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Research Paper

An Evaluation For Optimizing Construction And Operation Costs Of Metro Systems

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Abstract: In this paper, it was summarized with the same named continuing PhD Dissertation of the author. The topic of this study; developing a method for, calculating and offering the most pertinent solution to a metro system's construction and operation costs which includes different alternatives for capacity, train sets, construction methods, etc. For this purpose, a software has been developed for optimizing metro systems construction and operation costs. Travel demand results that have been prepared for the proposed metro alignment corridor and other variable data of this region are the inputs of the cost optimization software Alternative longitudinal profiles shall be offered according to the light of vertical design criteria and it presents the appropriate station types and track types by the algorithms. This software shall suggest total construction cost of the optimum metro system. These recommendations shall be found based on each type of construction costs between 4-8 vehicles in a train set. BB-BC Genetic Algorithm method and Results of the Simulator X were used for the optimization. This software shall be used as basis source for the feasibility studies done for metro systems. Finally, the study aims to offer; proposed software model must meet the estimated transport demand for the target year and also satisfies minimum construction and operating costs with alternatives.

Keywords: Metro, Construction costs, Operating costs, Cost Optimization

1. Introduction

The best way to meet the transportation needs of the citizens is spreading public transport (PT) system across the city. Up to 1950s, developed western countries established urban public transport network for the metropolitan cities because of the facing problems in roadway traffic. Primarily they have also established the network of underground metro system in the city center and suburban transit system that integrated with the city's subway system for servicing to the suburb areas. Berlin, London and Paris can be given such as examples to these cities. Traffic congestion problem in these city centers is still ongoing and city rulers trying to encourage people to use public transportation systems versus to use of their own private vehicles. Furthermore, they have started to restrict using private vehicles in the central areas. Despite these problems in the city, people's public transport needs are mainly met by means of the public transportation system's accessibility. The life comfort of the citizens living in these cities are increasing thanks to the PT System [1].

Metro systems considered important in Turkey but on the other hand it has not reached to the desired level yet. Investments are mostly oriented to the roadways and rubber-tired PT systems in Turkey up to 2000s, urban rail systems have been largely neglected. However, it is observed from the comparisons for case studies of Istanbul city, that : Rail systems used less space as 5.5 times according to the roadway systems with the same travel demand unit [2]. These results showed us reasons of the necessity for giving priority to urban rail systems. As the primary mode in urban railway transport in terms of criteria such as capacity, safety, environmental impacts and punctuality, metro systems have still a comparably lower modal share in Istanbul's urban transport network, despite its ever-growing expansion recently.

The scope of this study is to present recommendations and evaluations for the construction and operation of the metro systems from derived the studies in the world and based on existing experience with a new approach method.

2. Purpose

Notwithstanding its crucial advantages, metro systems have also certain disadvantages, chiefly capital costs and long periods of implementation. Therefore, it is highly critical to adopt the right decisions before deciding or implementing metro system investments. Any transportation project created with the wrong decision will affect other transportation investments' location and form. First of all, planners must take into consideration for the land use decisions for establishing an effective transport network while planning of any city's transportation system. [3].

Systems are considered in the feasibility studies that organized before the construction of metro systems. During the feasibility studies conducted prior to the civil works stage, planners take into account the most feasible options that ensure optimal construction and operating costs. Estimated volume of ridership is the most important input affecting the entire system architecture in metro projects [4]. In this respect, it is essential to minimize estimation errors in feasibility studies, for the accuracy of the passenger demand has a direct impact upon the revenues, and hence profitability of the operations. Each subsystem should be designed not only at minimum cost but also to satisfy the demand. Stations have a substantial share in the overall cost, which makes it highly important to correctly plan the stations.

Feasibility studies play a crucial role in urban rail systems for taking the decision of the investment. Feasibility studies should be prepared according to the closest to actual cost and reliable demand. Nowadays, there are many differences in the feasibility studies between their results and actual values.

Flyvbjerg has found that large percentages of demand and cost forecast have error in his research for 210 feasibility study of the rail system [5]. There are also many mistakes in the feasibilty studies for estimating construction costs of the metro system. Some of these mistakes are because of using global costs based on previous or other city's data.

