AN APPROACH FOR IMPROVING ENERGY EFFICIENCY IN A COMMERCIAL BUILDING WITH LEARNING CONSIDERATION AND AVAILABILITY CONSTRAINTS

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ABSTRACT

AN APPROACH FOR IMPROVING ENERGY EFFICIENCY IN A COMMERCIAL BUILDING WITH LEARNING CONSIDERATION AND AVAILABILITY CONSTRAINTS

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Energy efficiency applications are increasingly becoming more popular as available natural resources such as natural gas and fossils have been running out. In this study, we address the scheduling problem of the heating, ventilation and air conditioning (HVAC) system of a commercial building with a supporting automation system that controls the energy resources so as to increase energy efficiency. We formulate the problem as a multilevel generalized assignment model to obtain the schedule for the HVAC system and to determine the units of the system that should work in different periods of a day. The objective is to minimize the electricity consumption subject to the user requirements. In our formulation we consider the dynamic nature of weather conditions, multi-level structures, availability conditions and learning effects of the resources, and the circulation of people in the building as well. Moreover, we propose a tabu search algorithm with ejection chains to solve such a complex and large model in reasonable times, and present the computational results. Our tabu search algorithm provides satisfactory results with a significant amount of reduction in electricity consumption, without remarkably increasing the computational effort required.

Keywords: Energy Efficiency, Learning Effect, Availability Constraints, Multilevel Generalized Assignment, Tabu Search

ÖZ

ÖĞRENME ETKİLERİ VE UYGUNLUK KISITLARI OLAN ORTAMDA TİCARİ BİNALARIN ENERJİ VERİMLİLİĞİNİ ARTTIRMAYA YÖNELİK BİR YAKLAŞIM

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Doğal gaz ve fosiller gibi sınırlı kaynakların gün geçtikçe azalması nedeniyle enerji verimliliği uygulamaları gittikçe yaygın hale gelmektedir. Bu çalışmada, ısıtma, soğutma ve havalandırma sağlayan sistemlerin bir otomasyon sistemi ile kontrol edilebildiği ticari binalarda enerji verimliliğini yükseltmek amacıyla sistemin çizelgelenme problemini ele almaktayız. Çalışmamızda, kullanıcı ihtiyaçlarına göre en düşük elektrik tüketimini elde edecek şekilde havalandırma sistemindeki birimlerin günün değişik zamanlarında hangi seviyede çalışacağını belirlemek için çok-seviyeli atama problemine yeni bir yaklaşım getirmekteyiz. Formulasyonumuzda ayrıca hava koşullarının dinamikliğini, havalandırma sistemindeki birimlerin birden fazla seviyede çalışabilirliğini, bu birimlerin bakım programlarını, öğrenme yeteneklerini ve tesisteki insan hareketlerini de hesaba katmaktayız. Ayrıca böyle karışık ve büyük bir modeli uygun sürelerde çözmek için ejection chainleri kullanan yeni bir tabu arama algoritması önermekte ve bu algoritmanın sonuçlarını sunmaktayız. Tabu arama algoritmamız ile gereken çözüm süresini çok fazla arttırmadan, önemli derecede enerji tasarrufu sağlayan tatmin edici sonuçlara ulaşılmıştır.

Anahtar Kelimeler: Enerji verimliliği, Öğrenme etkisi, Uygunluk kısıtları, Çok-seviyeli atama, Tabu Araması

Gökçe, my passionate love

definitely for you

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I am really grateful to my only love Gökçe. She is my first and only inspiration who always supported me during this period.

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CHAPTER 1

INTRODUCTION

Energy consumption has increased considerably during the recent years more than the previous decades due to the fact that buildings and industries consume enormous energy to deliver service and goods demanded by the society. After the year 1998, the annual service sector deliveries have started to increase compared to the previous decades, and there has been a substantial increase in primary energy usage and CO_2 emission all over the world. Figure 1 below shows that primary energy consumption has boosted with an average annual increase of 2% when the reference year is considered to be 1984 (Pe´rez-Lombard et al., 2008). Moreover, it can also be seen that annual CO_2 emission has increased with an average annual value of 1.8%.

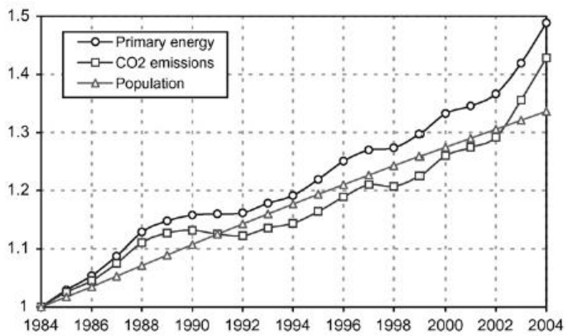

Figure 1 Total Energy Consumption, CO_2 Emission and Population in the world (Reference year: 1984)

Public and municipal assets, industrial and commercial buildings are the most important types of assets in consuming energy. Among them, commercial buildings have remarkable energy consumption values when comparing their total share against other facilities like factories, public assets and residential buildings. Since there is not any recent research on the portion of buildings in the total energy consumption in the world, the findings of Pe´rez-Lombard et al. (2008) present how buildings can impact energy consumption at the time when the research was made. It is observed in Table 1 below that almost quarter of the world total energy consumption is due to buildings whereby the consumption of Europe stretches the value to 37% in 2004 (Pe´rez-Lombard et al., 2008).

Table 1 Buildings Energy Consumption in 2004

Final energy consumption (%)	Commercial	Residential	Total
USA	18	22	40
UK	11	28	39
EU	11	26	37
Spain	8	15	23
World	7	16	24

Besides, total energy consumption of commercial buildings and residential buildings is expected to grow from 28 quadrillion Btu to 42 quadrillion Btu which means an increase of 50% over the next 20 years. Figure 2 below shows that total energy consumption of non-OECD countries is forecasted as 18.1 quadrillion Btu in 2035, most likely due to the fact that new buildings and residential areas are growing faster so as to improve education, healthcare and hospitality services than ever in these countries (Energy Outlook, 2011).

