility 1
Order 13, Score 94.000000, "FireDepartment" and "GasStation" are swapped, with feasibility 1
Order 14, Score 90.000000, "Office" and "CarParkArea" are swapped, with feasibility 1
Order 15, Score 87.000000, "Infrastructure" and "GasStation" are swapped, with feasibility 1
Order 16, Score 94.000000, "Locomotive/WagonParkArea" and "Locomotive/WagonWarehouse" are swapped, with feasibility 1
Order 17, Score -1.000000, "ShuttleParkArea" and "ShuttleStop" are swapped, with feasibility -1
Order 18, Score -1.000000, "ShuttleParkArea" and "SocialPlace" are swapped, with feasibility -1
Order 19, Score -1.000000, "ShuttleParkArea" and "Infrastructure" are swapped, with feasibility -1
Order 20, Score -1.000000, "ShuttleStop" and "SocialPlace" are swapped, with feasibility -1
Order 21, Score -1.000000, "Truck/TIRParkArea" and "Truck/TIRWarehouse" are swapped, with feasibility -1
Order 22, Score 86.000000, "Truck/TIRParkArea" and "SocialPlace" are swapped, with feasibility 1
Order 23, Score -1.000000, "Truck/TIRWarehouse" and "SocialPlace" are swapped, with feasibility -1
Order 24, Score 90.000000, "FireDepartment" and "CarParkArea" are swapped, with feasibility 1
Order 25, Score 90.000000, "SocialPlace" and "Office" are swapped, with feasibility 1
Order 26, Score 86.000000, "SocialPlace" and "Infrastructure" are swapped, with feasibility 1
Order 27, Score 91.000000, "SocialPlace" and "CarParkArea" are swapped, with feasibility 1
Order 28, Score 89.000000, "GasStation" and "CarParkArea" are swapped, with feasibility 1

Depts "ShuttleStop" and "Truck/TIRWarehouse" in run 3 are swapped
Best score is 100.000000 with Index 5 in run 3



Result Layout is written to ResultOutput.txt
RUN IS FINISHED

CPU time used: 3.109000
```

Figure 5.9: Sample Results.txt - 3



```
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	1	0	1	1	0	0	1	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	0	0	1	1	0	0	1	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	1	0	1	0	0	1	0	0	1	1	0
0	0	0	1	0	1	0	1	0	0	0	1	1	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	1	0	1	0	1	1	0	0	0	1	0
0	0	0	1	0	1	0	1	1	0	0	1	0	0
0	0	0	0	0	0	0	0	0	0	1	0	0	0


Departments "Locomotive/WagonWarehouse" and "ShuttleStop" have same area size
Departments "Locomotive/WagonWarehouse" and "Truck/TIRWarehouse" have same area size
Departments "Locomotive/WagonWarehouse" and "FireDepartment" have same area size
Departments "Locomotive/WagonWarehouse" and "Infrastructure" have same area size
Departments "Locomotive/WagonWarehouse" and "GasStation" have same area size
Departments "ShuttleStop" and "Truck/TIRWarehouse" have same area size
Departments "ShuttleStop" and "FireDepartment" have same area size
Departments "ShuttleStop" and "Infrastructure" have same area size
Departments "ShuttleStop" and "GasStation" have same area size
Departments "Truck/TIRWarehouse" and "FireDepartment" have same area size
Departments "Truck/TIRWarehouse" and "Infrastructure" have same area size
Departments "Truck/TIRWarehouse" and "GasStation" have same area size
Departments "FireDepartment" and "Infrastructure" have same area size
Departments "FireDepartment" and "GasStation" have same area size
Departments "Office" and "CarParkArea" have same area size
Departments "Infrastructure" and "GasStation" have same area size
```

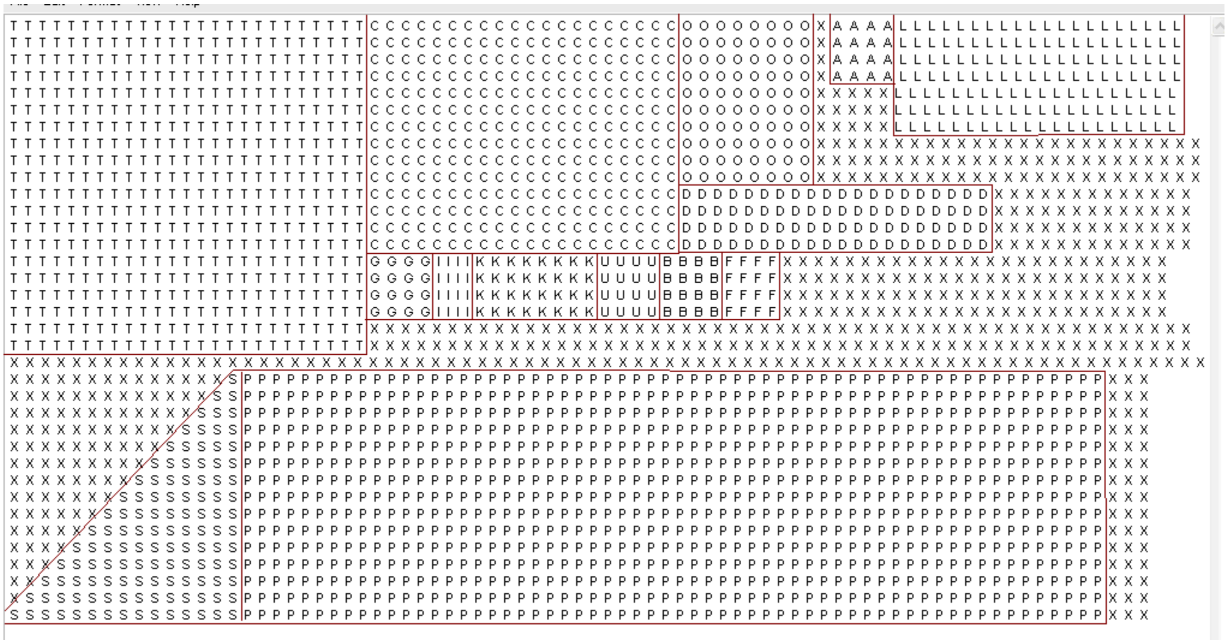
Figure 5.10: Sample SameSizeDepartments.txt

resulting in a total of 88 instances.

Mathematical model is coded in OPL 5.5 [25], and run with CPLEX 11.0. The operating system has 2 dual-core processors, each is 3 GHz Intel Xeon CPU 5160 and 4 GB of RAM.

Table 5.1 gives all of the parameters and the results for each instance. The explanation of column abbreviations are as follows:

1. I: instance number
2. S: system
3. P: platform structure
4. t: safety time interval
5. OP: number of original platforms



```
TTTTTTTTTTTTTTTTTTTTTTTTTCCCCCCCCCCCCCCCCCCCCOOOOOOOOXAAAALLLLLLLLLLLLLLLLLLLL
TTTTTTTTTTTTTTTTTTTTTTTTTCCCCCCCCCCCCCCCCCCCCOOOOOOOOXAAAALLLLLLLLLLLLLLLLLLLL
TTTTTTTTTTTTTTTTTTTTTTTTTCCCCCCCCCCCCCCCCCCCCOOOOOOOOXAAAALLLLLLLLLLLLLLLLLLLL
TTTTTTTTTTTTTTTTTTTTTTTTTCCCCCCCCCCCCCCCCCCCCOOOOOOOOXAAAALLLLLLLLLLLLLLLLLLLL
TTTTTTTTTTTTTTTTTTTTTTTTTCCCCCCCCCCCCCCCCCCCCOOOOOOOOXXXXXLLLLLLLLLLLLLLLLLLLL
TTTTTTTTTTTTTTTTTTTTTTTTTCCCCCCCCCCCCCCCCCCCCOOOOOOOOXXXXXLLLLLLLLLLLLLLLLLLLL
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TTTTTTTTTTTTTTTTTTTTTTTTTCCCCCCCCCCCCCCCCCCCCOOOOOOOOXXXXXXXXXXXXXXXXXXXXXXXXX
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TTTTTTTTTTTTTTTTTTTTTTTTTXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
XXXXXXXXXXXXXXSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
XXXXXXXXXXXXXSSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
XXXXXXXXXXXXSSSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
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XXXXXXXXXXSSSSSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
XXXXXXXXXSSSSSSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
XXXXXXXXSSSSSSSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
XXXXXXXSSSSSSSSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
XXXXXXSSSSSSSSSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
XXXXXSSSSSSSSSSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
XXXXSSSSSSSSSSSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
XXXSSSSSSSSSSSSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
XXSSSSSSSSSSSSSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
XSSSSSSSSSSSSSSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
SSSSSSSSSSSSSSSPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPPXXX
```

Figure 5.11: Sample ResultLayout.txt

6. AP: number of additional platforms
7. TP: total number of platforms
8. T: number of different (trains) required for two directions in a day
9. D: number of departures at two directions in a day
10. IM: % of difference between number of trains and departures to number of trains
11. TR: number of trucks carried in two directions in a day solely
12. TI: number of TIRs carried in two directions in a day solely
13. WV: averaged number of trucks/TIRs (total of 60% of TR and 40% of TI, 60% and 40% ratio is determined with the decision maker in IMPL), giving total transported number of trucks/TIRs
14. OF: optimal value of objective function (best integer)

Table 5.1: Result of mathematical model

I	**S**	**P**	**t**	**OP**	**AP**	**TP**	**T**	**D**	**IM**	**TR**	**TI**	**WV**	**OF**
1	O	L	5	6	6	12	84	92	9.52	4048	2024	3238	233772
2	O	L	5	6	5	11	84	92	9.52	4048	2024	3238	233772
3	O	L	5	6	4	10	84	92	9.52	4048	2024	3238	233772
4	O	L	6	5	5	10	72	76	5.56	3344	1672	2675	193116
5	O	L	6	5	4	9	72	76	5.56	3344	1672	2675	193116
6	O	L	7	5	5	10	62	66	6.45	2904	1452	2323	167706
7	O	L	7	5	4	9	62	66	6.45	2904	1452	2323	167706
8	O	L	7	5	3	8	62	66	6.45	2904	1452	2323	167706
9	O	L	8	4	4	8	56	58	3.57	2552	1276	2042	147378
10	O	L	8	4	3	7	56	58	3.57	2552	1276	2042	147378
11	O	L	9	4	4	8	50	52	4	2288	1144	1830	132132
12	O	L	9	4	3	7	50	52	4	2288	1144	1830	132132
13	O	L	10	3	3	6	42	48	14.3	2112	1056	1690	121968
14	O	L	10	3	2	5	42	48	14.3	2112	1056	1690	121968
15	O	L	12	3	3	6	38	40	5.26	1760	880	1408	101640
16	O	L	12	3	2	5	38	40	5.26	1760	880	1408	101640
17	O	C	5	6	6	12	82	92	12.2	4048	2024	3238	233772
18	O	C	5	6	5	11	82	92	12.2	4048	2024	3238	233772
19	O	C	5	6	4	10	82	92	12.2	4048	2024	3238	233772
20	O	C	6	5	5	10	72	76	5.56	3344	1672	2675	193116
21	O	C	6	5	4	9	72	76	5.56	3344	1672	2675	193116
22	O	C	7	5	5	10	62	66	6.45	2904	1452	2323	167706
23	O	C	7	5	4	9	62	66	6.45	2904	1452	2323	167706
24	O	C	7	5	3	8	62	66	6.45	2904	1452	2323	167706
25	O	C	8	4	4	8	54	58	7.41	2552	1276	2042	147378
26	O	C	8	4	3	7	54	58	7.41	2552	1276	2042	147378
27	O	C	9	4	4	8	50	52	4	2288	1144	1830	132132
28	O	C	9	4	3	7	50	52	4	2288	1144	1830	132132
29	O	C	10	3	3	6	42	48	14.3	2112	1056	1690	121968
30	O	C	10	3	2	5	42	48	14.3	2112	1056	1690	121968
31	O	C	12	3	3	6	38	40	5.26	1760	880	1408	101640
32	O	C	12	3	2	5	38	40	5.26	1760	880	1408	101640
33	M	L	5	8	9	17	94	100	6.38	4000	2600	3440	212520
34	M	L	5	8	8	16	94	100	6.38	4000	2600	3440	212520
35	M	L	6	7	8	15	76	84	10.5	3360	2184	2890	178517
36	M	L	6	7	7	14	76	84	10.5	3360	2184	2890	178517
37	M	L	7	6	7	13	66	72	9.09	2880	1872	2477	153014
38	M	L	7	6	6	12	66	72	9.09	2880	1872	2477	153014
39	M	L	8	5	6	11	56	64	14.3	2560	1664	2202	136013
40	M	L	8	5	5	10	56	64	14.3	2560	1664	2202	136013
41	M	L	9	5	6	11	52	58	11.5	2320	1508	1995	123262
42	M	L	9	5	5	10	52	58	11.5	2320	1508	1995	123262
43	M	L	10	4	5	9	46	52	13	2080	1352	1789	110510
44	M	L	10	4	4	8	46	52	13	2080	1352	1789	110510
45	M	L	12	4	5	9	40	44	10	1760	1144	1514	93508,8
46	M	L	12	4	4	8	40	44	10	1760	1144	1514	93508,8
47	M	C	5	8	9	17	92	100	8.7	4000	2600	3440	212520
48	M	C	5	8	8	16	92	100	8.7	4000	2600	3440	212520
49	M	C	6	7	8	15	74	84	13.5	3360	2184	2890	178517
50	M	C	6	7	7	14	74	84	13.5	3360	2184	2890	178517

Continued on next page

Table 5.1 – continued from previous page

I	S	P	t	OP	AP	TP	T	D	IM	TR	TI	WV	OF
51	M	C	7	6	7	13	64	72	12.5	2880	1872	2477	153014
52	M	C	7	6	6	12	64	72	12.5	2880	1872	2477	153014
53	M	C	8	5	6	11	56	64	14.3	2560	1664	2202	136013
54	M	C	8	5	5	10	56	64	14.3	2560	1664	2202	136013
55	M	C	9	5	6	11	50	58	16	2320	1508	1995	123262
56	M	C	9	5	5	10	50	58	16	2320	1508	1995	123262
57	M	C	10	4	5	9	44	52	18.2	2080	1352	1789	110510
58	M	C	10	4	4	8	44	52	18.2	2080	1352	1789	110510
59	M	C	12	4	5	9	40	44	10	1760	1144	1514	93508,8
60	M	C	12	4	4	8	40	44	10	1760	1144	1514	93508,8
61	E	L	5	6	9	15	84	108	28.6	4752	2376	3802	274428
62	E	L	5	6	8	14	84	108	28.6	4752	2376	3802	274428
63	E	L	6	5	9	14	70	90	28.6	3960	1980	3168	228690
64	E	L	6	5	8	13	70	90	28.6	3960	1980	3168	228690
65	E	L	7	5	7	12	58	76	31	3344	1672	2675	193116
66	E	L	7	5	6	11	58	76	31	3344	1672	2675	193116
67	E	L	8	4	7	11	52	68	30.8	2992	1496	2394	172788
68	E	L	8	4	6	10	52	68	30.8	2992	1496	2394	172788
69	E	L	9	4	7	11	48	62	29.2	2728	1364	2182	157542
70	E	L	9	4	6	10	48	62	29.2	2728	1364	2182	157542
71	E	L	10	3	5	8	44	56	27.3	2464	1232	1971	142296
72	E	L	10	3	4	7	44	56	27.3	2464	1232	1971	142296
73	E	L	12	3	5	8	36	46	27.8	2024	1012	1619	116886
74	E	L	12	3	4	7	36	46	27.8	2024	1012	1619	116886
75	E	C	5	6	8	14	82	108	31.7	4752	2376	3802	274428
76	E	C	5	6	7	13	82	108	31.7	4752	2376	3802	274428
77	E	C	6	5	9	14	70	90	28.6	3960	1980	3168	228690
78	E	C	6	5	8	13	70	90	28.6	3960	1980	3168	228690
79	E	C	7	5	7	12	58	76	31	3344	1672	2675	193116
80	E	C	7	5	6	11	58	76	31	3344	1672	2675	193116
81	E	C	8	4	7	11	52	68	30.8	2992	1496	2394	172788
82	E	C	8	4	6	10	52	68	30.8	2992	1496	2394	172788
83	E	C	9	4	8	12	46	62	34.8	2728	1364	2182	157542
84	E	C	9	4	7	11	46	62	34.8	2728	1364	2182	157542
85	E	C	10	3	4	7	42	56	33.3	2464	1232	1971	142296
86	E	C	10	3	3	6	42	56	33.3	2464	1232	1971	142296
87	E	C	12	3	5	8	36	46	27.8	2024	1012	1619	116886
88	E	C	12	3	4	7	36	46	27.8	2024	1012	1619	116886

Table 5.2 gives all of the model statistics. The explanation of column abbreviations are as follows:

1. I: instance number
2. S: system
3. P: platform structure
4. t: safety time interval

5. TP: total number of platforms
6. T: number of different (trains) required for two directions in a day
7. V: number of binary decision variables
8. C: number of constraints
9. NZC: non-zero coefficients
10. IT: number of iterations to find best integer
11. TIM: computation time to find best integer (seconds)
12. G: gap, % of the difference between the best node solution and a theoretical bound that an optimizer engine, i.e., CPLEX, etc. can provide according to the bound

Table 5.2: Statistics of mathematical model

I	**S**	**P**	**t**	**TP**	**T**	**V**	**C**	**NZC**	**IT**	**TIM**	**G**
1	O	L	5	12	84	483840	677684	2375520	479559	17697	0
2	O	L	5	11	84	443520	621616	2177560	476012	31193	0
3	O	L	5	10	84	403200	565548	1979600	532339	42255	0
4	O	L	6	10	72	285120	328236	1232380	275754	3034	0
5	O	L	6	9	72	256608	295754	1108872	279024	5486	0
6	O	L	7	10	62	219604	271246	1354038	290546	5996	0
7	O	L	7	9	62	198276	248846	1244028	244654	4062	0
8	O	L	7	8	62	176948	226454	1094118	257637	4366	0
9	O	L	8	8	56	140336	158234	758318	184084	2750	0
10	O	L	8	7	56	123424	142912	692010	163418	918	0
11	O	L	9	8	50	112000	586136	669234	124526	1103	0
12	O	L	9	7	50	98500	102796	516424	123381	714	0
13	O	L	10	6	42	65016	62454	335232	59218	123	0
14	O	L	10	5	42	54684	55048	282936	63207	137	0
15	O	L	12	6	38	49248	41838	221032	42685	61	0
16	O	L	12	5	38	41420	36708	186440	41963	58	0
17	O	C	5	12	82	470352	628002	2275920	463852	16254	0
18	O	C	5	11	82	431156	576074	2086260	458480	17487	0
19	O	C	5	10	82	391960	524146	1896600	449167	15390	0
20	O	C	6	10	72	285120	328236	1202380	275754	3034	0
21	O	C	6	9	72	256608	295754	1108872	279024	5486	0
22	O	C	7	10	62	219604	271246	1354038	290546	5996	0
23	O	C	7	9	62	198276	248846	1244028	244654	4062	0
24	O	C	7	8	62	176948	226454	1094118	257637	4366	0