Here, the aim should be to satisfy the transport demand for the target year, as well as to ensure minimum construction and operating costs. The basis of criteria would include different ridership capacities, various construction methods, different lengths for train series and other related items. This model attempts to construct a methodology which will propose optimal construction and operation scenarios.

Furthermore, this study aims to offer; proposed software model must meet the estimated transport demand for the target year and also satisfies minimum construction and operating costs with alternatives for the feasibility studies.

In this study, an optimization model will be improved for a new subway system that will benefit from the travel demand analysis and other design criteria. The software should offer vertical profiles for the metro line and station type selections with an alternative proposal, which should be expected the most economical. A cost library was established from the ongoing and finished construction cost of the metro stations in Istanbul. In addition, this cost library should be modified for any city for future certain items. Metro operation costs for Istanbul city were analyzed to gain metro operation cost for per square meter and vehicle-km values. Detailed information about values and formulas will be given mentioned PhD Dissertation.

3. Construction Methods (CM) for the Metro System's Elements

There are two basic elements of subway construction – building the stations and their entrances, and building the tunnels running between the stations. Stations and tunnels are constructed in very different ways. Stations are constructed from the surface by excavating the area to be occupied by the station "box." Construction staging areas are usually located adjacent to station construction sites.

Metro system's elements have different costs cause of while constructing with different methods. Construction methods for the metro system buildings should be set according its requirements. It is very important to select right method because of the construction cost differences between these methods. The foremost variable in selecting the method of these structures are ground conditions and so available method should be selected according to ground characteristics. Geological structure of the earth due to lack of a uniform, there are several construction methods in the literature for metro tracks and metro stations.

3.1 Construction Methods (CM) for the Metro Track Structures

Metro track structures should be built with various construction methods according to the position and ground conditions. These structures can be underground and above ground as elevated. Underground track structures can be constructed with bored tunnel or cut-cover methods. Recently, the tunnel boring machines (TBM) is the more common practice for digging metro tunnels. New Austrian Tunneling Method (NATM) is generally used for the platform tunnels, passenger tunnels and switch tunnels. In addition, these structures can be built with cut-cover and top-down methods.

3.2 Construction Methods (CM) for the Metro Stations.

Metro stations should be constructed with various construction methods according to the position and ground conditions. These structures can be underground and above ground as elevated. Station areas excavated whole platform size or some partial's of the platform size according to the different variables. Cut-cover method is commonly used for the stations, Top-down and bored tunnel (NATM) methods are rarely used for the stations in special conditions.

4. Metro Systems Construction and Operation Cost Analysis

There are many cost differences for construction and operating costs of the Metro systems from country to country. It varies even from city to city, even within the same country. The construction and operating costs in each city are determined by the city's own terms. Istanbul city's data has been used for the mentioned software for construction and operation of metro systems. Due to certain limitation, these cost and area functions are given in the mentioned PhD Thesis.

4.1 Construction Cost Analysis

The construction cost of a metro line varies even within the same city, as it depends on the technical characteristics (subsoil, housing situations) of each project, which are linked to local conditions [6].

Further factors that determine the cost of a metro are the length, planning and design parameters, the construction works and station equipment [7]. Large projects are characterized by wider variation in a scale from 40% to 200% [8-9], while the systematic underestimation and final overrun of costs which has been noted depends, strictly and incrementally on delays and extensive duration of the implementation phase [6][10]. Furthermore, regarding data presented by Flyvbjerg at all, underground metro lines are four to six times more costly than at-grade ones [10].

The average construction costs of the latest constructions of the existing Metro systems in Istanbul were used in the mentioned optimization software. Unit construction costs per m^2 were derived from civil works and electromechanical systems cost analysis of Kadikoy -Kartal metro system. Variable characteristics as cost basis of the metro systems in terms of functions and features were given in the following Table 1.

Construction cost and area functions were established to find metro stations' cost. Empirical parameters were used in the area functions for gaining minimum area for the metro stations that provide sufficient areas for the requirements.