The distressing aspect of increasing total energy consumption is the increasing consumption of the scarce resources to produce energy. Electricity and natural gas are the two of the most important resources around the world. Abdelaziz et al. (2011) claim that the portion of electricity and natural gas in electricity production will reach to 45% by 2030. It is obvious from Figure 3 below that natural gas which is one of the most polluting resources to produce energy is in the second order

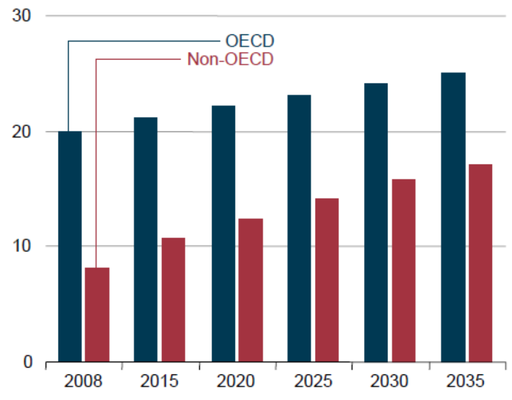

Figure 2 Forecasts for Buildings Energy Consumption in years 2008 through 2035 (quadrillion Btu)

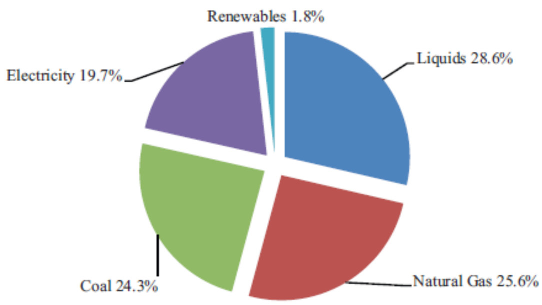

Figure 3 World Energy Share by 2030

following liquids and followed by coals and electricity in the world energy share in descending order. However, renewable resources are not expected to become popular by the end of the first quarter of this century, although general outlook shows the reverse direction (Building Research Energy Conservation Support Unit, 1997).

Owing to the decrease in natural consumable resources, researches on new energy resources have become more important than ever (Escrivá, 2011). Furthermore, CO_2 emission values and global warming effects of such resources cause them to be considered as harmful resources to the nature. In order to decrease the total consumption of energy and to find new resources, lots of companies and energy producers work on new technologies.

A few benchmarking systems have been established to increase the awareness and to obtain a database for organizations to compare the consumption of their buildings against similar buildings in the world (Chung et al., 2006; CIBSE, 2004). By the help of such systems, it has been recovered that there might be another way of decreasing both energy consumption and carbon foot print indeed.

Energy efficiency applications have been implemented more systematically with a holistic view since the last decade, and it has been observed that they have been more persistent and they cost less than constructing new resources to produce energy. Smart technologies, automation systems and trained employees are becoming more valuable than the traditional machines and unskilled personnel in commercial buildings so that energy can be used more efficiently.

It is obvious that energy consumption of commercial buildings increases steadily. Hence scientific methods should be one of the opportunities that can be used on such applications in order to manage energy delivery and increase the energy efficiency. For these reasons, in this study, the Headquarter of the Union of Chambers and Commodity Exchanges of Turkey (TOBB) has been audited and a new method of resource management is presented. A mathematical model for resource assignment is proposed, in which smart technologies of the building have been benefited from, and a tabu search algorithm is proposed which is a more practical and faster method to manage energy consumption in the building. The rest of the study is presented as follow:

In Chapter 2 the problem environment and core information are given to introduce the building specifications and energy audit of the building. To approximate the real-time occasions to the problem, characteristics and variables of the model are also given in this Chapter. Researches in the literature related to the problem overviewed are presented in Chapter 3 and the mathematical model proposed is discussed in Chapter 4. Tabu search algorithm and its features are given in Chapter 5, and comparisons and computational results are presented in Chapter 6. Conclusion and future research issues are discussed in Chapter 7.

CHAPTER 2

ENERGY AUDIT AND PROBLEM DEFINITION

In this chapter we describe the general problem environment, energy audit which is done in order to investigate the reasons of high energy consumption and the basic definitions of the mathematical model proposed.

2.1. General Terms

The building considered in this study is located at the very center of the capital city of Turkey. The Union of Commodity Exchanges and Chambers of Turkey (TOBB) had acquired the building in 2009 and before that time it was not used even though it was ready to be commissioned. The building is a well-designed one and smart in the sense of automation systems, energy systems, mechanical systems, heating, ventilation, air conditioning systems and boiling systems. Building was designed as two twin towers, where each of them consists of 32 flats and has height of 129 meters, plus 13 additional outbuildings serving as social activities such as food and beverages, sports, meeting rooms, etc. All departments of TOBB work in the building; besides them, there are 24 other firms working in the facility as tenants.

Since TOBB is a non-governmental organization, it is prohibited by laws to produce activities or goods which can be sold or served in order to make profit. Therefore, a private corporation had been founded in 2009 to lease and operate the facility in association with TOBB and four joint-ventures of TOBB. The main operation areas of the company are to operate all issues of the facility such as security, housekeeping, maintenance and leasing in order to satisfy the comfort and safety requirements of people working in the facility. The purpose of the company is to make as much profit as possible while providing the life standards of both the companies working in the facility and people living in the facility. The main income item is the service charges or service fees -collected from all tenants- which are calculated at the end of each month according to expenses during the month. Security personnel expenses, housekeeping personnel expenses, maintenance expenses, electricity and natural gas expenses are some sample expenses which directly affect the service charge invoiced to tenants (RICS, 2011). A more common definition of the service charge may be given as "every cost incurred due to all spaces beyond the ones demised to tenants by the landlord or the management company" (Morley, 2012).

Higher utilization of the facility is crucial for the company, since more tenants mean that empty flats or empty social areas would not be covered by the management company or the landlord. Therefore, making the facility more attractive would increase the demand for the facility and provide the company with more powerful and profitable work areas. The only easiest way of increasing both the demand and profit are to decrease the service charges if the company could manage its operations with minimized costs.

2.2. Service Charges

All companies located in the facility have to pay service charges including all expenses spent related with the facility. There are seven main groups of expenses in the service charge, namely; management, electricity, natural gas, water, security, housekeeping and maintenance.

Management expenditures include all wages and taxes about wages of all in-house employees working in the company, all lunch and dinners of the company personnel, all paper-work and other consumable materials such as drinks, housekeeping materials, etc. In other words, all expenses of the personnel employed by the company can be considered as the management expenditures.

Electricity, natural gas and water bills used in the facility are invoiced by the government or public-private initiatives which are the same as with all other buildings in Turkey; and they are all paid by the company on behalf of all her tenants. After payment, the amount paid is somehow reflected to the tenants in their service charge invoices.