25	O	C	8	8	54	134460	145150	759314	145410	1673	0
26	O	C	8	7	54	188260	131152	669234	135231	1191	0
27	O	C	9	8	50	112000	586136	669234	124526	1103	0
28	O	C	9	7	50	98500	102796	516424	123381	714	0
29	O	C	10	6	42	65016	62454	335232	59218	123	0
30	O	C	10	5	42	54684	55048	282936	63207	137	0
31	O	C	12	6	38	49248	41838	221032	42685	61	0

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Table 5.2 – continued from previous page

I	S	P	t	TP	T	V	C	NZC	IT	TIM	G
32	O	C	12	5	38	41420	36708	186440	41963	58	0
33	M	L	5	17	94	853332	1723850	5248172	703418	38207	0
34	M	L	5	16	94	803136	1622782	4939456	691397	30739	0
35	M	L	6	15	76	510720	918448	2944440	553991	28366	0
36	M	L	6	14	76	476672	857492	2748144	588377	37873	0
37	M	L	7	13	66	336204	563398	2331432	415993	9469	0
38	M	L	7	12	66	310860	523752	2156364	410077	13985	0
39	M	L	8	11	56	213248	312242	1377776	242575	3547	0
40	M	L	8	10	56	194320	286924	1256112	238112	3951	0
41	M	L	9	11	52	180336	253204	1095270	213020	2961	0
42	M	L	9	10	52	164320	232404	996524	234125	2293	0
43	M	L	10	9	46	116748	144902	657364	128716	806	0
44	M	L	10	8	46	104144	130834	586760	138539	1451	0
45	M	L	12	9	40	85920	93416	434952	91568	306	0
46	M	L	12	8	40	76640	84284	388152	90233	375	0
47	M	C	5	17	92	832048	1640548	5080280	719635	19572	0
48	M	C	5	16	92	783104	1544380	4781440	707193	24511	0
49	M	C	6	15	74	495060	866786	2839860	524722	19329	0
50	M	C	6	14	74	462056	809274	2650536	552880	21748	0
51	M	C	7	13	64	324352	530534	2264928	408881	10960	0
52	M	C	7	12	64	299904	493408	2094960	403250	14749	0
53	M	C	8	11	56	213248	312242	1377776	242575	3547	0
54	M	C	8	10	56	194320	286924	1256112	238122	3951	0
55	M	C	9	11	50	172300	235258	1056686	192764	2539	0
56	M	C	9	10	50	157000	216082	963244	202945	3213	0
57	M	C	10	9	44	110880	133128	633352	108334	829	0
58	M	C	10	8	44	98912	120360	565400	112828	965	0
59	M	C	12	9	40	85920	93416	434952	91568	306	0
60	M	C	12	8	40	76640	84284	388152	90233	375	0
61	E	L	5	15	84	708120	1263144	4344840	590199	24951	0
62	E	L	5	14	84	660912	1179372	4055184	797791	60709	0
63	E	L	6	14	70	458640	707292	2585100	495002	27649	0
64	E	L	6	13	70	425880	657104	2400450	491026	65382	0
65	E	L	7	12	58	280140	408572	1975156	322830	7235	0
66	E	L	7	11	58	257288	378430	1815068	330638	7116	0
67	E	L	8	11	52	206024	273472	1345608	226786	3000	0
68	E	L	8	10	52	187720	251604	1226784	224799	6197	0
69	E	L	9	11	48	189312	241992	1169820	199200	3519	0
70	E	L	9	10	48	158400	205584	979520	195143	6678	0
71	E	L	10	8	44	117216	123306	646920	114733	609	0
72	E	L	10	7	44	91872	99838	509786	159385	2336	0
73	E	L	12	8	36	70128	66336	361496	61321	146	0
74	E	L	12	7	36	61632	59414	317982	99287	337	0
75	E	C	5	14	82	640584	1017586	3731784	531780	63172	0
76	E	C	5	13	82	594828	945370	3465228	750002	69136	0
77	E	C	6	14	70	456680	650592	2475060	466112	24061	0
78	E	C	6	13	70	424060	604454	2298270	459409	40291	0
79	E	C	7	12	58	280140	408572	1975156	322830	7235	0
80	E	C	7	11	58	257288	378430	1815068	330638	7116	0
81	E	C	8	11	52	204880	248040	1296680	217875	3553	0
82	E	C	8	10	52	186680	228484	1182304	206494	3411	0

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Table 5.2 – continued from previous page

I	S	P	t	TP	T	V	C	NZC	IT	TIM	G
83	E	C	9	12	46	180320	219590	1123196	870738	9492	0
84	E	C	9	11	46	165600	203246	1031918	772420	11216	0
85	E	C	10	7	42	87108	89200	485688	94744	859	0
86	E	C	10	6	42	75096	78958	419328	95877	1402	0
87	E	C	12	8	36	70128	66336	361496	61321	146	0
88	E	C	12	7	36	61632	59414	317982	99287	337	0

Parameters differ for each system and for each platform structure and transfer time changes. OP is the original platforms, where trains are allowed to depart a second time, but in AP (additional platforms), this is not possible to ensure that each time a train departs. In each system, the number of trucks/TIRs carried in one trip differs, so for each instance, the total number of transported trucks/TIRs is calculated. Objective function is to minimize the total of three cost elements (transportation, haulage and maintenance). Number of constraints is the total number of all types of constraints ($\leq$, $\geq$, $=$). As t decreases, the number of departures gets more frequent and the number of variables and constraints increases. Instance 33 has the most number of variables and constraints, with 850,000 and 1,720,000, respectively. Scheduling of trains is an NP-hard problem [26, 38, 51]. In the scheduling models, as the number of variables and constraints increases, the chance to solve the problem in a reasonable amount of time decreases. Also, in this train scheduling problem, there are many alternative optima. The number of alternative optima depends on the number of trains, platforms and periods. As the values of these parameters increase, the number of alternative optima also increases exponentially. This is an additional factor that affects the complexity of the problem to cause long computational times. For example, in instance 33, CPLEX 11 engine found objective function value 212,520 in 38207 seconds. In general, when the computation time of all of the instances is analyzed, although this is a scheduling problem having many alternative optima with great number of variables and constraints, it can be said that computation time is fairly low. The reason for this can be the effective constraints which leads to shrinking solution space as much as possible. In order to decrease the fixed costs of train locomotives and wagons, the same train should be departed as much as possible. Therefore, it is better if the percentage of difference between the number of trains and departures to the number of trains is higher. In instances 83 and 84, 34.8% is the best value, i.e., 35% of the trains depart second time. In these instances, the trains are used the most frequently. In instances 61, 62, 75 and 76, the largest number of trucks/TIRs (3802) are carried in one travel. This means that the excess demand can be met with limited supply as much as possible.

Appendix B contains the Gantt charts of the results of sample trains and platforms in the train scheduling problem.

5.4 Sensitivity of Model to Logic Constraints

In the mathematical model explained in 4.3, the constraints are partitioned into two sets. The constraints between (4.2) and (4.22) are the logic constraints, while the remaining constraints are time constraints. As seen in table 5.2, although there exist large number of variables and constraints in some instances, the time to find the best integer is low and the gap is 0. In order to explain the issues of the model, the structure of the constraints should be highlighted. The presence of all of the time constraints are mandatory to schedule all of the train operations in a sensible manner to prevent all of the conflicts. Therefore, logic constraints can be evaluated deeply to understand the structure of the IP model.

To fully understand the effect of logic constraints, the model were run without some of the logic constraints. For this analysis, the instance 16 with Oekombi system, linear platform structure, safety time interval of 12 mins and 5 platforms in one station is chosen as a sample instance because it requires lower computation time. The model in this instance was run by removing some of the logic constraints. Table 5.3 gives all of the information about computation time and solution quality in some cases. The explanation of column abbreviations are as follows:

1. CN: case number
2. RC: removed constraint(s)
3. BI: best integer (objective function) value
4. BN: best node value
5. T: computation time to find best integer (seconds)

6. G: gap, % of the difference between the best node solution and a theoretical bound that an optimizer engine, i.e., CPLEX, etc. can provide according to the bound
7. F: feasibility of the model

Table 5.3: Results of Sample Instance with subject to Logic Constraints

CN	**RC**	**BI**	**BN**	**T**	**G**	**F**
1	none	242000	242000	58	0	feasible
2	(4.2)	242000	242000	64	0	infeasible
3	(4.3)	242000	242000	67	0	feasible
4	(4.4)	242000	242000	69	0	feasible
5	(4.5)	242000	242000	123	0	feasible
6	(4.6)	242000	242000	68	0	feasible
7	(4.7)	242000	242000	91	0	feasible
8	(4.8)	242000	242000	112	0	feasible
9	(4.9)	242000	242000	64	0	feasible
10	(4.10)	242000	242000	89	0	infeasible
11	(4.11)	242000	242000	61	0	feasible
12	(4.12-13)	242000	242000	1325	0	feasible
13	(4.14-15)	242000	241690	86400	0.128796	feasible
14	(4.16-17)	242000	242000	132	0	feasible
15	(4.18-19)	242000	242000	71	0	feasible
16	(4.20-21)	242000	242000	65	0	feasible
17	(4.22)	242000	242000	60	0	feasible
18	(4.3,12-13,16-22)	242000	241960	86400	0.018384	feasible
19	(4.3-4,9,11-13,16-22)	242000	241950	86400	0.020818	feasible
20	(4.12-13,16-22)	242000	241968	86400	0.014941	feasible
21	(4.4-9,12-13,16-22)	242000	241951	86400	0.020253	feasible

In table 5.3, 21 cases of instance 16 are evaluated. In each case, some logic constraints were removed from the model and the model was run again. In case 1, none of the logic constraints were removed. In case 2, constraint (4.2) was removed and it gives optimal solution again with gap 0, requiring more computation time. In case 2, both constraints (4.12) and (4.13) were removed. In case 18, constraints (4.3), (4.12), (4.13), (4.16), (4.17), (4.18), (4.19), (4.20), (4.21) and (4.22) were removed. In cases 2 and 10, infeasible solution was found, therefore the constraints (4.2) and (4.10) are very important for the feasibility of the model. In five cases (13, 18, 19, 20 and 21), although the optimizer engine was able to find the best integer, it couldn't reduce the gap to 0. The computation time limit for these cases was 24 hours (86400 seconds). For instance in case 13, only constrains (4.14) and (4.15) were removed. Although, instance 16 can be solved in 58 seconds with all of the logic constraints, in case 13, after 86400 seconds, the gap was not 0, meaning that these two constraints are critical for the solution quality, ie., to obtain the optimal solution in low time. The status that optimizer engine could not find the optimal solution with 0 gap explains the importance of the logic constraints for this model. With the implementation of these effective logic constraints, in all 88 instances, the optimal solutions are obtained with 0 gap and with low computation times. The pattern of these logic constraints in instance 16 is applicable to all of the 88 instances which were covered in the mathematical model.

5.5 Costs of Train Operations

In this thesis, the purpose is to study an integrated model for Marmaray system. Three main cost elements are expected to occur: fixed cost of investment for stations, fixed cost of investment for trains (locomotives and wagons) and variable cost of operational actions.

Cost of stations is the first investment cost. Also, cost of land can be included in this type of investment cost. Production costs of loading/unloading platforms also is part of the cost of stations. Cost of one platform is 25,000 YTL in Oekombi and Eurotunnel systems, while this is 100,000 YTL in Modalohr. The platform investment cost is high in Modalohr, because, it requires more complex equipment, compared to other systems. In OE and EU, truck or TIR is not subject to any operation, loaded immediately to wagon linearly. But in MO, for TIR, tractor and trailer are separated apart, each is loaded into different type of wagons. Also, loading of trailers is done with a crosswise angle, thus requiring two hydraulic equipments: 1. under wagon, to lift wagon and move in crosswise direction, 2. on the road, to lock road and wagon to load trailer from road to wagon. Because of these and other special equipments and operations required by unique structure of loading in Modalohr, the platform cost is high. When all three initial station layouts are considered, the area is a rectangular space, in average, 250,000 m^2 size of area is required.

Train investment cost is the total cost for all of the equipments of a train. This cost includes locomotive (engine) and wagon cost. Based on the data obtained from MTTR and TLEI, diesel engine locomotive type DE 33000 will be used for Ro-La transportation. Cost of this type of locomotive is 3,750,000 YTL, and its technical life is 35 years, if maintenance is handled periodically. For one (unit) technical life, fixed cost is 100,000 YTL. According to data from TRMI and the Greenbrier Companies (supplier of transportation equipment and services to the railroad industry), cost of a wagon is 380,000 YTL, with technical life of 40 years. So, fixed cost of unit life is 9,500 YTL. Because of special loading structure in MO, wagon properties are more unique, but the cost of equipments bringing this uniqueness is considered in the platform cost, instead of the train cost.