Table 1 : Variable Characteristics

Variable Type	Variable Characteristics							
Station Passenger Capacity (pass/hour)	10000 and under	10000 - 15000	15000 and above					
Number of Vehicles in a Train set	4	5	6	8				
Platform Construction Method	Viaduct	Grade	Bored Tunnel	Cut-Cover	Top-Down			
Concourse Construction Method	Viaduct	Grade	Bored Tunnel	Cut-Cover	Top-Down			
Rail Top Level	Between 15 m and 99 m	Between 7 m and 15 m	Between (-3) m and 7 m	Between (-3) m and (-15) m	Between (-15) m and (-22) m	Between (-22) m and (-27) m	Between (-27) m and (-35) m	Between (-35) m and (-99) m

These construction costs analysed within 3 titles in the mentioned Ph.D study.

- Concourse Building Construction Costs
- Platform Structure Construction Costs
- Other Structures Construction Costs

4.2 Metro Systems Operation Cost Analysis

Operating costs for urban rail systems need to focus on an issue. The purpose of this study constituting the other wing rail cost optimization operating costs were examined under three topics; station operating costs, metro track operating costs and overall metro operating costs. With reference to the operational costs, these are increased by the existence of characteristics, such as ventilation, lighting, air conditioning or platform screen doors, but simultaneously these factors increase the satisfaction of customers by providing them comfort, reliability and quality of services [11].

Operation costs include mainly staff, energy and maintenance costs. The operation outputs of Istanbul Ulasim Company that is the operator of Istanbul metro system were investigated for this purpose. The most important components of the metro system's operation have analyzed in the scope of this study.

- Metro System Station Operation Cost Analysis
- Metro System Track Operation Cost Analysis
- Metro System General Operation Cost Analysis

5. Operating Method of Cost Optimization Software

In order to optimize the construction and operation costs of a metro line, a software was developed in Microsoft Visual Studio with C# language by using object oriented programming approach. The software uses Big Bang - Big Crunch algorithm for the optimization process.

Cost optimization program was prepared utilizing an energy simulation program and via optimization algorithm. Consumed energy of the metro trains was obtained from the functions based on the multi-train simulator's output. Train operation and movements were simulated in Simulator X software. Movement between the two stations for a train set consisting 6-car with AW3 load was simulated Simulator X using for different values of the distance and slope.

An algorithm is a heuristic search method that imitates the process of natural evolution. It is motivated by the principles of natural selection and survival of the fittest individuals. This method is commonly used to generate useful solutions to optimization problems. There is now considerable evidence that algorithms are useful for global function optimization and NP-hard problems despite continuous arguments. [12] Firstly, it was decided to use two algorithms (Genetic Algorithm & Big Bang Big Crunch Algorithm) in the optimization software. But after a lot of trials, it is decided to use only Big Bang Big Crunch Algorithm. These software and algorithm are explained in the following clauses.

5.1 Multi-train simulation program: SimuX

Simulator X (or shortly SimuX) is a multi-line, multi-train simulation program for electrified rail transportation systems. SimuX enables user to simulate transportation systems in great detail and flexibility. It is under continuous development with new features as per new needs and developments emerge in the sector.

In simulation of transportation systems, there are hundreds of parameters to be entered into the model by the user in order to have a satisfactory simulation. Inputs include parameters for tracks/lines, power feeding system, traction power supply system with any protection device such as voltage limiting device, all types of rolling stocks to be used, and operational data and constraints. With these powerful dynamic simulation algorithms SimuX avoids over sizing of the system, ensuring that simulation-based capital investment decisions are the right ones.

With support for multiple train types, train consists; SimuX supports the development and optimization of integrated operating plans.

SimuX supports the assessment of future operating plans in terms of on-time performance predictions, energy usage, vehicle requirements, and the ability of the traction power system to support the proposed train service level under "normal" and "contingency" operations. [13].

5.2 Big Bang Big Crunch Algorithm:

The BB-BC algorithm is a population-based evolutionary computation method. The algorithm is shown to be fast convergent, both in unimodal and multimodal topologies. In this section, a brief summary of the BB-BC algorithm is presented and the new crunching operator is introduced.

Aside from the random initial population, in each iteration the population is created in the big bang phase. In this phase, the candidate solutions are spread over the search space using normal distribution. The standard deviation of the distribution is adjusted with respect to the iteration count and the mean value of the distribution is taken as the last representative point found. The impermissible candidates are handled at this phase. Once the new population is created, the candidate individuals are assigned a fitness value to be used in the following big crunch phase. Big crunch is a multiple input single output operator. [14].