Security expenses cover all personnel wages and taxes about wages of security officers, uniforms (official clothes) of officers, lunches and dinners of officers, over-payments, if any, training and new-user licenses expenses and other consumables such as weapon maintenance, official declarations to government offices, etc.

Housekeeping expenditures are related to all personnel working in cleaning and organizing the facility. Wages and taxes about wages, uniforms, training and new-user licenses, lunches and dinners, housekeeping materials such as detergent, soap, paper towel, etc. and other consumable expenses can be considered as housekeeping expenses.

Maintenance is all about electrical, electronic and mechanical systems. Most of the devices are under the control of in-house employees of the company itself, whereas some of them are outsourced. For those which are guaranteed by the producer, the company makes yearly contracts and hence periodical expenses occur. Therefore, expenditures about the contracts can be predictable. However, most of the maintenance expenses consist of unforeseen breakdowns and material and labor expenses related to the breakdowns.

A sample list of monthly expenditures in the service charge invoices is shown in Table 2 below regarding total amount (a) and percentages (b). It can be seen from Table 2(b) that the highest cost was incurred due to electricity with the percentage of 27% in average for the last year. It is followed by management, housekeeping and security expenses in descending percentages.

According to the company contracts with the security and housekeeping sub-contractors, these expenses are nearly constant for the next 3 years. Natural gas is only used for cooking and water is consumed only for cleaning. That is why there is no room for improvement for these types of expenditures. Management expenses are mainly salaries of employees, which are determined by a highly reputable council in which the President of TOBB and his crew take roles.

Table 2 Service Charge Distribution in 2012

(a) Total Amounts of Service Charge Items (TL)

Period	Management	Electricity	Natural Gas	Water	Security	Housekeeping	Maintenance
Jan.12	220,722.23	244,579.19	162,329.24	14,259.80	176,448.38	187,220.29	61,952.72
Feb.12	221,182.23	264,724.58	183,460.76	14,319.80	177,636.68	178,816.65	55,905.09
Mar.12	226,160.34	268,266.22	146,871.74	18,317.30	171,021.86	184,923.34	78,479.10
Apr.12	235,727.48	262,802.07	41,305.22	19,779.80	182,138.42	178,627.80	119,617.01
May 12	246,090.52	307,826.79	24,647.20	26,867.30	184,296.04	203,083.09	133,599.41
Jun.12	241,144.38	327,575.51	10,147.90	30,752.30	174,326.00	179,051.01	134,275.59
Jul.12	228,350.18	354,714.66	2,553.52	32,177.30	185,611.68	181,900.72	112,923.03
Aug.12	245,830.23	322,413.47	2,239.87	29,754.80	179,941.15	186,929.96	100,635.32
Sep.12	274,383.10	297,655.83	2,272.10	25,622.30	185,583.81	201,449.99	129,457.33
Oct.12	258,399.72	291,898.70	14,833.09	26,049.80	173,710.15	189,636.66	99,421.62
Nov.12	252,069.79	348,483.79	81,041.10	8,094.80	185,965.11	197,589.32	108,217.34
Dec.12	217,985.25	280,730.98	63,524.60	26,049.80	176,676.18	194,049.02	151,085.75
Grand Total	2,868,045.43	3,571,671.78	735,226.34	272,045.10	2,153,355.45	2,263,277.85	1,285,569.30

Table 2 (continued)

(b) Percentages of Service Charge Items per Month

Period	Management	Electricity	Natural Gas	Water	Security	Housekeeping	Maintenance
Jan.12	0.21	0.23	0.15	0.01	0.17	0.18	0.06
Feb.12	0.20	0.24	0.17	0.01	0.16	0.16	0.05
Mar.12	0.21	0.25	0.13	0.02	0.16	0.17	0.07
Apr.12	0.23	0.25	0.04	0.02	0.18	0.17	0.12
May.12	0.22	0.27	0.02	0.02	0.16	0.18	0.12
Jun.12	0.22	0.30	0.01	0.03	0.16	0.16	0.12
Jul.12	0.21	0.32	0.00	0.03	0.17	0.17	0.10
Aug.12	0.23	0.30	0.00	0.03	0.17	0.18	0.09
Sep.12	0.25	0.27	0.00	0.02	0.17	0.18	0.12
Oct.12	0.25	0.28	0.01	0.02	0.16	0.18	0.09
Nov.12	0.21	0.29	0.07	0.01	0.16	0.17	0.09
Dec.12	0.20	0.25	0.06	0.02	0.16	0.17	0.14
Average	0.22	0.27	0.06	0.02	0.16	0.17	0.10

Taking all these facts into account, the only item the company is able to minimize in their expenditures is electricity which already corresponds to the highest cost portion. In order to decrease total electricity consumption of the facility, a systematic approach has been used as detailed in Section 2.3 and the following sections. Primarily, it is important to be familiar and to analyze the way energy flows into facility and the way how energy is delivered inside the facility. Getting some comprehensive results from these analyses, further applications and solution-oriented proposals would be possible.

2.3. Energy Audit

As it is mentioned in Section 2.2, electricity has the highest portion in the service charges amongst all other expenses. Therefore, to understand processes within the facility and to figure out internal and external connections of problems related with electricity consumption, an investigation process has been practiced named as energy audit. An explanation of energy audit is recently provided by Abdelaziz, et al. (2011) as *"an inspection, survey and analysis of energy flows for energy conservation to reduce the amount of energy input into the system without negatively affecting the output"*.

According to this definition, energy audit includes inspections, surveys, interviews and data analysis. Hence, several end-user, technical crew and producers of the machines are interviewed at different times and all systems in the facility are analyzed based on some certain measures. As a result of these explorations, a fish-bone diagram given in Figure 4 is developed. Interpretations on energy audit are given in five clusters which are "Systems", "Machines, Centrals and Equipment", "Facility Itself", "Laws and Regulations" and "End-User".

Systems

Since the building is very high, there are several automation centers through the floors that help the company to manage every five floors directly. In each center, there are four different groups of systems that control different types of machines, equipment, lighting, etc.