Operation costs include the cost of operators working for loading/unloading operation at platforms, energy costs and maintenance costs of platforms. This cost element does not consist of the first investment cost of loading/unloading platforms, because this investment cost is part of the station investment cost. Based on data from SRTR, transportation cost for a train in 1 km is 9 YTL. When road transportation is analyzed, as another mode other than rail, fuel consumption cost of TIR is 0.8 YTL/km. When the road passage costs are included to this (length of travel is 231 km between Çerkezköy and Köseköy), transportation cost becomes 0.97 YTL/km. On the other hand, consumption cost of a truck is 0.5 YTL/km, and total transportation cost is 0.67 YTL/km.

The transportation cost for each truck/TIR in a train can be calculated with 9 YTL/km and for 231 km distance. In Oekombi system, 22 TIRs are carried in one travel. If the number of TIRs is considered approximately 20, transportation cost for one TIR is 0.45 YTL/km. This cost value is much lower than 0.97 YTL, cost of road transportation. For truck, in a travel, 40 trucks can be carried, so resulting in 0.225 YTL/km cost in rail transportation. Also, this is much better than 0.67 YTL, in road mode. When the transportation cost of one vehicle in two modes is compared, the great cost advantage of rail mode, i.e., Ro-La transportation, can be observed clearly.

Table 5.4 include the transportation costs (YTL/km) of truck and TIR in rail and road modes, in 231 km distance, for each system.

According to data obtained from the systems, Table 5.5 shows all of the cost elements (YTL/km) and by using these data, Table 5.6 gives transportation costs (YTL/km) for each vehicle in rail and road.

When the values in Tables 5.4 and 5.6 are compared, it is seen that the cost elements

Table 5.4: Transportation costs based on SRTR data

	Vehicle	**TIR**		**Truck**	
		Rail	**Road**	**Rail**	**Road**
System					
Oekombi		0.42	0.97	0.21	0.67
Modalohr		0.34	0.97	0.22	0.67
Eurotunnel		0.5	0.97	0.25	0.67

Table 5.5: Cost elements in systems

	Cost	**Transportation**	**Haulage**	**Maintenance**
System				
Oekombi		4	6	1
Modalohr		0.6	6	2.6
Eurotunnel		4	6	1

Table 5.6: Transportation costs based on systems' data

	Vehicle	**TIR**		**Truck**	
		Rail	**Road**	**Rail**	**Road**
System					
Oekombi		0.5	0.97	0.25	0.67
Modalohr		0.35	0.97	0.23	0.67
Eurotunnel		0.61	0.97	0.3	0.67

from SRTR and the systems are very close to each other, which means that the data obtained from the systems are reasonable, and applicable to real life.

Table 5.7 shows all of the costs for each instance. This table is prepared by using values in Table 5.6. The explanation of column abbreviations are as follows:

1. I: instance number
2. S: system
3. P: platform structure
4. t: safety time interval
5. OP: number of original platforms
6. AP: number of additional platforms
7. TP: total number of platforms
8. T: number of different (trains) required for two directions in a day
9. D: number of departures at two directions in a day
10. TR: number of trucks carried in two directions in a day solely
11. TI: number of TIRs carried in two directions in a day solely
12. OF: optimal value of objective function (best integer)
13. TC: unit year fixed cost of all trains (locomotives+wagons)
14. PC: fixed cost of investment for platforms
15. $ACTR$: additional road transportation cost for trucks
16. $ACTI$: additional road transportation cost for TIRs
17. ARC: additional averaged road cost (total of 60% of ACTR and 40% of ACTI)
18. TOC: total of rail transportation cost (OF) and additional averaged road cost (ARC)

Table 5.7: Transportation costs of instances

I	**S**	**P**	**t**	**TP**	**T**	**D**	**TR**	**TI**	**OF**	**TC**	**PC**	**ACTR**	**ACTI**	**ARC**	**TOC**
1	O	L	5	12	84	92	4048	2024	233772	18396000	300000	108958.08	129064.32	117000.6	350772.6
2	O	L	5	11	84	92	4048	2024	233772	18396000	275000	108958.08	129064.32	117000.6	350772.6
3	O	L	5	10	84	92	4048	2024	233772	18396000	250000	108958.08	129064.32	117000.6	350772.6
4	O	L	6	10	72	76	3344	1672	193116	15768000	250000	217916.16	207936.96	213924.5	407040.5
5	O	L	6	9	72	76	3344	1672	193116	15768000	225000	217916.16	207936.96	213924.5	407040.5
6	O	L	7	10	62	66	2904	1452	167706	13578000	250000	286014.96	257232.36	274501.9	442207.9

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Table 5.7 – continued from previous page

I	S	P	t	TP	T	D	TR	TI	OF	TC	PC	ACTR	ACTI	ARC	TOC
7	O	L	7	9	62	66	2904	1452	167706	13578000	225000	286014.96	257232.36	274501.9	442207.9
8	O	L	7	8	62	66	2904	1452	167706	13578000	200000	286014.96	257232.36	274501.9	442207.9
9	O	L	8	8	56	58	2552	1276	147378	12264000	200000	340494	296668.68	322963.9	470341.9
10	O	L	8	7	56	58	2552	1276	147378	12264000	175000	340494	296668.68	322963.9	470341.9
11	O	L	9	8	50	52	2288	1144	132132	10950000	200000	381353.28	326245.92	359310.3	491442.3
12	O	L	9	7	50	52	2288	1144	132132	10950000	175000	381353.28	326245.92	359310.3	491442.3
13	O	L	10	6	42	48	2112	1056	121968	9198000	150000	408592.8	345964.08	383541.3	505509.3
14	O	L	10	5	42	48	2112	1056	121968	9198000	125000	408592.8	345964.08	383541.3	505509.3
15	O	L	12	6	38	40	1760	880	101640	8322000	150000	463071.84	385400.4	432003.3	533643.3
16	O	L	12	5	38	40	1760	880	101640	8322000	125000	463071.84	385400.4	432003.3	533643.3
17	O	C	5	12	82	92	4048	2024	233772	17958000	300000	108958.08	129064.32	117000.6	350772.6
18	O	C	5	11	82	92	4048	2024	233772	17958000	275000	108958.08	129064.32	117000.6	350772.6
19	O	C	5	10	82	92	4048	2024	233772	17958000	250000	108958.08	129064.32	117000.6	350772.6
20	O	C	6	10	72	76	3344	1672	193116	15768000	250000	217916.16	207936.96	213924.5	407040.5
21	O	C	6	9	72	76	3344	1672	193116	15768000	225000	217916.16	207936.96	213924.5	407040.5
22	O	C	7	10	62	66	2904	1452	167706	13578000	250000	286014.96	257232.36	274501.9	442207.9
23	O	C	7	9	62	66	2904	1452	167706	13578000	225000	286014.96	257232.36	274501.9	442207.9
24	O	C	7	8	62	66	2904	1452	167706	13578000	200000	286014.96	257232.36	274501.9	442207.9
25	O	C	8	8	54	58	2552	1276	147378	11826000	200000	340494	296668.68	322963.9	470341.9
26	O	C	8	7	54	58	2552	1276	147378	11826000	175000	340494	296668.68	322963.9	470341.9
27	O	C	9	8	50	52	2288	1144	132132	10950000	200000	381353.28	326245.92	359310.3	491442.3
28	O	C	9	7	50	52	2288	1144	132132	10950000	175000	381353.28	326245.92	359310.3	491442.3
29	O	C	10	6	42	48	2112	1056	121968	9198000	150000	408592.8	345964.08	383541.3	505509.3
30	O	C	10	5	42	48	2112	1056	121968	9198000	125000	408592.8	345964.08	383541.3	505509.3
31	O	C	12	6	38	40	1760	880	101640	8322000	150000	463071.84	385400.4	432003.3	533643.3
32	O	C	12	5	38	40	1760	880	101640	8322000	125000	463071.84	385400.4	432003.3	533643.3
33	M	L	5	17	94	100	4000	2600	212520	36660000	1700000	116387.04	0	69832.22	282352.2
34	M	L	5	16	94	100	4000	2600	212520	36660000	1600000	116387.04	0	69832.22	282352.2
35	M	L	6	15	76	84	3360	2184	178517	29640000	1500000	215439.84	93213.12	166549.2	345066
36	M	L	6	14	76	84	3360	2184	178517	29640000	1400000	215439.84	93213.12	166549.2	345066
37	M	L	7	13	66	72	2880	1872	153014	25740000	1300000	289729.44	163122.96	239086.8	392101.2
38	M	L	7	12	66	72	2880	1872	153014	25740000	1200000	289729.44	163122.96	239086.8	392101.2
39	M	L	8	11	56	64	2560	1664	136013	21840000	1100000	339255.84	209729.52	287445.3	423458.1
40	M	L	8	10	56	64	2560	1664	136013	21840000	1000000	339255.84	209729.52	287445.3	423458.1
41	M	L	9	11	52	58	2320	1508	123262	20280000	1100000	376400.64	244684.44	323714.2	446975.8
42	M	L	9	10	52	58	2320	1508	123262	20280000	1000000	376400.64	244684.44	323714.2	446975.8
43	M	L	10	9	46	52	2080	1352	110510	17940000	900000	413545.44	279639.36	359983	470493.4
44	M	L	10	8	46	52	2080	1352	110510	17940000	800000	413545.44	279639.36	359983	470493.4
45	M	L	12	9	40	44	1760	1144	93508,8	15600000	900000	463071.84	326245.92	408341.5	501850.3
46	M	L	12	8	40	44	1760	1144	93508,8	15600000	800000	463071.84	326245.92	408341.5	501850.3
47	M	C	5	17	92	100	4000	2600	212520	35880000	1700000	116387.04	0	69832.22	282352.2
48	M	C	5	16	92	100	4000	2600	212520	35880000	1600000	116387.04	0	69832.22	282352.2
49	M	C	6	15	74	84	3360	2184	178517	28860000	1500000	215439.84	93213.12	166549.2	345066
50	M	C	6	14	74	84	3360	2184	178517	28860000	1400000	215439.84	93213.12	166549.2	345066
51	M	C	7	13	64	72	2880	1872	153014	24960000	1300000	289729.44	163122.96	239086.8	392101.2
52	M	C	7	12	64	72	2880	1872	153014	24960000	1200000	289729.44	163122.96	239086.8	392101.2
53	M	C	8	11	56	64	2560	1664	136013	21840000	1100000	339255.84	209729.52	287445.3	423458.1
54	M	C	8	10	56	64	2560	1664	136013	21840000	1000000	339255.84	209729.52	287445.3	423458.1
55	M	C	9	11	50	58	2320	1508	123262	19500000	1100000	376400.64	244684.44	323714.2	446975.8
56	M	C	9	10	50	58	2320	1508	123262	19500000	1000000	376400.64	244684.44	323714.2	446975.8
57	M	C	10	9	44	52	2080	1352	110510	17160000	900000	413545.44	279639.36	359983	470493.4

Continued on next page

Table 5.7 – continued from previous page

I	S	P	t	TP	T	D	TR	TI	OF	TC	PC	ACTR	ACTI	ARC	TOC
58	M	C	10	8	44	52	2080	1352	110510	17160000	800000	413545.44	279639.36	359983	470493.4
59	M	C	12	9	40	44	1760	1144	93508,8	15600000	900000	463071.84	326245.92	408341.5	501850.3
60	M	C	12	8	40	44	1760	1144	93508,8	15600000	800000	463071.84	326245.92	408341.5	501850.3
61	E	L	5	15	84	108	4752	2376	274428	24780000	375000	0	50191.68	20076.67	294504.7
62	E	L	5	14	84	108	4752	2376	274428	24780000	350000	0	50191.68	20076.67	294504.7
63	E	L	6	14	70	90	3960	1980	228690	20650000	350000	122577.84	138923.4	129116.1	357806.1
64	E	L	6	13	70	90	3960	1980	228690	20650000	325000	122577.84	138923.4	129116.1	357806.1
65	E	L	7	12	58	76	3344	1672	193116	17110000	300000	217916.16	207936.96	213924.5	407040.5
66	E	L	7	11	58	76	3344	1672	193116	17110000	275000	217916.16	207936.96	213924.5	407040.5
67	E	L	8	11	52	68	2992	1496	172788	15340000	275000	272395.2	247373.28	262386.4	435174.4
68	E	L	8	10	52	68	2992	1496	172788	15340000	250000	272395.2	247373.28	262386.4	435174.4
69	E	L	9	11	48	62	2728	1364	157542	14160000	275000	313254.48	276950.52	298732.9	456274.9
70	E	L	9	10	48	62	2728	1364	157542	14160000	250000	313254.48	276950.52	298732.9	456274.9
71	E	L	10	8	44	56	2464	1232	142296	12980000	200000	354113.76	306527.76	335079.4	477375.4
72	E	L	10	7	44	56	2464	1232	142296	12980000	175000	354113.76	306527.76	335079.4	477375.4
73	E	L	12	8	36	46	2024	1012	116886	10620000	200000	422212.56	355823.16	395656.8	512542.8
74	E	L	12	7	36	46	2024	1012	116886	10620000	175000	422212.56	355823.16	395656.8	512542.8
75	E	C	5	14	82	108	4752	2376	274428	24190000	350000	0	50191.68	20076.67	294504.7
76	E	C	5	13	82	108	4752	2376	274428	24190000	325000	0	50191.68	20076.67	294504.7
77	E	C	6	14	70	90	3960	1980	228690	20650000	350000	122577.84	138923.4	129116.1	357806.1
78	E	C	6	13	70	90	3960	1980	228690	20650000	325000	122577.84	138923.4	129116.1	357806.1
79	E	C	7	12	58	76	3344	1672	193116	17110000	300000	217916.16	207936.96	213924.5	407040.5
80	E	C	7	11	58	76	3344	1672	193116	17110000	275000	217916.16	207936.96	213924.5	407040.5
81	E	C	8	11	52	68	2992	1496	172788	15340000	275000	272395.2	247373.28	262386.4	435174.4
82	E	C	8	10	52	68	2992	1496	172788	15340000	250000	272395.2	247373.28	262386.4	435174.4
83	E	C	9	12	46	62	2728	1364	157542	13570000	300000	313254.48	276950.52	298732.9	456274.9
84	E	C	9	11	46	62	2728	1364	157542	13570000	275000	313254.48	276950.52	298732.9	456274.9
85	E	C	10	7	42	56	2464	1232	142296	12390000	175000	354113.76	306527.76	335079.4	477375.4
86	E	C	10	6	42	56	2464	1232	142296	12390000	150000	354113.76	306527.76	335079.4	477375.4
87	E	C	12	8	36	46	2024	1012	116886	10620000	200000	422212.56	355823.16	395656.8	512542.8
88	E	C	12	7	36	46	2024	1012	116886	10620000	175000	422212.56	355823.16	395656.8	512542.8

OF shows the optimal value of the objective function in the train scheduling mathematical model for each instance. Also, with this model, the number of trains (T), departures (D), and trucks/TIRs (TR/TI) can be calculated. Calculation of the cost of rail transportation of trucks/TIRs solely is not sufficient to analyze the cost aspect of the system. The cost of trucks/TIRs that are transported on the road should also be evaluated to understand all of the costs that Ro-La transportation requires and which instance(s) is(are) more effective than others. In a daily time of operations, as a result of limited time, some trucks/TIRs are not able to be transported by rail, so Ro-La transportation cannot serve for them, and they will travel by road. The cost of road transportation of these trucks/TIRs is the additional cost to rail cost of Ro-La and must be analyzed to investigate the situation fully.