5.3 Operating mechanism of the optimization software

Working mechanism of the cost optimization software can be summarized as follows. Firstly, input values shall be loaded into the program. Station type variables for rail systems that used in the software, was given in the Table 1. (Page 4)
Inputs :

- Location information of the station, from GIS
- The number of passengers arriving at the station, from Travel Demand Analysis
- Station construction method (CM) proposal, if it is known
- Platform & Switch CM proposal, if it is known
- Constrains for the proposed metro line, if it is known
- Cost Information (2^{nd} phase for other countries).

The software processes the data at hand in accordance with the design criteria and standards. Primarily, vertical profile design process starts according to existing ground levels. Secondly, bottom and top level of the constraints of the vertical profile values are handled by the software. If there is no information given by the user in the depth of the line then the subsequent stations will be established according to the position of the alternate longitudinal section. Cost optimization starts after this stage. The cost values of the elements of the metro system can be derived from the library cost.

These alternative longitudinal profiles will be offered according to the light of vertical design criteria and it presents the appropriate station types and track types by the algorithms described above. Herewith total construction cost of the optimum metro system will be offered by this software. These recommendations will be found based on each type of construction costs between 4-8 vehicles in a train set. As mentioned above, the operating costs will be found under three titles. Simux outputs will be utilized especially to find the energy consumption values of the metro vehicles, according to the characteristics of the metro line. In addition, operating cost (energy) values of all alternative profiles will be calculated.

Herewith total construction cost of the optimum metro system will be offered by this software. These recommendations will be found based on each type of construction costs between 4-8 vehicles in a train set. As mentioned above, the operating costs will be found under three titles.

Simux simulation program outputs will be utilized especially to find the energy consumption values of the metro vehicles, according to the characteristics of the metro line. In addition, operating cost values of all alternative profiles will be calculated.

According to the results of the optimization software, total energy consumption of the metro system will be determined for various operating methods. Station operating cost values will be calculated according to system needs additionally. Optimization result for the vertical design can be shown in the Figure 1. Finally, general operation costs will be added to this calculation. In this manner, the overall operating cost will be found. For comparing each operation methods in healthy way, operating costs will be calculated for a period of 20 years for the feasibility study. Operation costs calculated for 20 years, because of heavy maintenance (renovation of the facilities) process start for the installations after this year. Heavy maintenance for the installations is not added to the operation costs.

The most appropriate construction and operating costs will be proposed for all alternatives according to the different operation methods at the end of the optimization process. As a result of this optimization for the rail system being studied, the output of the program is as follows;

- System design criteria
- Vertical geometry design criteria
- Station sizing design criteria (according to the type of system)
- System business metrics
- Approximate cost analysis for the metro system.

Screenshots of this software were given at below figures from figure 1 to figure 5.