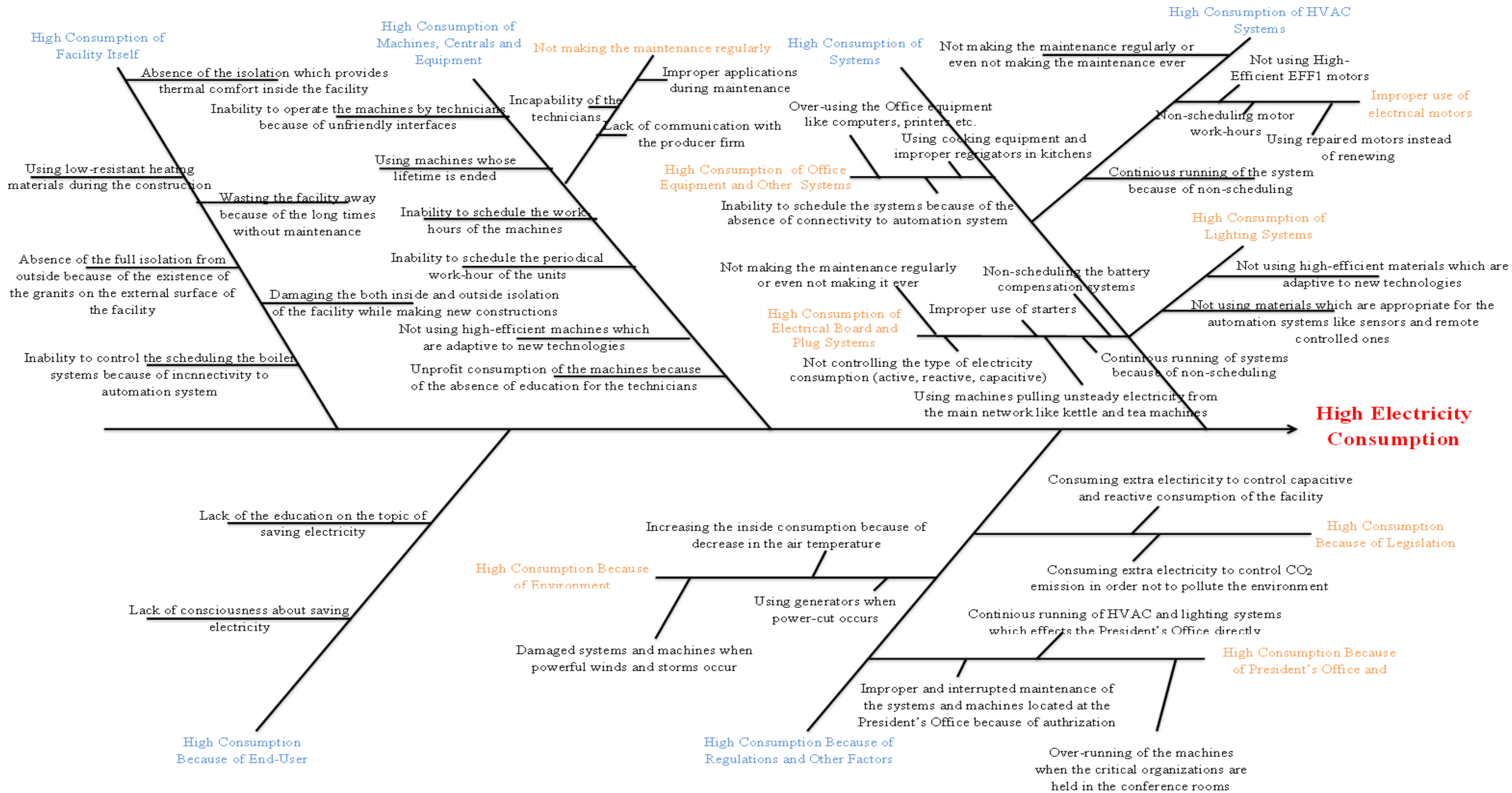

Figure 4 Fishbone Diagram

The first and the most important system is Heating, Ventilation and Air Conditioning (HVAC) system. HVAC is used for controlling all climatic conditions such as heating when the inside temperature falls below certain degrees or cooling when the temperature goes up to certain degrees. Degrees determining when HVAC system would be on or off are defined by the employees working in the automation center under current circumstances. All HVAC systems can be controlled from the special software which can let operator shut down or start up the machines, and even program the whole day by setting how and at which level machines would work. However, because of the lack of experience and know-how about scheduling, all systems run during the whole day resulting in high consumption of electricity.

Another important controlling system is the lighting system which helps company manage all lamps, armatures, and the environment and exterior lights around the facility. Most of the materials are not appropriate for the automation system which means that there is no connectivity between electrical circuits of the materials and automation centers. Therefore, company cannot control and manage the work-hours of the lighting materials. What company is able to do is to shut down certain circuits or to start them up. However, inability to schedule the lighting system causes high electricity consumption.

The other two systems are office systems and electrical board and plug systems. These two systems have similar specifications for controlling. Both of them can be controlled from the automation center in the sense of fuse policies which means that if energy requirement raised by flats exceeds the capacity of the facility, they are shut down and they are not opened again until a safe level is reached. Electrical systems increase energy consumption due to several reasons such as irregular maintenance schedule, continuous running, improper use of personnel equipment (kettles, coffee machines). The biggest effect to the consumption by which electrical board and plug systems cause is not to schedule the compensation system, which stabilizes the main power pulled from the city network so that inert power may be blocked, because of the lack of trained personnel and complexity of the user interface of the software.

Machines, Centrals and Equipment

The facility has more than 100 different machines and more than 20 centers that control these machines. All pumping machines, boilers, generators, substitute energy resources are some samples of these machines. All of the machines consume electricity in order to serve for the related equipment. However, lack of efficient maintenance schedule and inability to maintain give rise to machines overrun or higher consumption of electricity by the machines. Moreover, owing to the fact that the new machines with newer technologies are not used around the facility, company cannot utilize the saving advantages of such technologies. For this reason, machines cannot be scheduled in order to decrease the electricity consumption, since they do not have any characteristic to achieve this because of their old technology.

Facility Itself

The building was constructed in 1990s and that is why most of the construction materials are not appropriate for the new technologies. Especially, the insulation materials are old, causing loss of indoor heat; therefore, it increases the total electricity consumption of the facility by forcing systems to satisfy indoor heating conditions.

Another reason which increases the electricity consumption is that the building has not been used for a long time after completion of the construction; therefore, the materials and assets have been degraded and depreciated because of lack of proper maintenance. After moving into the building, the building was enlarged by TOBB; however, the new added areas to the building are not properly constructed in terms of insulation. Furthermore, the old technology prevents controlling some systems in the facility such as boilers, therefore they work continuously during the whole year, regardless of the season or the outdoor temperature or any related parameter in the facility.