In order to understand which instance(s) is(are) more effective, the maximum number of carried trucks/TIRs should be calculated. Instance 61 has the maximum number of trucks, 4,752 in all instances. For TIRs, instance 33 has the maximum number, 2,600. These values are for all travels in two directions. In Section 5.2, for initial station layouts, the area of department Truck/TIR Park Area should consist of only 4752/2=2,376 trucks or only 2600/2=1,300 TIRs. Because of standard universal dimensions of a truck and TIR, the area of 1 TIR is approximately equivalent to the area of 2 trucks. Park area for 1,300 TIRs is already sufficient for 2,376 trucks. In the meetings with the decision maker in IMPL, it is determined that Truck/TIR Park Area should maintain a maximum of 1,600 trucks/TIRs. If the ratio of trucks and TIRs are 60% and 40%, respectively, in all of trucks/TIRs, a park area size with 1,300 TIRs is sufficient to handle 1,600 trucks/TIRs. Therefore, for all of the instances, the Truck/TIR Park Area should be designed such as to let 1,300 TIRs park at the same time.

It is possible to determine the best instance for each system and platform structure by analyzing train investment, platform investment and total transportation costs in Table 5.7. Although railroad transportation costs (objective function) is high (OE; 233,772 YTL, MO; 212,520 YTL, EU; 274,428 YTL) in instances with safety time interval 5 mins, when the additional road transportation costs of vehicles that could not be carried by rail is seen, total transportation cost (TOC) is minimum in instances with safety time interval of 5 mins. The most important factor is that, according to rail and road transportation cost values in Tables 5.4 and 5.6, because rail cost is much lower than road costs, the best and the most efficient way to minimize costs is to carry as many trucks/TIRs as possible with trains, while not violating system capacity. Therefore, based on the total operational costs, instances with t=5 should be selected.

The purpose of the integrated facility layout and train scheduling model is to find the number of platforms with the train scheduling model, and based on this number of platforms, to analyze how the facility layout reacts to this number of platforms, and what will be the total fixed and variable costs. As the number of platforms change, sizes of most departments will change, so the layout of facility will totally change. Because the number of parallel loading/unloading platforms is very critical for both problems, platform investment costs is very important to differentiate instances having the same safety time interval. For example, instances 1, 2 and 3 all have t=5, total rail transportation costs and fixed train investment costs are same. But, the total number of parallel platforms are different (12, 11 and 10, respectively), so platform investment costs are different. As a result, instance 3 causes minimum platform investment costs with 10 platforms. In the same way, when all of the instances are analyzed for each system and platform structure, six instances (3, 19, 34, 48, 62 and 76) are selected. In Section 5.6, for these six instances, three initial layouts are run with seven scoring options.

5.6 Integrated Model

Facility layout improvement algorithm is run, based on the parameters of six instances: 3, 19, 34, 48, 62 and 76, for each initial layout and scoring option. The results are shown in Tables 5.8, 5.9, 5.10, 5.11, 5.12, 5.13 and 5.14. IL1 means initial layout 1. The explanation of column abbreviations are as follows:

1. I: instance number
2. S: system
3. P: platform structure
4. t: safety time interval
5. OP: number of original platforms
6. AP: number of additional platforms
7. TP: total number of platforms
8. S: score of initial layout
9. F: score of final layout
10. IM: % improvement of difference between scores of initial and final layouts according to score of initial layout
11. L: number of loops required to obtain this final layout
12. T: time of the algorithm (in seconds)

Table 5.8: Results of Adjacency-based scoring by weight

I	S	P	t	OP	AP	TP	IL1					IL2					IL3				
							S	F	IM	L	T	S	F	IM	L	T	S	F	IM	L	T
3	O	L	5	6	4	10	451	552	22	1	2.58	379	442	17	1	1.72	357	424	18.8	1	1.17
19	O	C	5	6	4	10	451	563	25	2	2.13	379	442	17	1	1.47	357	424	18.8	1	1.84
34	M	L	5	8	8	16	511	511	0	0	1.28	436	499	14	1	2.81	385	502	30.4	3	1.94
48	M	C	5	8	8	16	511	511	0	0	1.59	436	499	14	1	2.13	385	502	30.4	3	2.08
62	E	L	5	6	8	14	511	511	0	0	1.61	436	499	14	1	1.47	385	502	30.4	3	1.89
76	E	C	5	6	7	13	511	511	0	0	1.19	436	499	14	1	1.66	385	502	30.4	3	2.16

Table 5.9: Results of Adjacency-based scoring by flow

I	S	P	t	OP	AP	TP	IL1					IL2					IL3				
							S	F	IM	L	T	S	F	IM	L	T	S	F	IM	L	T
3	O	L	5	6	4	10	92	100	8.7	2	3.11	107	109	1.9	1	2.63	78	88	12.8	2	1.47
19	O	C	5	6	4	10	92	100	8.7	2	3.42	107	109	1.9	1	5.09	78	88	12.8	2	2.48
34	M	L	5	8	8	16	101	101	0	0	1.89	105	107	1.9	1	3.22	97	109	12.4	4	2.64
48	M	C	5	8	8	16	101	101	0	0	1.81	105	107	1.9	1	4.08	97	109	12.4	4	2.52
62	E	L	5	6	8	14	101	101	0	0	2.16	105	107	1.9	1	1.53	97	109	12.4	4	2.25
76	E	C	5	6	7	13	101	101	0	0	1.98	105	107	1.9	1	3.08	97	109	12.4	4	2

Table 5.10: Results of Adjacency-based scoring by normalized flow

I	S	P	t	OP	AP	TP	IL1					IL2					IL3				
							S	F	IM	L	T	S	F	IM	L	T	S	F	IM	L	T
3	O	L	5	6	4	10	0.31	0.33	8.7	2	3.41	0.36	0.36	1.9	1	2.89	0.26	0.29	12.8	2	1.63
19	O	C	5	6	4	10	0.31	0.33	8.7	2	3.22	0.36	0.36	1.9	1	4.36	0.26	0.29	12.8	2	3.78
34	M	L	5	8	8	16	0.34	0.34	0	0	1.86	0.35	0.36	1.9	1	2.52	0.32	0.36	12.4	4	2.48
48	M	C	5	8	8	16	0.34	0.34	0	0	1.67	0.35	0.36	1.9	1	1.69	0.32	0.36	12.4	4	2.36
62	E	L	5	6	8	14	0.34	0.34	0	0	1.72	0.35	0.36	1.9	1	1.59	0.32	0.36	12.4	4	1.86
76	E	C	5	6	7	13	0.34	0.34	0	0	1.61	0.35	0.36	1.9	1	1.89	0.32	0.36	12.4	4	2.28

Table 5.11: Results of Adjacency-based scoring by normalized (-)/(+) flow

I	S	P	t	OP	AP	TP	IL1					IL2					IL3				
							S	F	IM	L	T	S	F	IM	L	T	S	F	IM	L	T
3	O	L	5	6	4	10	0.33	0.35	7.2	2	2.66	0.37	0.38	1.6	1	2.03	0.29	0.32	10.3	2	2.3
19	O	C	5	6	4	10	0.33	0.35	7.2	2	2.28	0.37	0.38	1.6	1	2.77	0.29	0.32	10.3	2	1.84
34	M	L	5	8	8	16	0.36	0.36	0	0	1.53	0.37	0.37	1.6	1	2.06	0.34	0.38	10.3	4	2.27
48	M	C	5	8	8	16	0.36	0.36	0	0	1.75	0.37	0.37	1.6	1	6.45	0.34	0.38	10.3	4	2.38
62	E	L	5	6	8	14	0.36	0.36	0	0	1.8	0.37	0.37	1.6	1	1.94	0.34	0.38	10.3	4	3.75
76	E	C	5	6	7	13	0.36	0.36	0	0	1.69	0.37	0.37	1.6	1	1.97	0.34	0.38	10.3	4	2.2

Table 5.12: Results of Distance-based scoring by flow

I	S	P	t	OP	AP	TP	IL1					IL2					IL3				
							S	F	IM	L	T	S	F	IM	L	T	S	F	IM	L	T
3	O	L	5	6	4	10	7912	7520	-5	3	2.95	7428	7072	-5	6	2.52	10084	8972	-11	7	3.22
19	O	C	5	6	4	10	7912	7040	-11	6	2.88	7428	7072	-5	6	4.56	10084	8972	-11	7	4.36
34	M	L	5	8	8	16	9520	7760	-18	6	2.88	9712	8776	-10	8	3.02	11312	10752	-5	7	3.14
48	M	C	5	8	8	16	9520	8492	-11	5	3.89	9712	8776	-10	8	2.8	11312	10752	-5	7	3.3
62	E	L	5	6	8	14	9304	8256	-11	5	2.88	9664	8744	-10	8	2.73	11276	10484	-7	8	2.48
76	E	C	5	6	7	13	9352	8296	-11	5	3.02	9676	8756	-10	8	4.77	11352	10552	-7	8	2.5

Table 5.13: Results of Distance-based scoring by cost of flow

I	S	P	t	OP	AP	TP	IL1					IL2					IL3				
							S	F	IM	L	T	S	F	IM	L	T	S	F	IM	L	T
3	O	L	5	6	4	10	37735	26506	-30	5	3.6	28751	27670	-4	3	3	42875	29802	-30	10	3
19	O	C	5	6	4	10	37735	26506	-30	5	3.1	28751	27670	-4	3	2.2	42875	29802	-30	10	3
34	M	L	5	8	8	16	44587	30659	-31	14	5.1	39235	30057	-23	6	3.2	46329	43009	-7	6	2.5
48	M	C	5	8	8	16	44587	36789	-17	7	3.9	39235	30057	-23	6	2.8	46329	43009	-7	6	2.3
62	E	L	5	6	8	14	43525	35770	-18	7	3.3	40029	30942	-23	6	2.6	45677	42252	-7	6	3.2
76	E	C	5	6	7	13	43777	36026	-18	7	3.4	40168	31079	-23	6	4.2	46060	42635	-7	6	2.9

Table 5.14: Results of Distance-weighted adjacency based scoring

I	S	P	t	OP	AP	TP	IL1					IL2					IL3				
							S	F	IM	L	T	S	F	IM	L	T	S	F	IM	L	T
3	O	L	5	6	4	10	22445	21216	-5	3	2.3	19950	16571	-17	7	2.1	24080	22456	-7	1	2.1
19	O	C	5	6	4	10	22445	20980	-7	6	2.3	19950	16571	-17	7	2.4	24080	22456	-7	1	1.5
34	M	L	5	8	8	16	25512	22772	-11	4	2.1	23853	20513	-14	6	2.5	27920	25030	-10	9	2.1
48	M	C	5	8	8	16	25512	23740	-7	3	2	23853	20513	-14	6	2	27920	25030	-10	9	2.2
62	E	L	5	6	8	14	24911	23154	-7	3	1.6	23931	20426	-15	7	3.5	26654	23914	-10	6	1.8
76	E	C	5	6	7	13	25215	23458	-7	3	2.1	24022	20517	-15	7	2	26868	24158	-10	6	1.7

Table 5.15: Averages of Improvement Values for Scoring Options

Scoring option	**Average**
Adjacency-based scoring by weight	16.52029
Adjacency-based scoring flow	5.77079
Adjacency-based scoring by normalized flow	5.77075
Adjacency-based scoring by normalized (-)/(+) flow	4.77992
Distance-based scoring by flow	-8.98512
Distance-based scoring by cost of flow	-18.53592
Distance-weighted adjacency based scoring	-10.52127

When these tables are analyzed, for the first four adjacency-based scoring options, better score means lower score (minimizing objective function), IM values are positive. For other three scoring options, better score is higher score with negative IM values. In order to determine the best scoring option, absolute values of IM should be investigated. Table 5.15 gives average of 18 IM values for each scoring option.

The scoring option giving the highest absolute value of average improvements is "Distance-based scoring by cost of flow". So, from seven scoring options, "Distance-based scoring by cost of flow" is selected as the most improving scoring option.

In order to determine which initial layout is better, values of score of initial layout (S) can be analyzed. The initial layout having a higher score in adjacency-based scoring options, and having a lower score in other scoring options is better. In this manner, for adjacency-based scoring, descending S values are in order of IL1, IL3 and IL2, i.e., IL1 gives the maximum score. For other scoring options, ascending scores are; IL2, IL1 and IL3. Therefore, IL1 gives better (higher in adjacency-based and lower in distance-based) score. Also, average of IM values for each initial layout can be considered to find a better initial layout. Average IM values of IL1, IL2 and IL3 are 13.5, 8.6 and 13.3, respectively. These average values are calculated by adding all of the absolute values of improvement, for all of the scoring options. A lower IM average means that, at first, the departments in the initial layout are located so efficiently that it needs little improvement. So, IL2 can be selected.

Chapter 6

CONCLUSIONS

In this thesis, we have defined a heuristic method for improvement purposes in the facility layout problems. Although the facility layout improvement is extensively studied in the literature, this algorithm is different from the others in terms of operations and calculations performed on departments in the facility. Area sizes of each department and detailed results (score of layout, percentage improvement, etc.) of improvement algorithm are given in the facility layout problem for each instance and initial layout. Also, we have shown that, IP model of the train scheduling problem can schedule some very large problem instances in a reasonable amount of time. In this problem, the results (variable rail transportation costs, number of trucks/TIRs carried, number of departures, etc.) and Gantt charts (shows daily schedule of operations for sample trains and platforms for each system) are explained. For the integrated model, based on various number of platforms in the station, we developed schedules for all of the train operations and found the number of vehicles carried and all of the cost elements.

Railroad transportation brings a competitive advantage when compared to road in terms of travel time. If the train speed is assumed as 100 km/h, the travel time for 231 km distance (between Çerkezköy and Köseköy) is 140 minutes. If the speed is assumed as 50 km/h for truck or TIR to travel on road, then the travel time is 280 minutes. Therefore, in addition to the operational efficiency and cost advantages, rail transportation also brings time benefit and causes less traffic in roads which results in less air and noise pollution in the city center.

According to the results of the train scheduling model, the schedule of instance with Eurotunnel system, safety time interval 5 minutes, linear platform structure and a station having 15 parallel loading/unloading platforms is found to be the easiest so that the computational time is minimal for this instance.

When the total operational costs (train operation costs + additional road transportation costs) is considered, the system which causes minimum cost is Modalohr. According to the fixed train investment cost or platform investment cost, Oekombi system is the best. If the variable total operational costs is considered as the most important criterion, then Modalohr system should be chosen, otherwise for fixed investment costs, Oekombi system must be selected. Since the fixed cost between these two systems are very low and in the long term (while technical life of locomotive or wagon is at least 35 years) variable costs will be much important and will have higher percentage in total costs, Modalohr system must be determined. The Modalohr system with circular platform structure, 5 minutes of safety time interval and 12 platforms, causes less fixed train investment cost and the Modalohr system with these parameters can be chosen as the best instance.

In the facility layout problem, distance-based scoring by cost of flow is the best scoring option because it is the scoring option that causes the best average improvement in all of the scores of the initial layouts. Sample initial layout #1 gives higher score for adjacency-based scoring options and lower score for distance-based scoring options. Circular platform structure best meets the requirements according to possible future construction area locations of stations. Sample initial layout #1 is designed with circular platform structure and the results for this layout is significant in the algorithm. It is determined that the structure of the station can be designed with sample initial layout #1.

Our contribution to the literature with this thesis is threefold. First, we developed a novel heuristic method to improve an initial facility layout in train stations. The past works in the literature were generally between 1960 and 1970, and are not easily to be found, but our algorithm is a new method and the only required input for the algorithm is the initial layout. Although the algorithm reads several files for costs, flows and relationships between departments, because these parameters are fixed values, once they are set before starting of the algorithm, the algorithm can implement many functions with these parameters for varying initial layout options. Second, we developed a mathematical model to schedule (timetable) train operations. In the literature, train scheduling model is generally studied in the networks design and optimization area, but we defined a novel IP model which is generally based on implication of variables toward each other. Our model can schedule the operations and find the objective function value in a reasonable time, when it should be noted that the scheduling problems generally require long computational time due to their combinatorial nature. Third, the integrated model which is developed for facility layout and train scheduling problems is applied to the Marmaray system. We also analyzed Marmaray project in terms of environment, fixed and variable costs and traffic density of trucks/TIRs. Since intermodal transportation is a new area in the literature, analysis of Marmaray system-a Ro-La transportation system (intermodal transportation with road and rail modes)-in several aspects can be effective for the subsequent studies.