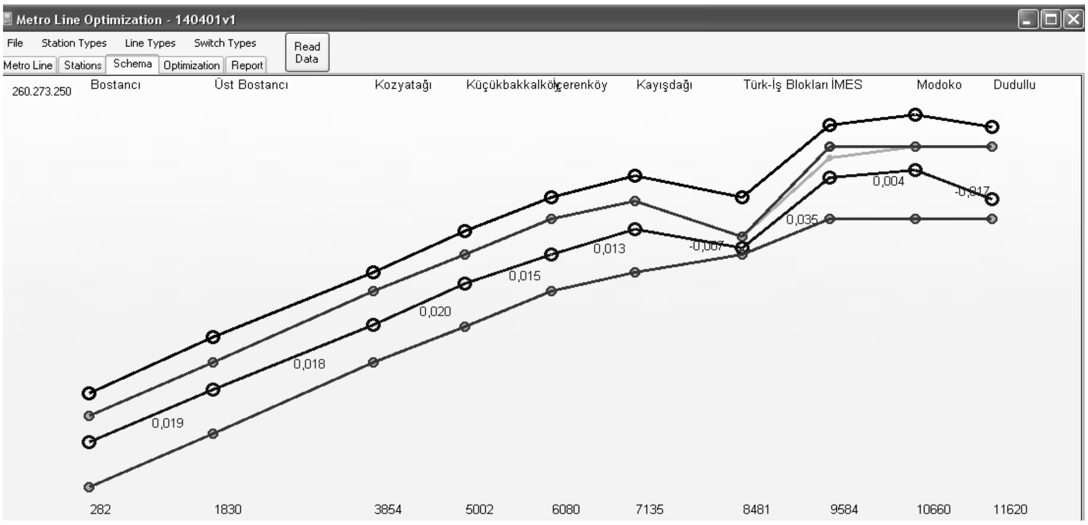

Figure 1: Screenshot from the Metro Cost Optimization Software

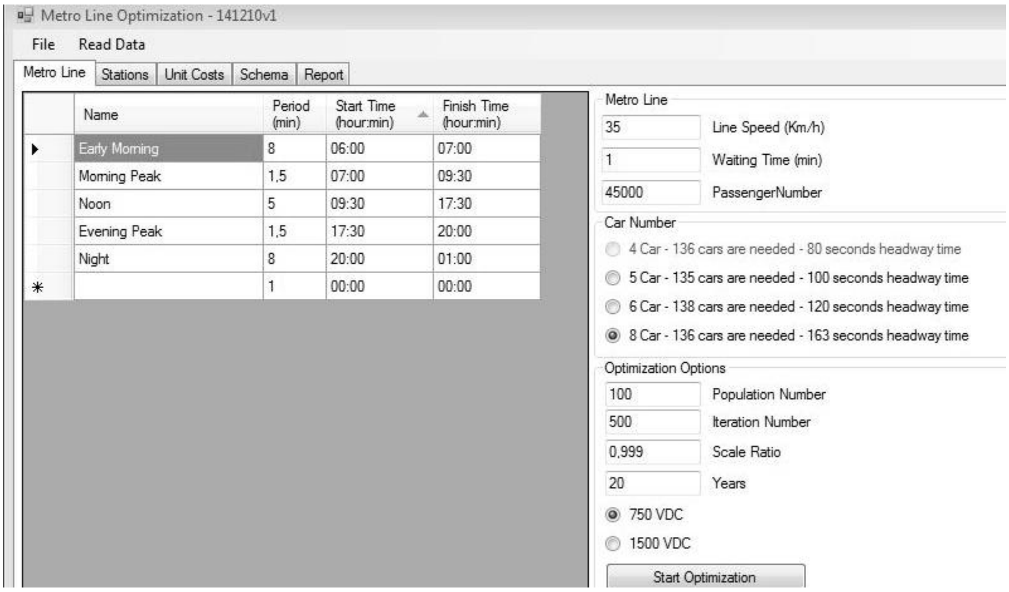

Figure 2: Proposed Metro System's Operation Information

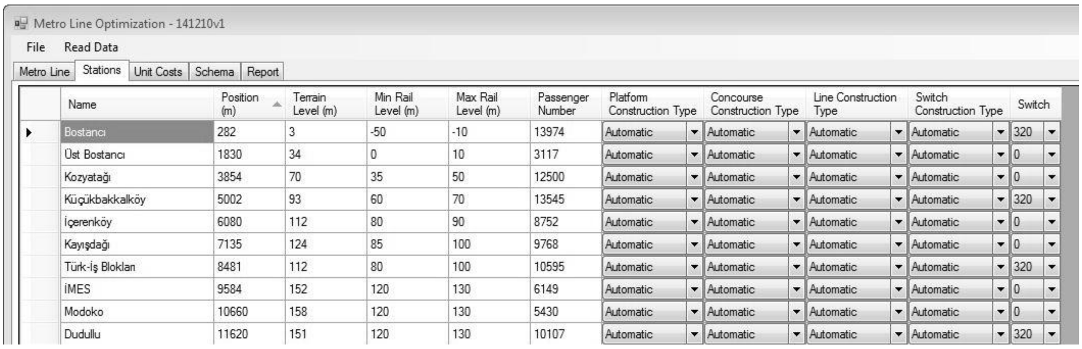

Figure 3: Proposed Metro System's Stations Location and Constr. Method Information

Figure 4. Proposed Metro System's Construction and Operating Cost Optimization Report

6. Evaluation and Analyses of the Software

Outlined in the section above all as a result of this process, the available software creates results by optimizing their suggestions.