Laws and Regulations

Laws and Regulations can be classified into three sub-groups based on the governmental regulations, the TOBB President's regulations and nature. Energy flow from the city network is distributed by corporate companies; however they are regulated by the government. The most important issue is that the reactive and capacitive electricity usage must be held under certain values. Reactive and capacitive electricity can be explained as the type of electricity that is returned to the city network after being processed by the facility. This type of electricity is not necessarily controlled by the distributors, but customers have to keep them within limits required by the legislation. If any overconsumption is detected, then penalty costs are applied per kilowatt-hour. Therefore capacitive and reactive consumption is controlled by the company via a control mechanism which consumes extra electricity. Moreover, the building should not emit CO_2 more than a certain level which is controlled by the company with the same control mechanism with reactive and capacitive controlling.

Besides the governmental regulations, the President's Hall and other VIP rooms have their own regulations. They have to be heated or cooled continuously; the water temperature has to be more than 45^{o} and all lighting and plug systems have to be open for 24 hours. Hence, the company cannot save electricity from these spaces.

Finally, the environment (the nature) affects the total energy consumption of the building. For instance, electricity shut-downs based on the city network damage the centralized automation system and may cause new setups or over-demand of generators which results in higher costs. Another effect of the environment is the outside temperature which affects the working principles of the heating and cooling system in such a way that the higher the outside temperature, the higher the electricity consumption, in order to provide cooler offices and vice versa.

End User

Approximately 2,500 people live in the building during the work hours and 200 people in average during the rest of the week. Lack of training on energy efficiency or lack of consciousness about saving energy is the main problem about the end users. Owing to the fact that personal equipment such as computers and printers cannot be controlled by any automation system, higher consumption of this equipment affects the total electricity consumption in the building in a negative way.

2.4. Problem Environment

The fishbone diagram explained in the previous section helps understand the basis of energy consumption in the facility. The following sections present first a number of numerical analyzes and then a broad definition of the problem.

2.4.1. Essence of the Problem

All reasons affecting the total electricity consumption may be categorized into three different categories such as controllable reasons, uncontrollable reasons and investment-based reasons. Any reason which can be prevented via the company's capital is considered as the investment-based reasons such as purchasing new lighting materials adaptive to new led technologies and refurbishing the building with new insulation materials. The reasons which cannot be controlled by the company because of the nature and the nature of work and technology is considered as the uncontrollable reasons such as high outside temperature, manually controlled boilers, or poor user interfaces of the software.

What we focus on during this study is the reasons which can be controlled by the automation center via the special internal software, since the investment-based reasons require higher bureaucracy and approval processes upon reaching exact decisions, and the uncontrollable reasons are naturally out of the control of the company. All reasons determined as the controllable reasons are listed in Table 3. Most of these reasons are related to the scheduling issues which generally arise from lack of the know-how. It is found out in Table 3 that continuous running of all systems and inability to schedule the controllable units are the most influencing reasons for total electricity consumption. Although there is an advantage of having an internal software that can arrange all settings of systems in the facility, it is not operated by the company due to lack of scheduling and training, and that is why all systems work according to 24 hours/7 day principle.

Moreover, to validate the idea that scheduling is the most important problem and to learn how much each system in the facility consumes electricity; reporting modules of the software have been rearranged and electricity consumption of each system in 2012 has been reported monthly.

Results given in Table 4 show that HVAC system whose main task is to satisfy the thermal and air condition of indoor offices is the most energy consuming system with 80% of energy consumption on the average. It is claimed that systematic scheduling of HVAC systems regarding outdoor temperature and some other parameters would

Table 3 List of the Controllable Reasons

Main Group	Description of the reasons
HVAC System	-Maintenance is not done regularly or maintenance has not been done on some units ever
HVAC System	-Electrical motors in the system are not scheduled according to work-hours
HVAC System	-All units of the system are run continuously, though the software provides scheduling of the work hours of the system
Electrical Board and Plug Systems	-Battery compensation system which regulates flow of stable current is not scheduled
Electrical Board and Plug Systems	-Starters in electrical boards in order to switch on/off are not used properly
Machines and Equipment (M&E)	-M&E software which enables online tracking breakdowns cannot be operated due to poor user interface
Machines and Equipment (M&E)	-All machines are run continuously, though the software provides scheduling of the work hours of some machines
Machines and Equipment (M&E)	-Lack of training about working principles of machines prevents saving more energy

reduce total electricity consumption in the facility. It is advocated from both Tables 3 and 4 that the main aim of the study is to decrease electricity consumption of the HVAC system regarding satisfaction of thermal and air conditions of indoor offices with the consideration of other constraints related to the HVAC systems. In order to define the size and complexity of the problem, it is better to explain the working principle of HVAC system.

The HVAC system is such a smart system in which heating, ventilation, air conditioning and cooling tasks can be operated regarding some parameters given by the users who manage, control and assign different levels of units of HVAC system to different zones in order to enhance reliability and efficiency of the facility. Zones are some different areas, offices or supplementary buildings of the facility that are combined virtually on the software in order to ease managing such systems.

Table 4 Energy Consumption Distribution of the Systems

(a) Total Amount (kwh) in 2012

Period	HVAC	Lighting	Electrical Board and Plug Systems	Office Equipment
Jan.12	830,466.26	32,578.78	67,368.90	149,298.13
Feb.12	933,453.35	47,532.30	73,830.85	61,923.96
Mar.12	900,682.87	42,133.55	72,280.13	117,369.77
Apr.12	847,410.47	39,822.82	69,760.43	154,610.09
May.12	1,076,053.48	57,706.67	85,323.53	80,641.72
Jun.12	1,074,338.34	44,994.46	91,420.33	107,353.87
Jul.12	1,105,060.06	60,449.85	96,585.22	166,839.88
Aug.12	1,095,091.27	47,533.83	90,556.75	63,204.16
Sep.12	941,217.60	44,191.62	81,704.35	133,141.43
Oct.12	882,946.39	37,839.71	76,106.01	116,643.89
Nov.12	852,339.44	43,166.85	68,499.71	84,863.00
Dec.12	864,650.10	51,132.27	70,409.36	48,592.87
Total	11,403,709.62	549,082.72	943,845.57	1,284,482.76