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Appendix A

FACILITY LAYOUT PROBLEM

Table A.1, A.2 and A.3 gives the dimensions of departments, Platforms, Siding, Truck/TIR Park Area and Locomotive/Wagon Park Area for each of the 88 instances of train scheduling problem for three initial layouts respectively. Columns are: I; instance number, S; system, PS: platform structure, t; safety time interval, TP; total number of platforms in a station, PL; length of Platforms, PW; width of Platforms, SL; length of Siding and SW; width of Siding. Only for table A.2, S1; length or width of first perpendicular isosceles triangle and S2 is for second triangle (length=width). Other columns are: TL; length of Truck/TIR Park Area, TW; width of Truck/TIR Park Area, TIR; number of TIRs in park area, TPL; number of TIRs that will be loaded to trains on platforms immediately after arrival, TPA; number of TIRS that goes to park immediately after arrival, T; number of different trains traveled for both directions in one day, D: number of departures at two stations, ST; number of backup trains in a station, UL; length of Locomotive/Wagon Park Area and UW; width of Locomotive/Wagon Park Area. Train length is 600 m, so PL is 600 m in tables A.1 and A.2, because all of the platforms are parallel. But in table A.3, two platforms are serial. PW contains not only width of platform but also width of railroad, loading/unloading ramps, required turn area for truck/TIR SL and SW are equal to PW, because in an equilateral triangle, curve at corner point has angle of 90+45=135, and this angle is within curve range for all of the systems. Maximum number of HGVs in park area can be 1300, determined with the help of decision maker in IMPL. Total of TPL and TPA is 1300. Standart dimensions of a TIR vehicle is 18 m length and 2.5 m width. If 250 TIRS are parked side by side, 2.5*250=625 m   600 m length is required. 25 m safety width is maintained for each TIR. A park area with 600 m length and 25 m width can serve 250 TIRs. ST is 20% of T. So, in each station, 10% of T amount of trains is parked to overcome a problem of main trains and to satisfy operational efficiency such that at each time, one train must depart. 200 m length is enough for LL, although locomotive and waggons can park side by side. If width is 15 m, UW is 15 multiplied by half of number of backup trains. This is half because two locomotives can park side by side.

Table A.1: Data of Sample Layouts

I	**S**	**PS**	**t**	**TP**	**PL**	**PW**	**SL**	**SW**	**TIR**	**TPL**	**TPA**	**TL**	**TW**	**T**	**D**	**ST**	**UL**	**UW**
1	OE	L	5	12	600	180	180	180	1000	264	736	600	70	84	92	9	200	68
2	OE	L	5	11	600	165	165	165	1000	242	758	600	70	84	92	9	200	68
3	OE	L	5	10	600	150	150	150	1000	220	780	500	100	84	92	9	200	68
4	OE	L	6	10	600	150	150	150	1000	220	780	500	100	72	76	8	200	60
5	OE	L	6	9	600	135	135	135	1000	198	802	500	100	72	76	8	200	60
6	OE	L	7	10	600	150	150	150	1000	220	780	500	100	62	66	7	200	53
7	OE	L	7	9	600	135	135	135	1000	198	802	500	100	62	66	7	200	53
8	OE	L	7	8	600	120	120	120	1000	176	824	520	100	62	66	7	200	53
9	OE	L	8	8	600	120	120	120	1000	176	824	520	100	56	58	6	200	45
10	OE	L	8	7	600	105	105	105	1000	154	846	530	100	56	58	6	200	45
11	OE	L	9	8	600	120	120	120	1000	176	824	520	100	50	52	5	200	38
12	OE	L	9	7	600	105	105	105	1000	154	846	530	100	50	52	5	200	38
13	OE	L	10	6	600	90	90	90	1000	132	868	540	100	42	48	5	200	38
14	OE	L	10	5	600	75	75	75	1000	110	890	550	100	42	48	5	200	38
15	OE	L	12	6	600	90	90	90	1000	132	868	540	100	38	40	4	200	30
16	OE	L	12	5	600	75	75	75	1000	110	890	550	100	38	40	4	200	30
17	OE	C	5	12	600	180	180	180	1000	264	736	600	70	82	92	9	200	68
18	OE	C	5	11	600	165	165	165	1000	242	758	600	70	82	92	9	200	68
19	OE	C	5	10	600	150	150	150	1000	220	780	500	100	82	92	9	200	68
20	OE	C	6	10	600	150	150	150	1000	220	780	500	100	72	76	8	200	60
21	OE	C	6	9	600	135	135	135	1000	198	802	500	100	72	76	8	200	60
22	OE	C	7	10	600	150	150	150	1000	220	780	500	100	62	66	7	200	53
23	OE	C	7	9	600	135	135	135	1000	198	802	500	100	62	66	7	200	53
24	OE	C	7	8	600	120	120	120	1000	176	824	520	100	62	66	7	200	53
25	OE	C	8	8	600	120	120	120	1000	176	824	520	100	54	58	6	200	45
26	OE	C	8	7	600	105	105	105	1000	154	846	530	100	54	58	6	200	45
27	OE	C	9	8	600	120	120	120	1000	176	824	520	100	50	52	5	200	38
28	OE	C	9	7	600	105	105	105	1000	154	846	530	100	50	52	5	200	38
29	OE	C	10	6	600	90	90	90	1000	132	868	540	100	42	48	5	200	38
30	OE	C	10	5	600	75	75	75	1000	110	890	550	100	42	48	5	200	38
31	OE	C	12	6	600	90	90	90	1000	132	868	540	100	38	40	4	200	30
32	OE	C	12	5	600	75	75	75	1000	110	890	550	100	38	40	4	200	30
33	MO	L	5	17	800	255	255	255	1000	442	558	480	70	94	100	10	200	75
34	MO	L	5	16	800	240	240	240	1000	416	584	500	70	94	100	10	200	75
35	MO	L	6	15	800	225	225	225	1000	390	610	510	70	76	84	8	200	60
36	MO	L	6	14	800	210	210	210	1000	364	636	530	70	76	84	8	200	60
37	MO	L	7	13	800	195	195	195	1000	338	662	540	70	66	72	7	200	53
38	MO	L	7	12	800	180	180	180	1000	312	688	550	70	66	72	7	200	53
39	MO	L	8	11	800	165	165	165	1000	286	714	580	70	56	64	6	200	45
40	MO	L	8	10	800	150	150	150	1000	260	740	600	70	56	64	6	200	45

Continued on next page

Table A.1 – continued from previous page

I	S	PS	t	TP	PL	PW	SL	SW	TIR	TPL	TPA	TL	TW	T	D	ST	UL	UW
41	MO	L	9	11	800	165	165	165	1000	286	714	580	70	52	58	6	200	45
42	MO	L	9	10	800	150	150	150	1000	260	740	600	70	52	58	6	200	45
43	MO	L	10	9	800	135	135	135	1000	234	766	610	70	46	52	5	200	38
44	MO	L	10	8	800	120	120	120	1000	208	792	500	100	46	52	5	200	38
45	MO	L	12	9	800	135	135	135	1000	234	766	600	70	40	44	4	200	30
46	MO	L	12	8	800	120	120	120	1000	208	792	500	100	40	44	4	200	30
47	MO	C	5	17	800	255	255	255	1000	442	558	480	70	92	100	10	200	75
48	MO	C	5	16	800	240	240	240	1000	416	584	500	70	92	100	10	200	75
49	MO	C	6	15	800	225	225	225	1000	390	610	510	70	74	84	8	200	60
50	MO	C	6	14	800	210	210	210	1000	364	636	530	70	74	84	8	200	60
51	MO	C	7	13	800	195	195	195	1000	338	662	540	70	64	72	7	200	53
52	MO	C	7	12	800	180	180	180	1000	312	688	550	70	64	72	7	200	53
53	MO	C	8	11	800	165	165	165	1000	286	714	580	70	56	64	6	200	45
54	MO	C	8	10	800	150	150	150	1000	260	740	600	70	56	64	6	200	45
55	MO	C	9	11	800	165	165	165	1000	286	714	580	70	50	58	5	200	38
56	MO	C	9	10	800	150	150	150	1000	260	740	600	70	50	58	5	200	38
57	MO	C	10	9	800	135	135	135	1000	234	766	600	70	44	52	5	200	38
58	MO	C	10	8	800	120	120	120	1000	208	792	500	100	44	52	5	200	38
59	MO	C	12	9	800	135	135	135	1000	234	766	600	70	40	44	4	200	30
60	MO	C	12	8	800	120	120	120	1000	208	792	500	100	40	44	4	200	30
61	EU	L	5	15	750	225	225	225	1000	330	670	540	70	84	108	9	200	68
62	EU	L	5	14	750	210	210	210	1000	308	692	550	70	84	108	9	200	68
63	EU	L	6	14	750	210	210	210	1000	308	692	550	70	70	90	7	200	53
64	EU	L	6	13	750	195	195	195	1000	286	714	580	70	70	90	7	200	53
65	EU	L	7	12	750	180	180	180	1000	264	736	600	70	58	76	6	200	45
66	EU	L	7	11	750	165	165	165	1000	242	758	600	70	58	76	6	200	45
67	EU	L	8	11	750	165	165	165	1000	242	758	600	70	52	68	6	200	45
68	EU	L	8	10	750	150	150	150	1000	220	780	500	100	52	68	6	200	45
69	EU	L	9	11	750	165	165	165	1000	242	758	600	70	48	62	5	200	38
70	EU	L	9	10	750	150	150	150	1000	220	780	500	100	48	62	5	200	38
71	EU	L	10	8	750	120	120	120	1000	176	824	520	100	44	56	5	200	38
72	EU	L	10	7	750	105	105	105	1000	154	846	530	100	44	56	5	200	38
73	EU	L	12	8	750	120	120	120	1000	176	824	520	100	36	46	4	200	30
74	EU	L	12	7	750	105	105	105	1000	154	846	530	100	36	46	4	200	30
75	EU	C	5	14	750	210	210	210	1000	308	692	550	70	82	108	9	200	68
76	EU	C	5	13	750	195	195	195	1000	286	714	580	70	82	108	9	200	68
77	EU	C	6	14	750	210	210	210	1000	308	692	550	70	70	90	7	200	53
78	EU	C	6	13	750	195	195	195	1000	286	714	580	70	70	90	7	200	53
79	EU	C	7	12	750	180	180	180	1000	264	736	600	70	58	76	6	200	45
80	EU	C	7	11	750	165	165	165	1000	242	758	600	70	58	76	6	200	45
81	EU	C	8	11	750	165	165	165	1000	242	758	600	70	52	68	6	200	45
82	EU	C	8	10	750	150	150	150	1000	220	780	500	100	52	68	6	200	45
83	EU	C	9	12	750	180	180	180	1000	264	736	600	70	46	62	5	200	38
84	EU	C	9	11	750	165	165	165	1000	242	758	600	70	46	62	5	200	38
85	EU	C	10	7	750	105	105	105	1000	154	846	530	100	42	56	5	200	38
86	EU	C	10	6	750	90	90	90	1000	132	868	540	100	42	56	5	200	38
87	EU	C	12	8	750	120	120	120	1000	176	824	520	100	36	46	4	200	30
88	EU	C	12	7	750	105	105	105	1000	154	846	530	100	36	46	4	200	30

Table A.2: Data of Sample Layouts

I	S	PS	t	TP	PL	PW	S1LW	S2LW	TIR	TPL	TPA	TL	TW	T	D	ST	UL	UW
1	OE	L	5	12	600	180	90	90	1000	264	736	600	70	84	92	9	200	68
2	OE	L	5	11	600	165	83	83	1000	242	758	600	70	84	92	9	200	68
3	OE	L	5	10	600	150	75	75	1000	220	780	500	100	84	92	9	200	68
4	OE	L	6	10	600	150	75	75	1000	220	780	500	100	72	76	8	200	60
5	OE	L	6	9	600	135	68	68	1000	198	802	500	100	72	76	8	200	60
6	OE	L	7	10	600	150	75	75	1000	220	780	500	100	62	66	7	200	53
7	OE	L	7	9	600	135	68	68	1000	198	802	500	100	62	66	7	200	53
8	OE	L	7	8	600	120	60	60	1000	176	824	520	100	62	66	7	200	53
9	OE	L	8	8	600	120	60	60	1000	176	824	520	100	56	58	6	200	45
10	OE	L	8	7	600	105	53	53	1000	154	846	530	100	56	58	6	200	45
11	OE	L	9	8	600	120	60	60	1000	176	824	520	100	50	52	5	200	38
12	OE	L	9	7	600	105	53	53	1000	154	846	530	100	50	52	5	200	38
13	OE	L	10	6	600	90	45	45	1000	132	868	540	100	42	48	5	200	38
14	OE	L	10	5	600	75	38	38	1000	110	890	550	100	42	48	5	200	38
15	OE	L	12	6	600	90	45	45	1000	132	868	540	100	38	40	4	200	30
16	OE	L	12	5	600	75	38	38	1000	110	890	550	100	38	40	4	200	30
17	OE	C	5	12	600	180	90	90	1000	264	736	600	70	82	92	9	200	68
18	OE	C	5	11	600	165	83	83	1000	242	758	600	70	82	92	9	200	68
19	OE	C	5	10	600	150	75	75	1000	220	780	500	100	82	92	9	200	68
20	OE	C	6	10	600	150	75	75	1000	220	780	500	100	72	76	8	200	60
21	OE	C	6	9	600	135	68	68	1000	198	802	500	100	72	76	8	200	60
22	OE	C	7	10	600	150	75	75	1000	220	780	500	100	62	66	7	200	53
23	OE	C	7	9	600	135	68	68	1000	198	802	500	100	62	66	7	200	53
24	OE	C	7	8	600	120	60	60	1000	176	824	520	100	62	66	7	200	53
25	OE	C	8	8	600	120	60	60	1000	176	824	520	100	54	58	6	200	45
26	OE	C	8	7	600	105	53	53	1000	154	846	530	100	54	58	6	200	45
27	OE	C	9	8	600	120	60	60	1000	176	824	520	100	50	52	5	200	38
28	OE	C	9	7	600	105	53	53	1000	154	846	530	100	50	52	5	200	38
29	OE	C	10	6	600	90	45	45	1000	132	868	540	100	42	48	5	200	38