- Design parameters of the proposed metro system
- Metro system operation plan proposal

Municipalities, Contractors and Consultants can use these outputs in preliminary design stage. Alignment designer can use vertical profile primarily and architect can design their stations according the results obtained from the software.

Istanbul Metro is a rapid transit railway network that serves the city of Istanbul,Turkey. It is operated by İstanbul Ulasim (Istanbul Transport), a public enterprise, controlled by the Istanbul Metropolitan Municipality. The oldest section is the metro is M1 line, which opened in 1989; it now includes 70 stations in service with 30 more under construction.

The system currently consists of five lines named M1, M2, M3, M4, and the M6 Mini-Metro. more lines are under construction or planned: M5 (Üsküdar-Çekmeköy/Sancaktepe) will be on the Asian side, while M7 (Mecidiyeköy-Mahmutbey) will be on the European side.

Dudullu – Bostancı metro line was selected and examined in the optimization software for different operation scenarios. Dudulu- Kayışdağı-İçerenköy- Bostancı metro line, which aims to ease transportation by integrating lines passing through one of the intensive regions of Asian side each other, will have a length of 11.90 km. The new metro line will connect two metros each other and will have 10 stations. Travelling time will last 21 minutes. Dudullu-Bostancı metro line will be integrated into Bostancı station of Marmaray. The new metro line will also will be integrated into Kadıköy-Kartal metro line and will combine with Üsküdar- Çekmeköy metro line, which is under construction, at Dudullu station through Bakkalköy, İçerenköy, Kayışdağı, Türkiş Blocks, Imes and Modoko. Dudullu-Bostancı metro line is planned to be completed by 2019. This line's location in the network can be seen in Figure 5.

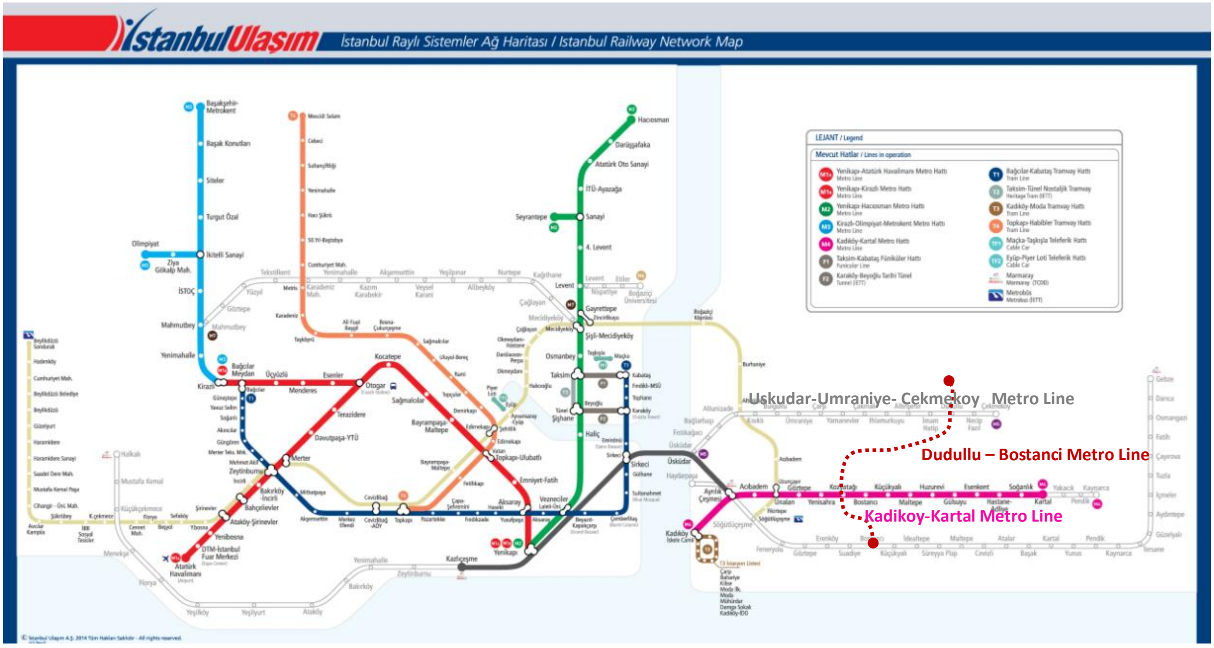

Figure 5: Existing Metro Systems of Istanbul City (2015)