(b) Percentages in 2012

Period	HVAC	Lighting	Electrical Board and Plug Systems	Office Equipment
Jan.12	0.77	0.03	0.06	0.14
Feb.12	0.84	0.04	0.07	0.06
Mar.12	0.80	0.04	0.06	0.10
Apr.12	0.76	0.04	0.06	0.14
May.12	0.83	0.04	0.07	0.06
Jun.12	0.82	0.03	0.07	0.08
Jul.12	0.77	0.04	0.07	0.12
Aug.12	0.84	0.04	0.07	0.05
Sep.12	0.78	0.04	0.07	0.11
Oct.12	0.79	0.03	0.07	0.10
Nov.12	0.81	0.04	0.07	0.08
Dec.12	0.84	0.05	0.07	0.05
Average	0.80	0.04	0.07	0.09

Combining different areas to construct the zones is not a duty which has been done according to a systematic approach like aggregation models or demand models that are commonly faced in literature, but according to some constructional constraints faced during the very early stage of construction of buildings and automation center. Pipelines structure, floor connectivity, insulation specifications are some of the factors which have been essential for defining the zones. Because of these reasons, it is out of the scope of this study to consider reorganizing the zones to make it more efficient to manage.

The HVAC system consists of 204 units that are run based on two simple principles which are temperature and air quality in the environment being operated by the help of two digital devices. All these devices are connected to the automation center that can all be controlled and managed by the employees in the automation center via the software. The most vital specification of the system is its ability to set and control certain target values for both temperature and air quality. For instance, if a target temperature interval between 18^o and 20^o is set, the system would run only below 18^o and above 20^o and would not run between these values. The most important thing is that even if all units of the system continue to run, the dampering mechanism, which can block heated or cooled air sent from units of HVAC system, prevents specific areas influenced by these flows in order to immobilize the current condition if condition is between the values set. To clarify, assume that there are some specific zones whose target temperatures were set between 18^o and 20^o, some specific zones whose target temperatures were set between 21^o and 24^o, current indoor temperature is 19^o and the current air flow sent by units is 23^o. Since flow is directed to the whole facility by the units, it completes its circuit starting from the first zone and ending at a returning receiver of units after leaving the last zone. While circulating, measurement devices in the zones whose temperature target values are defined to be between 18^o and 20^o simply send signals to the dampering mechanism commanding the closing of the flow channels from the main pipeline to the zone in order to prevent these zones to be warmed more. On the contrary, measurement devices in the zones whose temperature target values are defined to be between 21^o and 24^o send signals to the dampering mechanism to stay open in order to increase indoor temperature. This principle is the same for air conditioning, and according to this principle, all units of the HVAC system continue running until there is no zone left that does not satisfy the pre-defined target temperature and air values. The significant thing is that energy consumed by the HVAC system is strictly related to the density of flow which is affected directly by the number of zones which are not satisfied with their target values. The more unsatisfactory the zones are, the higher is the density the HVAC system sends to the facility which causes higher electricity consumption.

Another aspect of the problem is to understand the structure of the zones. There are 629 different zones within the facility and each zone contains no less than 7 different areas. An illustration of the sample zone map can be seen in Figure 5 below.

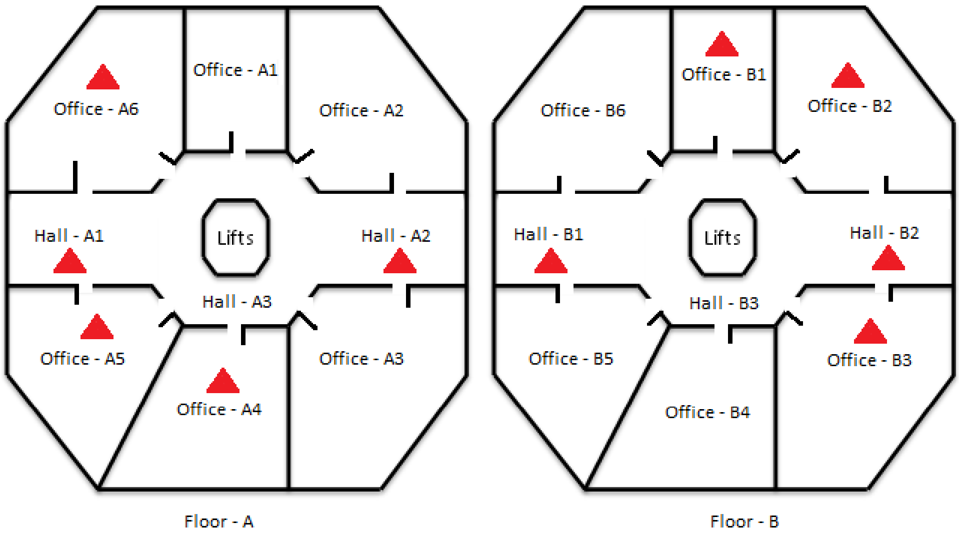

Figure 5 Sample Zone Map

Two adjacent floors are shown in this figure, and each office and each hall in floors can be considered as different areas in the facility. These offices and halls which are illustrated with a triangle on it are in the same zone in terms of the automation center software and the rest is defined as another zone as well. It may be somehow interesting to observe that offices next to each other in the same floor may be in different zones, however heating and cooling pipelines that are going to the offices and halls in the same zone were constructed together, so that settings related to these areas on the software cannot be made separately. In other words, whenever temperature target is set for such a zone, for example those that are shown in Figure

5, that target has to be satisfied in each different area of the related zone according to the principle described above.

Facility has two 32-flat towers including all work offices and 13 supplementary buildings which were constructed for meeting halls, conference centers, refectories etc. No two areas from the separate buildings are considered in the same zone according to again construction constraints. One of the most important specifications about zones arises from the insulation materials used at the construction time. Since the facility has two of the highest buildings in Turkey, most of the engineering issues for insulation must have been required such that floors had to be covered with materials that have higher insulation sensitivity regarding thermal and air conductivity. Due to this reason, thermal and air conductivity of the zones differ from each other. For example, any floor which is up to 20 meters higher was constructed with less sensitive insulation materials while any floor which is at least 100 meters higher was constructed with more sensitive insulation materials. Two factors that were taken into account while deciding what type of insulation materials had to be used were the position of the zones according to direction of the sun light and ground clearance of the zones. The reason why such categorization was applied may be that lower sensitive materials are cheaper than higher sensitive ones, so that construction cost might have been decreased by using less sensitive materials as much as possible.