30	OE	C	10	5	600	75	38	38	1000	110	890	550	100	42	48	5	200	38
31	OE	C	12	6	600	90	45	45	1000	132	868	540	100	38	40	4	200	30
32	OE	C	12	5	600	75	38	38	1000	110	890	550	100	38	40	4	200	30
33	MO	L	5	17	800	255	128	128	1000	442	558	480	70	94	100	10	200	75
34	MO	L	5	16	800	240	120	120	1000	416	584	500	70	94	100	10	200	75
35	MO	L	6	15	800	225	113	113	1000	390	610	510	70	76	84	8	200	60
36	MO	L	6	14	800	210	105	105	1000	364	636	530	70	76	84	8	200	60
37	MO	L	7	13	800	195	98	98	1000	338	662	540	70	66	72	7	200	53
38	MO	L	7	12	800	180	90	90	1000	312	688	550	70	66	72	7	200	53
39	MO	L	8	11	800	165	83	83	1000	286	714	580	70	56	64	6	200	45
40	MO	L	8	10	800	150	75	75	1000	260	740	600	70	56	64	6	200	45
41	MO	L	9	11	800	165	83	83	1000	286	714	580	70	52	58	6	200	45
42	MO	L	9	10	800	150	75	75	1000	260	740	600	70	52	58	6	200	45
43	MO	L	10	9	800	135	68	68	1000	234	766	610	70	46	52	5	200	38
44	MO	L	10	8	800	120	60	60	1000	208	792	500	100	46	52	5	200	38
45	MO	L	12	9	800	135	68	68	1000	234	766	600	70	40	44	4	200	30
46	MO	L	12	8	800	120	60	60	1000	208	792	500	100	40	44	4	200	30
47	MO	C	5	17	800	255	128	128	1000	442	558	480	70	92	100	10	200	75
48	MO	C	5	16	800	240	120	120	1000	416	584	500	70	92	100	10	200	75
49	MO	C	6	15	800	225	113	113	1000	390	610	510	70	74	84	8	200	60
50	MO	C	6	14	800	210	105	105	1000	364	636	530	70	74	84	8	200	60

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Table A.2 – continued from previous page

I	S	PS	t	TP	PL	PW	S1LW	S2LW	TIR	TPL	TPA	TL	TW	T	D	ST	UL	UW
51	MO	C	7	13	800	195	98	98	1000	338	662	540	70	64	72	7	200	53
52	MO	C	7	12	800	180	90	90	1000	312	688	550	70	64	72	7	200	53
53	MO	C	8	11	800	165	83	83	1000	286	714	580	70	56	64	6	200	45
54	MO	C	8	10	800	150	75	75	1000	260	740	600	70	56	64	6	200	45
55	MO	C	9	11	800	165	83	83	1000	286	714	580	70	50	58	5	200	38
56	MO	C	9	10	800	150	75	75	1000	260	740	600	70	50	58	5	200	38
57	MO	C	10	9	800	135	68	68	1000	234	766	600	70	44	52	5	200	38
58	MO	C	10	8	800	120	60	60	1000	208	792	500	100	44	52	5	200	38
59	MO	C	12	9	800	135	68	68	1000	234	766	600	70	40	44	4	200	30
60	MO	C	12	8	800	120	60	60	1000	208	792	500	100	40	44	4	200	30
61	EU	L	5	15	750	225	113	113	1000	330	670	540	70	84	108	9	200	68
62	EU	L	5	14	750	210	105	105	1000	308	692	550	70	84	108	9	200	68
63	EU	L	6	14	750	210	105	105	1000	308	692	550	70	70	90	7	200	53
64	EU	L	6	13	750	195	98	98	1000	286	714	580	70	70	90	7	200	53
65	EU	L	7	12	750	180	90	90	1000	264	736	600	70	58	76	6	200	45
66	EU	L	7	11	750	165	83	83	1000	242	758	600	70	58	76	6	200	45
67	EU	L	8	11	750	165	83	83	1000	242	758	600	70	52	68	6	200	45
68	EU	L	8	10	750	150	75	75	1000	220	780	500	100	52	68	6	200	45
69	EU	L	9	11	750	165	83	83	1000	242	758	600	70	48	62	5	200	38
70	EU	L	9	10	750	150	75	75	1000	220	780	500	100	48	62	5	200	38
71	EU	L	10	8	750	120	60	60	1000	176	824	520	100	44	56	5	200	38
72	EU	L	10	7	750	105	53	53	1000	154	846	530	100	44	56	5	200	38
73	EU	L	12	8	750	120	60	60	1000	176	824	520	100	36	46	4	200	30
74	EU	L	12	7	750	105	53	53	1000	154	846	530	100	36	46	4	200	30
75	EU	C	5	14	750	210	105	105	1000	308	692	550	70	82	108	9	200	68
76	EU	C	5	13	750	195	98	98	1000	286	714	580	70	82	108	9	200	68
77	EU	C	6	14	750	210	105	105	1000	308	692	550	70	70	90	7	200	53
78	EU	C	6	13	750	195	98	98	1000	286	714	580	70	70	90	7	200	53
79	EU	C	7	12	750	180	90	90	1000	264	736	600	70	58	76	6	200	45
80	EU	C	7	11	750	165	83	83	1000	242	758	600	70	58	76	6	200	45
81	EU	C	8	11	750	165	83	83	1000	242	758	600	70	52	68	6	200	45
82	EU	C	8	10	750	150	75	75	1000	220	780	500	100	52	68	6	200	45
83	EU	C	9	12	750	180	90	90	1000	264	736	600	70	46	62	5	200	38
84	EU	C	9	11	750	165	83	83	1000	242	758	600	70	46	62	5	200	38
85	EU	C	10	7	750	105	53	53	1000	154	846	530	100	42	56	5	200	38
86	EU	C	10	6	750	90	45	45	1000	132	868	540	100	42	56	5	200	38
87	EU	C	12	8	750	120	60	60	1000	176	824	520	100	36	46	4	200	30
88	EU	C	12	7	750	105	53	53	1000	154	846	530	100	36	46	4	200	30

Table A.3: Data of Sample Layouts

I	S	PS	t	TP	PL	PW	SL	SW	TIR	TPL	TPA	TL	TW	T	D	ST	UL	UW
1	O	L	5	12	600	165	165	165	1000	264	736	600	70	84	92	9	200	68
2	O	L	5	11	600	150	150	150	1000	242	758	600	70	84	92	9	200	68
3	O	L	5	10	600	150	150	150	1000	220	780	500	100	84	92	9	200	68
4	O	L	6	10	600	135	135	135	1000	220	780	500	100	72	76	8	200	60
5	O	L	6	9	600	150	150	150	1000	198	802	500	100	72	76	8	200	60
6	O	L	7	10	600	135	135	135	1000	220	780	500	100	62	66	7	200	53
7	O	L	7	9	600	120	120	120	1000	198	802	500	100	62	66	7	200	53

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Table A.3 – continued from previous page

I	S	PS	t	TP	PL	PW	SL	SW	TIR	TPL	TPA	TL	TW	T	D	ST	UL	UW
8	O	L	7	8	600	120	120	120	1000	176	824	520	100	62	66	7	200	53
9	O	L	8	8	600	105	105	105	1000	176	824	520	100	56	58	6	200	45
10	O	L	8	7	600	120	120	120	1000	154	846	530	100	56	58	6	200	45
11	O	L	9	8	600	105	105	105	1000	176	824	520	100	50	52	5	200	38
12	O	L	9	7	600	90	90	90	1000	154	846	530	100	50	52	5	200	38
13	O	L	10	6	600	75	75	75	1000	132	868	540	100	42	48	5	200	38
14	O	L	10	5	600	90	90	90	1000	110	890	550	100	42	48	5	200	38
15	O	L	12	6	600	75	75	75	1000	132	868	540	100	38	40	4	200	30
16	O	L	12	5	600	180	180	180	1000	110	890	550	100	38	40	4	200	30
17	O	C	5	12	600	165	165	165	1000	264	736	600	70	82	92	9	200	68
18	O	C	5	11	600	150	150	150	1000	242	758	600	70	82	92	9	200	68
19	O	C	5	10	600	150	150	150	1000	220	780	500	100	82	92	9	200	68
20	O	C	6	10	600	135	135	135	1000	220	780	500	100	72	76	8	200	60
21	O	C	6	9	600	150	150	150	1000	198	802	500	100	72	76	8	200	60
22	O	C	7	10	600	135	135	135	1000	220	780	500	100	62	66	7	200	53
23	O	C	7	9	600	120	120	120	1000	198	802	500	100	62	66	7	200	53
24	O	C	7	8	600	120	120	120	1000	176	824	520	100	62	66	7	200	53
25	O	C	8	8	600	105	105	105	1000	176	824	520	100	54	58	6	200	45
26	O	C	8	7	600	120	120	120	1000	154	846	530	100	54	58	6	200	45
27	O	C	9	8	600	105	105	105	1000	176	824	520	100	50	52	5	200	38
28	O	C	9	7	600	90	90	90	1000	154	846	530	100	50	52	5	200	38
29	O	C	10	6	600	75	75	75	1000	132	868	540	100	42	48	5	200	38
30	O	C	10	5	600	90	90	90	1000	110	890	550	100	42	48	5	200	38
31	O	C	12	6	600	75	75	75	1000	132	868	540	100	38	40	4	200	30
32	O	C	12	5	800	255	255	255	1000	110	890	550	100	38	40	4	200	30
33	M	L	5	17	800	240	240	240	1000	442	558	480	70	94	100	10	200	75
34	M	L	5	16	800	225	225	225	1000	416	584	500	70	94	100	10	200	75
35	M	L	6	15	800	210	210	210	1000	390	610	510	70	76	84	8	200	60
36	M	L	6	14	800	195	195	195	1000	364	636	530	70	76	84	8	200	60
37	M	L	7	13	800	180	180	180	1000	338	662	540	70	66	72	7	200	53
38	M	L	7	12	800	165	165	165	1000	312	688	550	70	66	72	7	200	53
39	M	L	8	11	800	150	150	150	1000	286	714	580	70	56	64	6	200	45
40	M	L	8	10	800	165	165	165	1000	260	740	600	70	56	64	6	200	45
41	M	L	9	11	800	150	150	150	1000	286	714	580	70	52	58	6	200	45
42	M	L	9	10	800	135	135	135	1000	260	740	600	70	52	58	6	200	45
43	M	L	10	9	800	120	120	120	1000	234	766	610	70	46	52	5	200	38
44	M	L	10	8	800	135	135	135	1000	208	792	500	100	46	52	5	200	38
45	M	L	12	9	800	120	120	120	1000	234	766	600	70	40	44	4	200	30
46	M	L	12	8	800	255	255	255	1000	208	792	500	100	40	44	4	200	30
47	M	C	5	17	800	240	240	240	1000	442	558	480	70	92	100	10	200	75
48	M	C	5	16	800	225	225	225	1000	416	584	500	70	92	100	10	200	75
49	M	C	6	15	800	210	210	210	1000	390	610	510	70	74	84	8	200	60
50	M	C	6	14	800	195	195	195	1000	364	636	530	70	74	84	8	200	60
51	M	C	7	13	800	180	180	180	1000	338	662	540	70	64	72	7	200	53
52	M	C	7	12	800	165	165	165	1000	312	688	550	70	64	72	7	200	53
53	M	C	8	11	800	150	150	150	1000	286	714	580	70	56	64	6	200	45
54	M	C	8	10	800	165	165	165	1000	260	740	600	70	56	64	6	200	45
55	M	C	9	11	800	150	150	150	1000	286	714	580	70	50	58	5	200	38
56	M	C	9	10	800	135	135	135	1000	260	740	600	70	50	58	5	200	38
57	M	C	10	9	800	120	120	120	1000	234	766	600	70	44	52	5	200	38
58	M	C	10	8	800	135	135	135	1000	208	792	500	100	44	52	5	200	38

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Table A.3 – continued from previous page

I	S	PS	t	TP	PL	PW	SL	SW	TIR	TPL	TPA	TL	TW	T	D	ST	UL	UW
59	M	C	12	9	800	120	120	120	1000	234	766	600	70	40	44	4	200	30
60	M	C	12	8	750	225	225	225	1000	208	792	500	100	40	44	4	200	30
61	E	L	5	15	750	210	210	210	1000	330	670	540	70	84	108	9	200	68
62	E	L	5	14	750	210	210	210	1000	308	692	550	70	84	108	9	200	68
63	E	L	6	14	750	195	195	195	1000	308	692	550	70	70	90	7	200	53
64	E	L	6	13	750	180	180	180	1000	286	714	580	70	70	90	7	200	53
65	E	L	7	12	750	165	165	165	1000	264	736	600	70	58	76	6	200	45
66	E	L	7	11	750	165	165	165	1000	242	758	600	70	58	76	6	200	45
67	E	L	8	11	750	150	150	150	1000	242	758	600	70	52	68	6	200	45
68	E	L	8	10	750	165	165	165	1000	220	780	500	100	52	68	6	200	45
69	E	L	9	11	750	150	150	150	1000	242	758	600	70	48	62	5	200	38
70	E	L	9	10	750	120	120	120	1000	220	780	500	100	48	62	5	200	38
71	E	L	10	8	750	105	105	105	1000	176	824	520	100	44	56	5	200	38
72	E	L	10	7	750	120	120	120	1000	154	846	530	100	44	56	5	200	38
73	E	L	12	8	750	105	105	105	1000	176	824	520	100	36	46	4	200	30
74	E	L	12	7	750	210	210	210	1000	154	846	530	100	36	46	4	200	30
75	E	C	5	14	750	195	195	195	1000	308	692	550	70	82	108	9	200	68
76	E	C	5	13	750	210	210	210	1000	286	714	580	70	82	108	9	200	68
77	E	C	6	14	750	195	195	195	1000	308	692	550	70	70	90	7	200	53
78	E	C	6	13	750	180	180	180	1000	286	714	580	70	70	90	7	200	53
79	E	C	7	12	750	165	165	165	1000	264	736	600	70	58	76	6	200	45
80	E	C	7	11	750	165	165	165	1000	242	758	600	70	58	76	6	200	45
81	E	C	8	11	750	150	150	150	1000	242	758	600	70	52	68	6	200	45
82	E	C	8	10	750	180	180	180	1000	220	780	500	100	52	68	6	200	45
83	E	C	9	12	750	165	165	165	1000	264	736	600	70	46	62	5	200	38
84	E	C	9	11	750	105	105	105	1000	242	758	600	70	46	62	5	200	38
85	E	C	10	7	750	90	90	90	1000	154	846	530	100	42	56	5	200	38
86	E	C	10	6	750	120	120	120	1000	132	868	540	100	42	56	5	200	38
87	E	C	12	8	750	105	105	105	1000	176	824	520	100	36	46	4	200	30
88	E	C	12	7	600	180	180	180	1000	154	846	530	100	36	46	4	200	30

Appendix B

TRAIN SCHEDULING PROBLEM

Figures B.1, B.2, B.3, B.4, B.5 and B.6 shows the Gantt charts of the results of train scheduling model. These sample Gantt charts of instances are selected because they illustrate the most congested traffic of operations with safety time interval 5 mins, circular platform structure. There are 6 Gantt charts for each 3 system, for one train and one platform schedule.