Optimization results are presented below Table 2.It could be easily analyzed that the metro system is able to carry same passengers with low capital investment. Approximately 22 percent difference between the 4 cars and 8 cars train settled systems in both operation and construction optimized costs. Similar values are found between comparisons for every city. by simple calculation; a 200 km 4 car train set system can be constructed with a 6 billion euro budget, but a 164 km 8 car train set system can be built with same budget. Constructing bigger stations is not only increasing the capital investment, operating costs will also rise because of the expanding station buildings. Table 2 is the proof of this statement.

Table 2: Optimized Metro System Construction & Operating Costs (1)

Line	Dudullu- Bostancı Metro		No's of Stations	10								
Length	11.90 km		Passenger Capacity	35000	Pphpd *							
			Capital Cost				Operating Cost					TOTAL
Number of Vehicles in a Trainset	Required Minimum Headway (Second)	Energy (VDC)**	Total Station Construction Cost (€)	Total Track Line Construction Cost (€)	Total Vehicle Cost (€)	Total Capital Cost (€)	Total Station Operating Cost (€) (20 years)	Total Metro System Track Operating Cost (€) (20 years)	Total Metro System General Operating Cost (€) (20 years)	Total Metro System Operating Cost (€) (20 years)	Total Metro System Operating + Capital Cost (€) (20 years)
4	99	1500	93.717.263	102.260.092	108.000.000	303.977.355	118.176.815	139.413.863	71.964.682	329.555.360	633.532.715
5	120	1500	114.527.531	100.159.658	115.000.000	329.687.189	130.307.910	151.275.727	76.597.791	358.181.428	687.868.617
6	150	1500	135.494.600	98.058.705	108.000.000	341.553.305	142.439.004	151.280.978	74.390.900	368.110.882	709.664.187
8	210	1500	176.821.138	93.858.692	104.000.000	374.679.830	166.701.193	155.650.152	74.897.119	397.248.464	771.928.294

* Pphpd = Passenger per hour per Direction

** VDC= Volts Direct Current

7. Conclusion

Establishing metro system in any city requires a long process of decision-making, and because of this, there can be many modifications in the projects from the beginning. Transport investments have long lasting effects on economical, social and physical life of cities, and this is particularly true for rail transit investments, which have fixed infrastructure resulting in a permanent change in urban areas. This fixed infrastructure also makes rail transit projects extremely expensive investments. Rapid rail transit systems require the highest amount of investment costs. Considering the high cost involved in the development of these systems, it is particularly important that their performance justifies this high cost and that expectations from these investments are met. [15]. Detailed cost optimization should be done for metro systems before taking construction decisions. Looking at the M4 Metro system as an example (Istanbul), this system has an 8 car train set system with 70.000 pphpd (Passenger per hour per Direction) capacity. However, this system carries a maximum of 250,000 passengers per day. In this line's feasibility study, total demand was estimated at approximately one million passengers after 20 years operation start in the feasibility. It is not known when it will use all of its capacity. Because these lines are extending, but also parallel, lines connecting to this line will be established in the future network plan. It is possible that this line will never use its full capacity.

In this study, summary of the PhD Dissertation and metro systems construction and operation cost optimization software was also explained. This software will be beneficial for the policy of establishing metro systems for the city's decision makers and will be eligible to make every difference on the model and the parameters. Retrieving closest values to the actual total cost from the output of the established software was one of the targets in this study. These values can be used also in the feasibility study.

Furthermore, outputs produced by this software should be used as a base design for the all project stages. In this study outlined thesis is targeted to be completed in the second half of 2015. This software will provide the results of cost optimization as shown in the above figures and following table.

As a result, and looking from economical point of view, choosing shorter metro systems will become more reasonable for countries who have financial concerns and whose future development plans are ever-changing like Turkey.

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