Having known the two significant aspects of the problem, it would be better to recognize a few of the most important specifications of the HVAC system. As it is mentioned before, the HVAC system is produced by a smart technology in it which provides the system with the decision on how intensive it would run. Decision making process of the system arises from its multilevel structure. All units in the system have different working levels which are changeable according to the density of the flow pushed to the zones that the related unit is responsible from. A specific unit can provide heating and air conditioning to the zones in different levels in which higher levels cause higher electricity consumption. To clarify the situation, assume that there is a zone requiring 2^o to be heated and there are three units in the HVAC system each of which has two levels. Requirement may be met by one unit running at its second level and producing more intensive flow as well as it may be met by two units running at their first level and that sum of their flow equals the flow produced by one unit running at its second level. Both conditions satisfy the zone requirement; however, difference comes from the fact that electricity consumption of one unit running at its second level would be higher than sum of electricity consumption of two units running at their first level. Therefore, basically, how much electricity would be consumed by the units of the system is determined by the levels that these units would run at.

The second significant specification of the units is that they consume less energy when they run continuously. This is because of the fact that the units of the system have warm up periods when they start to run. During that warm up period, the units firstly try to calculate how much flow they could push to the system regarding the number of zones they would serve, together with pushing flow to the facility as well. Afterwards, they return to their standard running principle in which they only push flow to the facility, so that they consume less electricity compared to the warm up period. A sample profile of energy consumed by a specific unit through time is presented in Figure 6.

Whenever a unit starts to run, it consumes HL kwh per unit time and consumption per unit time slightly goes down after a certain time which is dependent on the unit. After a while, when time comes to a point for the unit when it learns how to serve more efficiently, electricity consumption again starts to stabilize at LL kwh per unit time, until the unit is shut down. Note that levels differ from unit to unit. Learning specification of the system and its consequences for the problem addressed is given in Sections 3 and 4 in detail.

The third feature of the HVAC system arises from its construction. Main tasks of the HVAC system are strictly connected with producing fresh air and temperature. That is why most of the parts used in the system are mechanical parts which have to be maintained in order to prevent unpredictable breakdowns. In order not to face an unpredictable breakdown, preventive maintenance schedules are used for all units of the system by the technical crew of the company and it lets the company predict and take precautions for the units of the system. These preventive maintenance schedules may be named as the availability conditions of the units of the system.

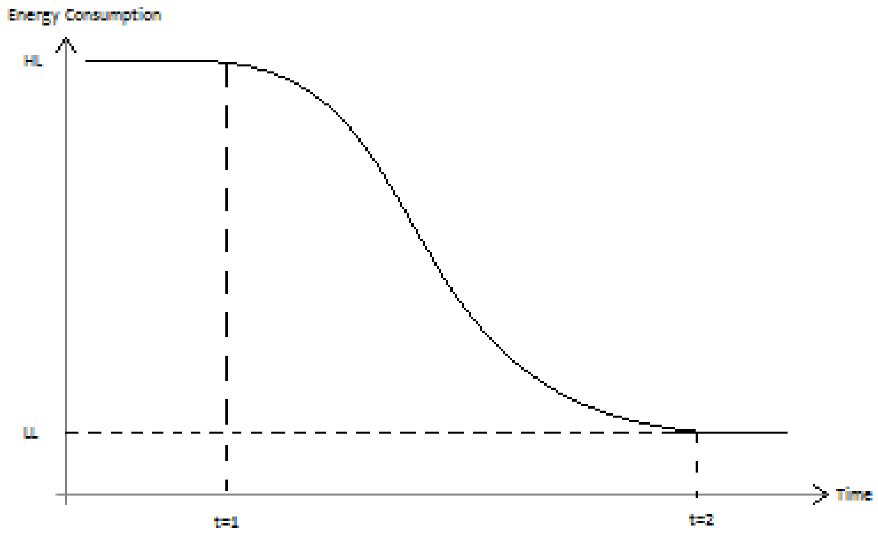

Figure 6 Energy Consumption Profile of a Sample Unit

There are two particular types of schedules for each unit of the system. First schedule is implemented based on the number of consecutive periods they continue to run and the second schedule is implemented based on the total number of periods they run. The first maintenance is somehow shorter than the second one, since they are maintenance operations in which minor inspections are held and minor settings are done to the units of the system. The second maintenance prevents units of the system from running continuously for long periods, since those are maintenances in which major replacements are modified and major setting changes are done.

2.4.2. Problem Definition

According to all specifications of the facility, energy management issue is what the company must do properly in order to be sustainable and profitable in the market. Having analyzed the root causes of high electricity consumption via both qualitative and quantitative data, it is more efficient to describe the problem in a more systematic way.

Although similar problems are introduced in Chapter 3, it might be useful to give the most related topics in the literature in this Chapter. Specifications of the HVAC system bring the idea that assigning specific levels to the units of the system properly would decrease total energy consumption of the system regarding temperature and air quality of indoor offices, in contrast to the current situation in which all units are run at their highest levels. When learning ability of the HVAC system and availability constraints are eliminated, the problem turns out to be a multilevel generalized assignment problem (MGAP) which has been recently researched by several authors (Laguna et al., 1995; Pierskalla, 1968; Pentico, 2007).

Tables 5 and 6 represent the size of the problem by giving some numbers about units of the HVAC system. It is seen from Table 5 that there are 204 units in the HVAC system which have different levels and different number of zones to affect. Even if the number of zones on which units have effects is not expected to increase the size of the problem, because assignment is going to be done between units and their levels, Table 6 shows how many of the units have how many zones to affect.

Table 5 Number of Levels of the Units of the HVAC System

Number of Units	# of Levels
50	3
57	4
52	5
45	6

If the time horizon of the problem is eliminated, there would be 908 assignments at most, which is the sum of the multiplications of the number of levels and number of units. However, to utilize the advantage of learning effects and to provide availability constraints of the units, a suitable time horizon have to be defined, which makes the problem more complex to solve in reasonable times.