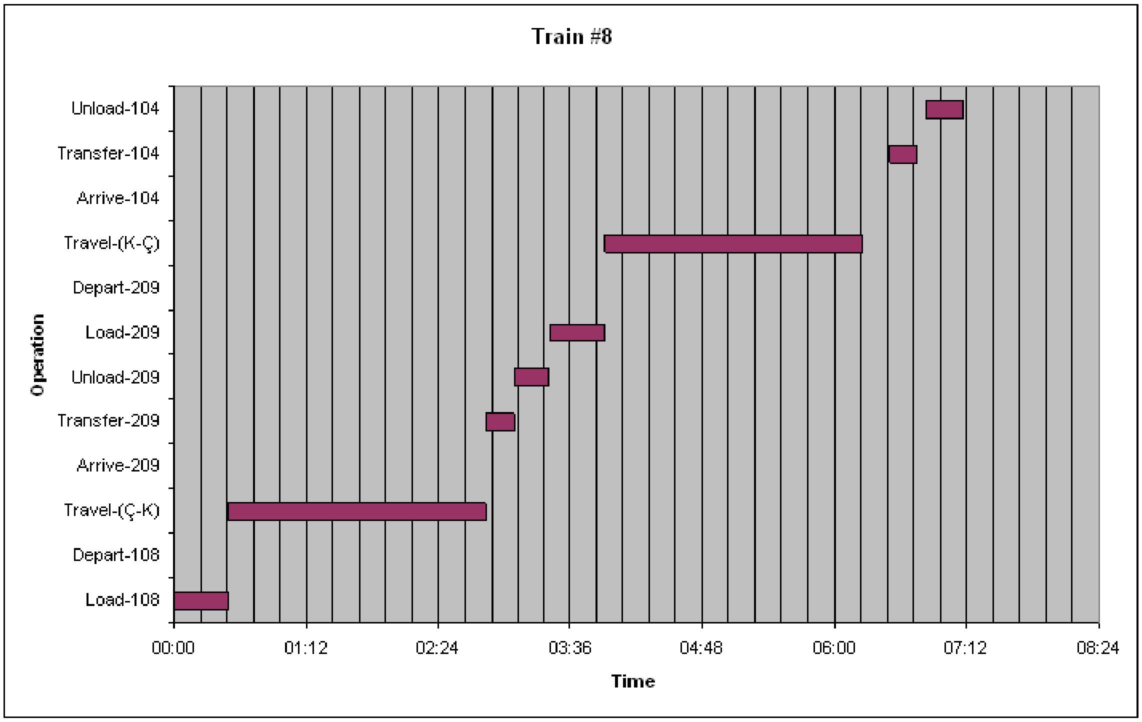

Figure B.1: Sample train schedule in Oekombi system

Figure B.1 shows all of the daily operations for train number 8. These Gantt charts are prepared with Microsoft Excel 2003, "stacked horizontal bar chart" option. In Excel, it is

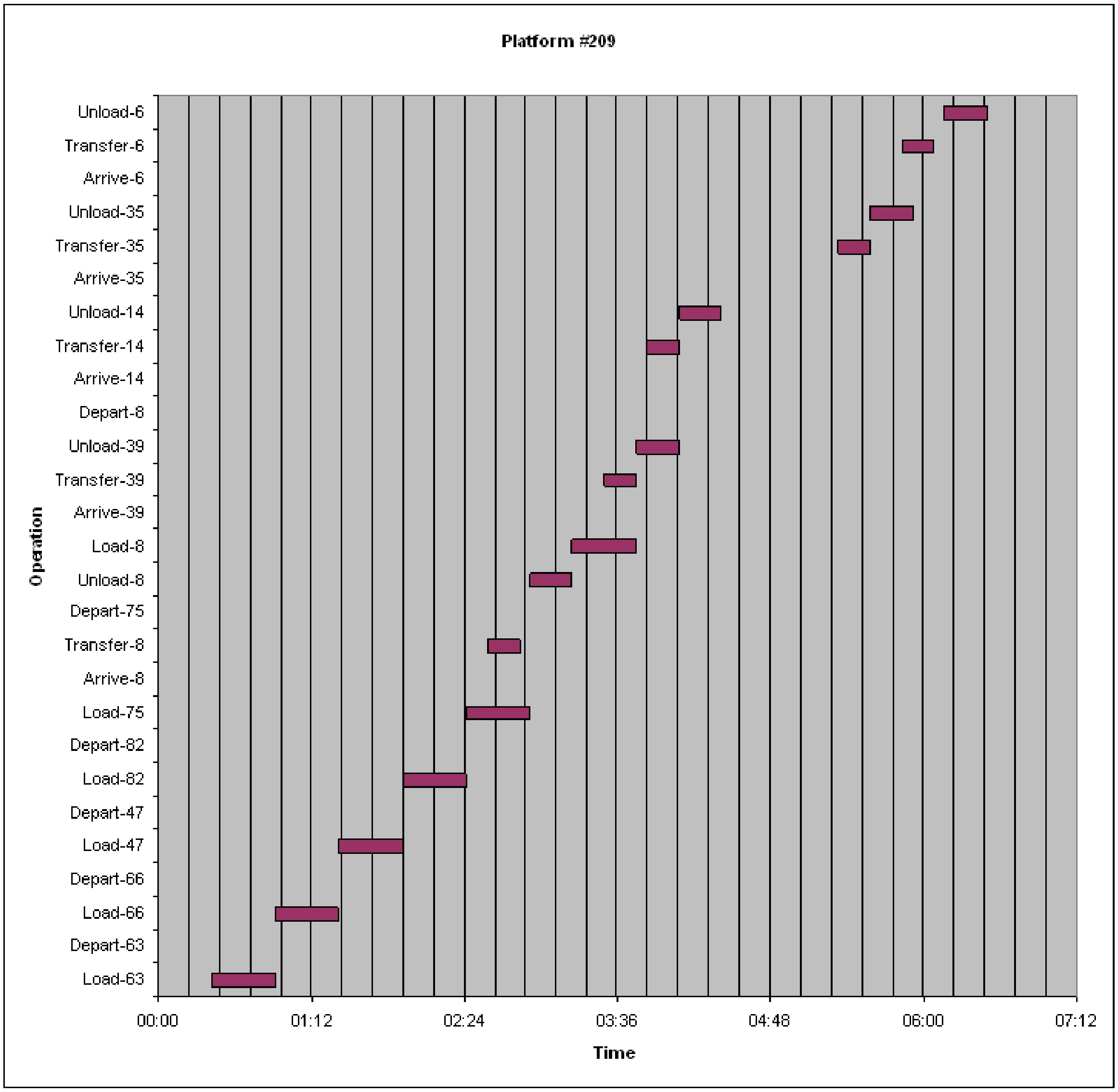

Figure B.2: Sample platform schedule in Oekombi system

not possible to show both times before 00:00 and after 00:00, so, in fact loading operation to train 8 starts at 23:50, but it is shown with 00:00. So, all of the real times of operation are 10 mins early of times in Gantt chart. First departure of train 8 occurs at 00:20 from platform 108 (station 1, Çerkeköy, because the number of platform is in 100s), travels to station 2 (Köseköy) in 140 mins (shown with Travel-(Ç-K) in Gantt chart) and arrives to Köseköy at 02:40. Then, it starts transfer immediately to platform 209. The unloading and

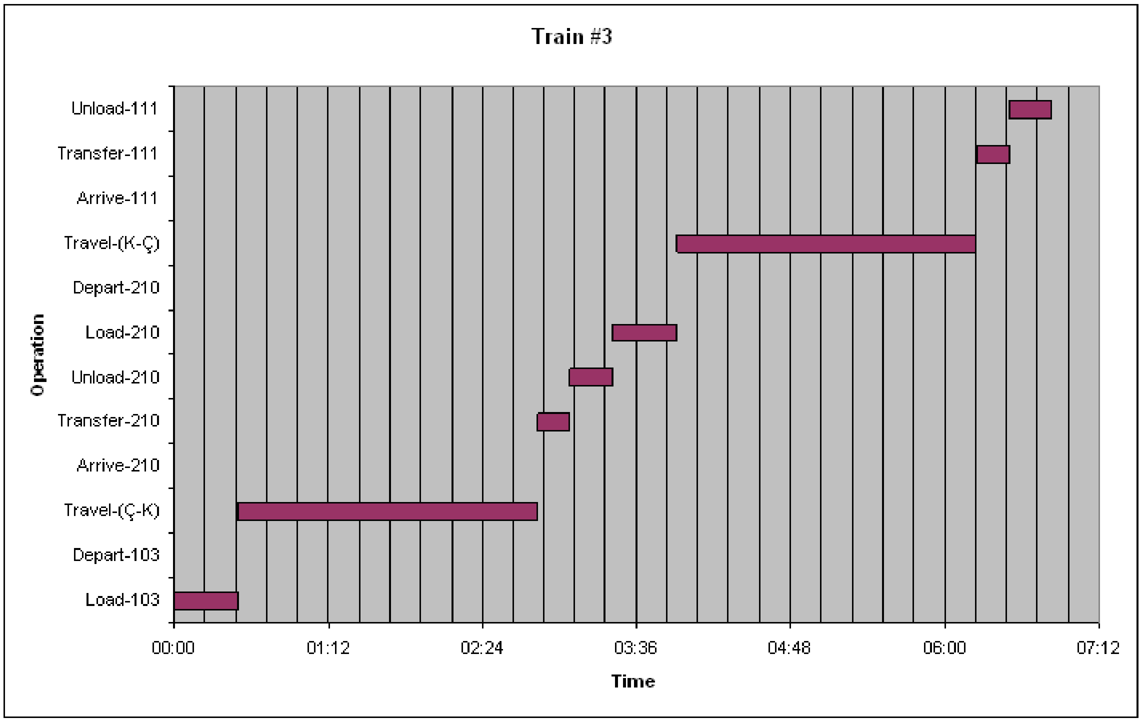

Figure B.3: Sample train schedule in Modalohr system

loading operations start at 02:55, with duration of 20 mins, and 03:15, with duration of 30 mins, respectively. Then, train 8 departs second time from Köseköy, going to Çerkezköy, arrives at 06:05 and all of the operations for this train ends at the latest of 07:00, with the end of unloading.

Figure B.2 is for the schedule of platform 209 in Köseköy. This platform is selected to give sample Gantt chart, because this platform is used by train 8, as in figure B.1. First train 63 is loaded in 30 mins starting from 00:25, and then loading operations continue for trains 66, 47, 82 and 75 sequentially. All these trains depart as soon as the loading operation ends. Train 8 arrives to station 2, and makes transfer for 15 mins, starting at 02:35. Train 8 arrives to platform 209 at 02:50, and expected to have unloading immediately, but cannot, because platform is busy with train 75 for loading operation, so train 8 waits for 75 in the siding raillines. Loading of train 75 ends at 02:55, and this time, unloading of train 8 starts, and after 20+30 mins, train 8 departs second time. Then, trains 39, 14, 35 and 6 arrives to

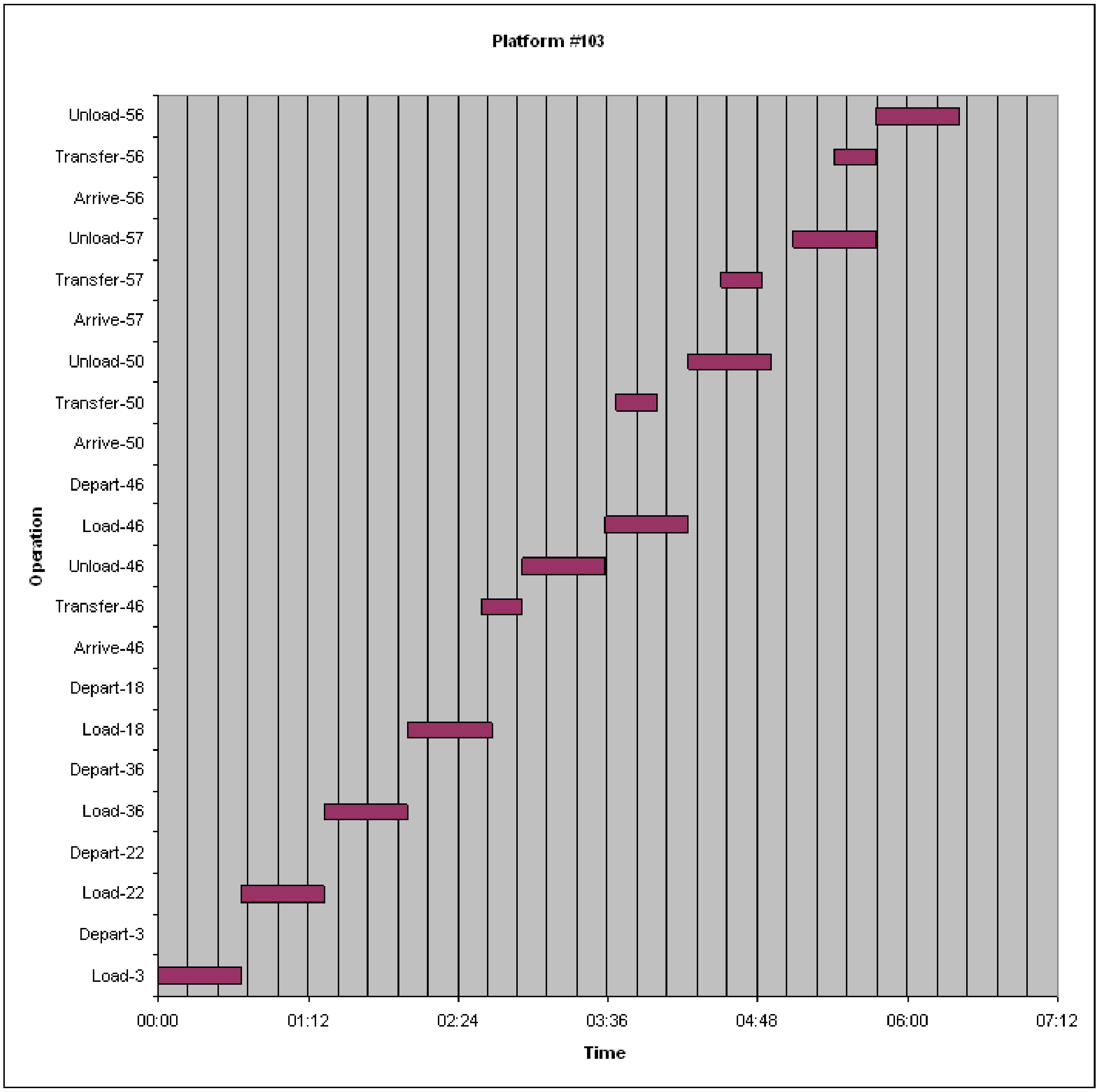

Figure B.4: Sample platform schedule in Modalohr system

platform 209 at 03:30, 03:50, 05:20 and 05:50, respectively, having transfer and unloading operation only. They are not subject to loading, because the time limit of arriving to other station before 06:00 do not allow them to depart second time.

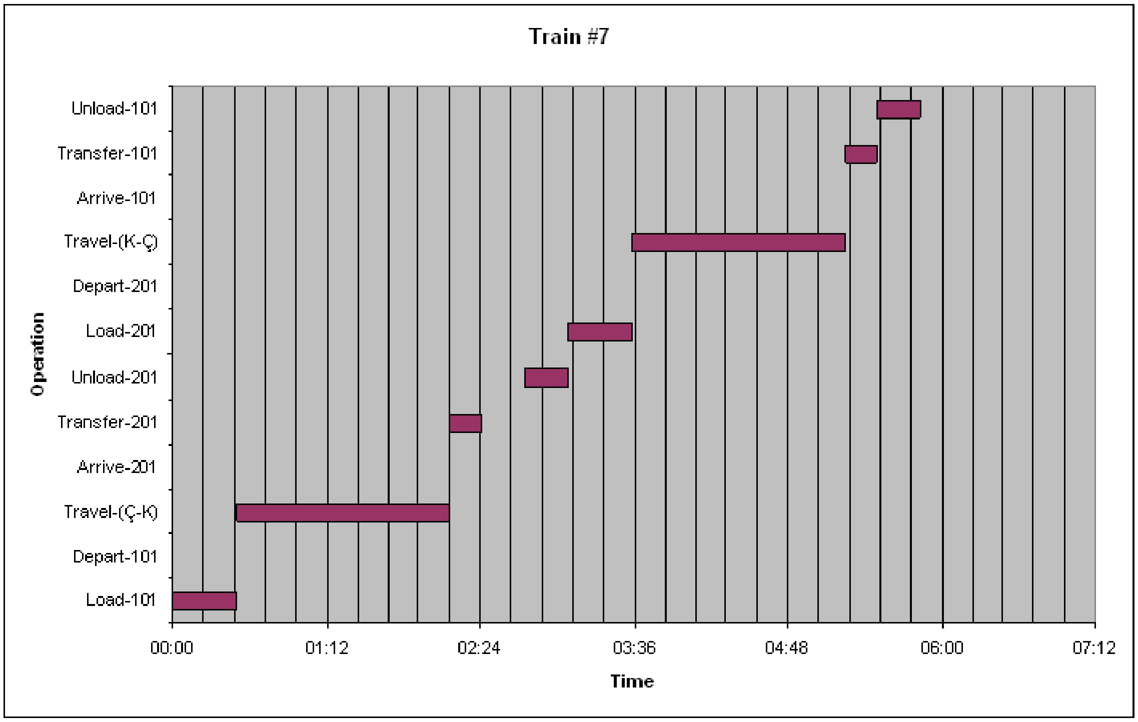

Figure B.5: Sample train schedule in Eurotunnel system

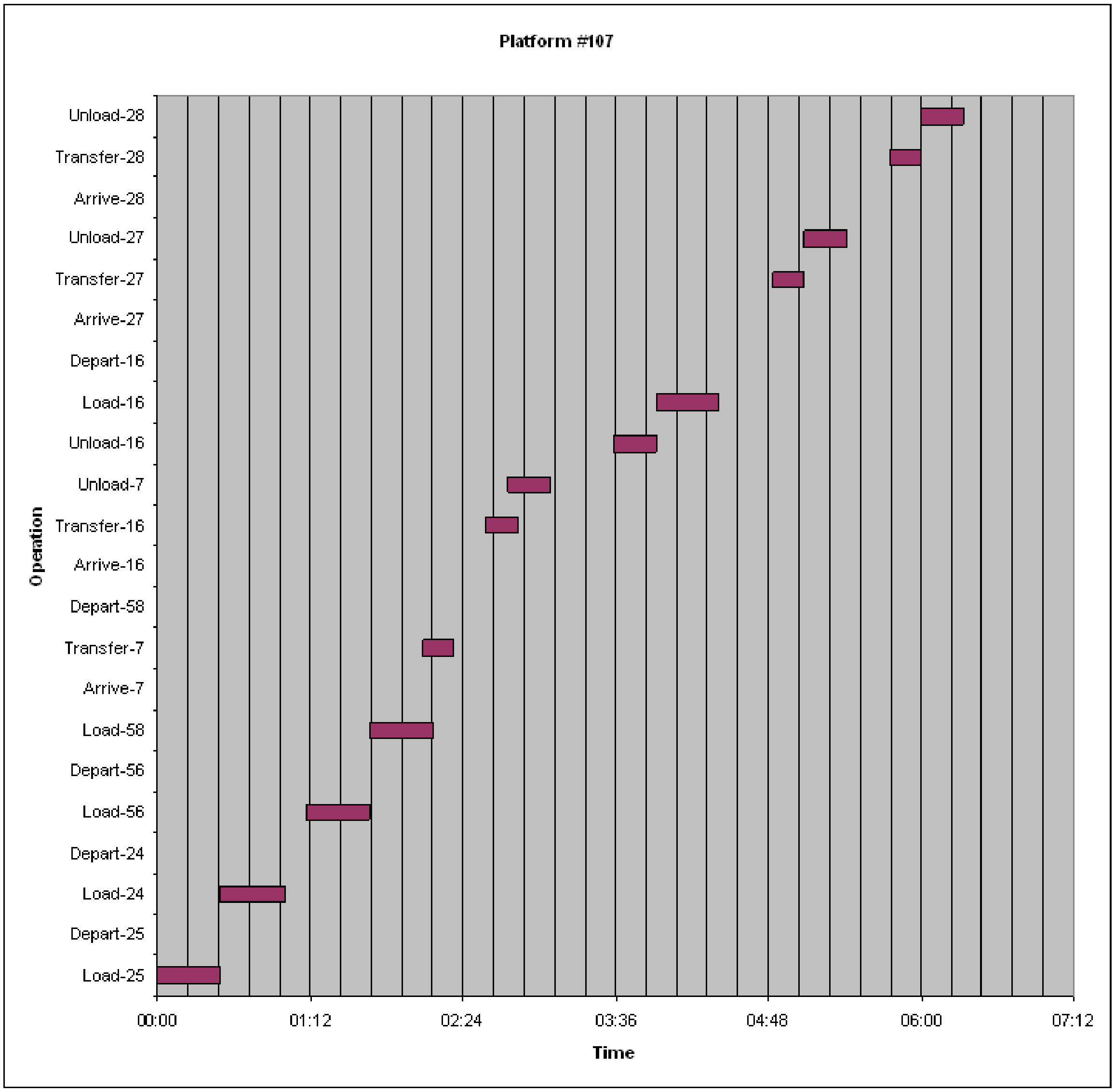

Figure B.6: Sample platform schedule in Eurotunnel system

Appendix C

ANALYSIS OF MARMARAY SYSTEM

C.1 Environmental Effects of Rail and Road

The energy consumption and environmental aspects of transportation modes are also as important as the other properties, such as costs, efficiency, etc. Table C.1 gives environmental costs of transported trucks/TIRs both in rail and road. Columns are: I; instance number, S; system, P; platform structure, t; safety time interval, D; number of departures at two directions in a day, WT; number of trucks carried in one travel, TTR; number of trucks carried in two directions in a day solely, WTI; number of TIRs carried in one travel, TTI; number of TIRs carried in two directions in a day solely, ATR; additional number of trucks transported with road (cannot be transported with rail, because of limited capacity of trains in a day), ATI; additional number of TIRs transported with road (cannot be transported with rail, because of limited capacity of trains in a day), RTR; environmental cost of one truck in rail in one travel, RTI; environmental cost of one TIR in rail in one travel (environmental cost of a train truck on road is \$ 7.19 for one travel), TCR; total environmental cost of rail transportation (addition of 60% of total truck environmental cost and 40% of total TIR environmental cost), HATR; environmental cost of additional trucks on road (environmental cost of a truck on road is \$ 56.6856 for one travel), HATI; environmental cost of additional TIRs on road (environmental cost of a truck on road is \$ 56.86 for one travel), TCAH; total environmental cost of road and TCS; total environmental cost of all transported vehicles with rail and road.

Table C.1: Environmental Costs of Instances

I	S	P	t	D	WT	TTR	WTI	TTI	ATR	ATI	RTR	RTI	TCR	HATR	HATI	TCAH
1	O	L	5	92	44	4048	22	2024	704	576	0.16	0.33	661	39907	32751	72658
2	O	L	5	92	44	4048	22	2024	704	576	0.16	0.33	661	39907	32751	72658
3	O	L	5	92	44	4048	22	2024	704	576	0.16	0.33	661	39907	32751	72658
4	O	L	6	76	44	3344	22	1672	1408	928	0.16	0.33	546	79813	52766	132579
5	O	L	6	76	44	3344	22	1672	1408	928	0.16	0.33	546	79813	52766	132579
6	O	L	7	66	44	2904	22	1452	1848	1148	0.16	0.33	475	104755	65275	170030
7	O	L	7	66	44	2904	22	1452	1848	1148	0.16	0.33	475	104755	65275	170030
8	O	L	7	66	44	2904	22	1452	1848	1148	0.16	0.33	475	104755	65275	170030
9	O	L	8	58	44	2552	22	1276	2200	1324	0.16	0.33	417	124708	75283	199991
10	O	L	8	58	44	2552	22	1276	2200	1324	0.16	0.33	417	124708	75283	199991
11	O	L	9	52	44	2288	22	1144	2464	1456	0.16	0.33	374	139673	82788	222461
12	O	L	9	52	44	2288	22	1144	2464	1456	0.16	0.33	374	139673	82788	222461
13	O	L	10	48	44	2112	22	1056	2640	1544	0.16	0.33	345	149650	87792	237442
14	O	L	10	48	44	2112	22	1056	2640	1544	0.16	0.33	345	149650	87792	237442
15	O	L	12	40	44	1760	22	880	2992	1720	0.16	0.33	288	169603	97799	267403
16	O	L	12	40	44	1760	22	880	2992	1720	0.16	0.33	288	169603	97799	267403
17	O	C	5	92	44	4048	22	2024	704	576	0.16	0.33	661	39907	32751	72658
18	O	C	5	92	44	4048	22	2024	704	576	0.16	0.33	661	39907	32751	72658
19	O	C	5	92	44	4048	22	2024	704	576	0.16	0.33	661	39907	32751	72658
20	O	C	6	76	44	3344	22	1672	1408	928	0.16	0.33	546	79813	52766	132579
21	O	C	6	76	44	3344	22	1672	1408	928	0.16	0.33	546	79813	52766	132579
22	O	C	7	66	44	2904	22	1452	1848	1148	0.16	0.33	475	104755	65275	170030
23	O	C	7	66	44	2904	22	1452	1848	1148	0.16	0.33	475	104755	65275	170030
24	O	C	7	66	44	2904	22	1452	1848	1148	0.16	0.33	475	104755	65275	170030
25	O	C	8	58	44	2552	22	1276	2200	1324	0.16	0.33	417	124708	75283	199991
26	O	C	8	58	44	2552	22	1276	2200	1324	0.16	0.33	417	124708	75283	199991
27	O	C	9	52	44	2288	22	1144	2464	1456	0.16	0.33	374	139673	82788	222461
28	O	C	9	52	44	2288	22	1144	2464	1456	0.16	0.33	374	139673	82788	222461
29	O	C	10	48	44	2112	22	1056	2640	1544	0.16	0.33	345	149650	87792	237442
30	O	C	10	48	44	2112	22	1056	2640	1544	0.16	0.33	345	149650	87792	237442
31	O	C	12	40	44	1760	22	880	2992	1720	0.16	0.33	288	169603	97799	267403
32	O	C	12	40	44	1760	22	880	2992	1720	0.16	0.33	288	169603	97799	267403
33	M	L	5	100	40	4000	26	2600	752	0	0.18	0.28	719	42628	0	42628
34	M	L	5	100	40	4000	26	2600	752	0	0.18	0.28	719	42628	0	42628
35	M	L	6	84	40	3360	26	2184	1392	416	0.18	0.28	604	78906	23654	102560
36	M	L	6	84	40	3360	26	2184	1392	416	0.18	0.28	604	78906	23654	102560
37	M	L	7	72	40	2880	26	1872	1872	728	0.18	0.28	518	106115	41394	147510
38	M	L	7	72	40	2880	26	1872	1872	728	0.18	0.28	518	106115	41394	147510
39	M	L	8	64	40	2560	26	1664	2192	936	0.18	0.28	460	124255	53221	177476
40	M	L	8	64	40	2560	26	1664	2192	936	0.18	0.28	460	124255	53221	177476
41	M	L	9	58	40	2320	26	1508	2432	1092	0.18	0.28	417	137859	62091	199950
42	M	L	9	58	40	2320	26	1508	2432	1092	0.18	0.28	417	137859	62091	199950
43	M	L	10	52	40	2080	26	1352	2672	1248	0.18	0.28	374	151464	70961	222425
44	M	L	10	52	40	2080	26	1352	2672	1248	0.18	0.28	374	151464	70961	222425
45	M	L	12	44	40	1760	26	1144	2992	1456	0.18	0.28	316	169603	82788	252391
46	M	L	12	44	40	1760	26	1144	2992	1456	0.18	0.28	316	169603	82788	252391
47	M	C	5	100	40	4000	26	2600	752	0	0.18	0.28	719	42628	0	42628
48	M	C	5	100	40	4000	26	2600	752	0	0.18	0.28	719	42628	0	42628
49	M	C	6	84	40	3360	26	2184	1392	416	0.18	0.28	604	78906	23654	102560
50	M	C	6	84	40	3360	26	2184	1392	416	0.18	0.28	604	78906	23654	102560

Continued on next page

Table C.1 – continued from previous page

I	S	P	t	D	WT	TTR	WTI	TTI	ATR	ATI	RTR	RTI	TCR	HATR	HATI	TCAH
51	M	C	7	72	40	2880	26	1872	1872	728	0.18	0.28	518	106115	41394	147510
52	M	C	7	72	40	2880	26	1872	1872	728	0.18	0.28	518	106115	41394	147510
53	M	C	8	64	40	2560	26	1664	2192	936	0.18	0.28	460	124255	53221	177476
54	M	C	8	64	40	2560	26	1664	2192	936	0.18	0.28	460	124255	53221	177476
55	M	C	9	58	40	2320	26	1508	2432	1092	0.18	0.28	417	137859	62091	199950
56	M	C	9	58	40	2320	26	1508	2432	1092	0.18	0.28	417	137859	62091	199950
57	M	C	10	52	40	2080	26	1352	2672	1248	0.18	0.28	374	151464	70961	222425
58	M	C	10	52	40	2080	26	1352	2672	1248	0.18	0.28	374	151464	70961	222425
59	M	C	12	44	40	1760	26	1144	2992	1456	0.18	0.28	316	169603	82788	252391
60	M	C	12	44	40	1760	26	1144	2992	1456	0.18	0.28	316	169603	82788	252391
61	E	L	5	108	44	4752	22	2376	0	224	0.16	0.33	777	0	12737	12737
62	E	L	5	108	44	4752	22	2376	0	224	0.16	0.33	777	0	12737	12737
63	E	L	6	90	44	3960	22	1980	792	620	0.16	0.33	647	44895	35253	80148
64	E	L	6	90	44	3960	22	1980	792	620	0.16	0.33	647	44895	35253	80148
65	E	L	7	76	44	3344	22	1672	1408	928	0.16	0.33	546	79813	52766	132579
66	E	L	7	76	44	3344	22	1672	1408	928	0.16	0.33	546	79813	52766	132579
67	E	L	8	68	44	2992	22	1496	1760	1104	0.16	0.33	489	99767	62773	162540
68	E	L	8	68	44	2992	22	1496	1760	1104	0.16	0.33	489	99767	62773	162540
69	E	L	9	62	44	2728	22	1364	2024	1236	0.16	0.33	446	114732	70279	185011
70	E	L	9	62	44	2728	22	1364	2024	1236	0.16	0.33	446	114732	70279	185011
71	E	L	10	56	44	2464	22	1232	2288	1368	0.16	0.33	403	129697	77784	207481
72	E	L	10	56	44	2464	22	1232	2288	1368	0.16	0.33	403	129697	77784	207481
73	E	L	12	46	44	2024	22	1012	2728	1588	0.16	0.33	331	154638	90294	244932
74	E	L	12	46	44	2024	22	1012	2728	1588	0.16	0.33	331	154638	90294	244932
75	E	C	5	108	44	4752	22	2376	0	224	0.16	0.33	777	0	12737	12737
76	E	C	5	108	44	4752	22	2376	0	224	0.16	0.33	777	0	12737	12737
77	E	C	6	90	44	3960	22	1980	792	620	0.16	0.33	647	44895	35253	80148
78	E	C	6	90	44	3960	22	1980	792	620	0.16	0.33	647	44895	35253	80148
79	E	C	7	76	44	3344	22	1672	1408	928	0.16	0.33	546	79813	52766	132579
80	E	C	7	76	44	3344	22	1672	1408	928	0.16	0.33	546	79813	52766	132579
81	E	C	8	68	44	2992	22	1496	1760	1104	0.16	0.33	489	99767	62773	162540
82	E	C	8	68	44	2992	22	1496	1760	1104	0.16	0.33	489	99767	62773	162540
83	E	C	9	62	44	2728	22	1364	2024	1236	0.16	0.33	446	114732	70279	185011
84	E	C	9	62	44	2728	22	1364	2024	1236	0.16	0.33	446	114732	70279	185011
85	E	C	10	56	44	2464	22	1232	2288	1368	0.16	0.33	403	129697	77784	207481
86	E	C	10	56	44	2464	22	1232	2288	1368	0.16	0.33	403	129697	77784	207481
87	E	C	12	46	44	2024	22	1012	2728	1588	0.16	0.33	331	154638	90294	244932
88	E	C	12	46	44	2024	22	1012	2728	1588	0.16	0.33	331	154638	90294	244932

Because, for one travel, environmental cost of one train ($ 7.19) is very low, compared to environmental costs in road ($ 56.6856 for truck and $ 56.86 for TIR), a vehicle is preferred to be transported with rail in terms of consumption. In these environmental costs, gases carbon monoxide (CO), nitrogen oxides (NOx), volatile organic hydrocarbons (VOC), fine particulates (PM) and carbon dioxide (CO^2) are considered. Costs of these elements are obtained from Victoria Transport Policy Institute, an independent research organization dedicated to developing innovative and practical solutions to transportation problems. Because, in instances with safety time interval 12 mins (least frequent of departures), least number of trucks or TIRs are carried in rail, which causes most number of vehicles to be transported by road, and because of the huge environmental cost of road, the greatest total environmental costs (TCS) are seen in these instances.

VITA

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