The challenging question is how to arrange the time horizon of the assignments by considering work hours of the facility. Generally, work hours of people working in

Table 6 Number of Zones the Units Can Deliver Service

Number of Zones	Number of Units	Number of Zones	Number of Units	Number of Zones	Number of Units
9	1	17	22	24	2
10	3	18	19	25	6
11	1	19	18	26	7
12	7	20	14	27	1
13	6	21	21	28	1
14	10	22	14	29	1
15	14	23	10	31	1
16	25				

the facility starts at 08:00 a.m. and finish at 18:00 p.m. In the current situation, all units of the system are run at their highest levels during this period and at their lowest levels during the rest of the day in which only security personnel and a few other employees work in the facility. Two significant inspirations to determine the time horizon arises from the data provided by the governmental organizations for weather forecasts and the learning ability of the units of the HVAC system. Weather forecasts have an important role in the problem, since level assignments would be done based on the temperature and air values published in the forecasts. Time horizon of the forecasts is five days, and they are published based on hourly periods in a day. Moreover, together with the forecasts, governmental organizations publish their claims on how frequent major and minor changes in temperature and air quality would occur during that time horizon. It has been claimed for last seven years that no more than 3 hours period could have major effect on temperature and air. In other words, any change in temperature and air within up to 3 hours period could be ignored. Therefore, consecutive periods in the problem studied should be comprised of 3 hours.

Additionally, it is better to investigate the learning ability of the units of the HVAC system in order to determine how long it takes to achieve its stable condition for each unit, LL point given in Figure 6 above. User manuals are utilized to learn about the total estimated duration for each unit to reach its stable level. Although each unit has a different number of levels and different energy consumption values in different levels, learning conditions look very similar for each unit because of the fact that they are all produced by the same manufacturer and production processes and quality assessments are probably the same for each unit. Table 7 below shows the learning specifications of the units taken from their manuals.

Table 7 Learning Specifications of the Units

Group No	Number of Units	Time to Learn (min)	Time to Stabilization (min)	Learning Rate (%)
1	2	90	4.0	65
2	8	100	3.6	62
3	21	107	3.2	60
4	50	110	3.0	50
5	117	120	2.5	45
6	6	150	1.5	40

According to Table 7, there are six different kinds of units in the facility and each group has different abilities to decrease their energy consumption. For instance, the first group has two units whose time to learn, which is time to t_1 shown in Figure 6, is 90 minutes and time to stabilization, which is the difference between t_1 and t_2 in Figure 6, is 4 minutes. Average time of the whole system to learn is 116 minutes and average time to stabilization is 2.7 minutes. Another important specification of the units given in Table 7 is their learning rates, which can be given as ratio of HL over LL in Figure 6. Average learning rate of the HVAC system is 48.5%. One can interpret these values as follows: for instance, units in group 2 have the ability to decrease their energy consumption in 3.6 minutes after running 100 minutes continuously by 62% of its first consumption value.

Having known the average times of the units of the HVAC system to learn, it is easy to define the time horizons regarding both the data from governmental organizations and data given in Table 7. Since the average time to learn of the HVAC system is 116 minutes which is less than the time limit governmental organizations advocates for which differences in temperature and air can be ignored, time horizon of the problem is divided into two-hour periods of the day in order to utilize learning specification of the system in a periodic basis. However, period starting from 6:00 p.m. to 06:00 a.m. is still not divided, because during these hours there are not necessarily people working in the facility. One last extension is made for the period starting from 06:00 a.m. to 08:00 a.m. as it is the period for preparing the facility for the forthcoming employees and visitors before they arrive.

CHAPTER 3

LITERATURE REVIEW AND INDICATIONS TO PROBLEM

The problem we address in this thesis can be considered to be the Multilevel Generalized Assignment Problem (MGAP) ignoring the advanced specifications of the HVAC system. However, learning effects and availability constraints of the units should be included in the problem definition and subsequently in the mathematical models and solutions. Firstly, attention to MGAP and its solution procedures established in literature to date need to be explained. Apparently, what we focus in this study is not only the general assignment problem, but also the extension of the problem with the addition of the two constraints: learning effect and availability constraints. Thus, three pods of the tripod, namely MGAP itself, learning effect and availability constraints, are researched separately, since there is no paper combining all three dimensions of the problem addressed. Consequently, a new mathematical model and a tabu search algorithm are proposed to solve the problem in the next chapters.

3.1. Multilevel Environment

Assignment problems have been widely used to find out practical implications of difficult problems in manufacturing environment. Kuhn (1955) was the first to introduce the classic assignment problem and its exact solution with the Hungarian algorithm. However, this model could be applicable to problems which have only two dimensions such as assigning tasks to machines for some exact time horizons. It has been an attractive topic for researchers and practitioners to pay attention to different extensions of the assignment problems. Most of them have been discussing the two dimensional problems, whereas Pentico (2007) presents a broad range of different types of assignment problems with examples and solution methods.

However, the most similar problem to our problem is researched by Glover et al. (1979), who are the first introducing MGAP to the literature, formulating a MGAP for a major manufacturing firm. Essence of the problem is to assign n jobs to m agents regarding l efficiency levels of the agents where constraints are capacities of the agents and necessity to assign each job to only one agent. The mathematical model they propose is as follows:

$$\text{Min } \sum_{\mathrm{i}} \sum_{\mathrm{j}} \sum_{\mathrm{k}} c_{ijk} x_{ijk} \qquad (1)$$

s.t

$$\sum_{i} \sum_{k} x_{ijk} = 1, \qquad j = 1, \ldots, n \qquad (2)$$

$$\sum_{j} \sum_{k} a_{ijk} x_{ijk} \leq b_i, \quad i = 1, \ldots, m \qquad (3)$$

$$\mathrm{x}_{ijk} = 0 \; or \; 1, \qquad i = 1, \ldots, m, \quad j = 1, \ldots, n, \quad k = 1, \ldots, l \qquad (4)$$

The model includes the decision variable x_{ijk} that is defined to be 1 if task j is assigned to agent i at the k-th level and 0 otherwise (4). There is a cost, c_{ijk}, that identifies the cost of assignment of task j to agent m with efficiency level l and a multiplier, a_{ijk}, that identifies the amount of capacity that would be allocated when that assignment is made. The objective function (1) minimizes the total cost of the assignment. Each task has to be assigned to only one agent (2) and assignments have to be provided such that the agents do not exceed their capacity limits, b_i, which can be calculated as the sum of agent-dependent requirements of a particular task (3). They also graphically represent their model as given in Figure 7 below.

Looking at that network, each task j (supply) has to be assigned to one agent amongst m agents (demand limits) with respect to the related capacity of the agent to which the task is assigned. Graph has m + n nodes and m x n x l arcs at most. Costs are enclosed in boxes whereas capacity multipliers are enclosed in triangles and integrality constraints are represented with asterisks.

When the problem addressed in this thesis is purified from the advanced specifications of the HVAC system, which are learning and availability constraints, it

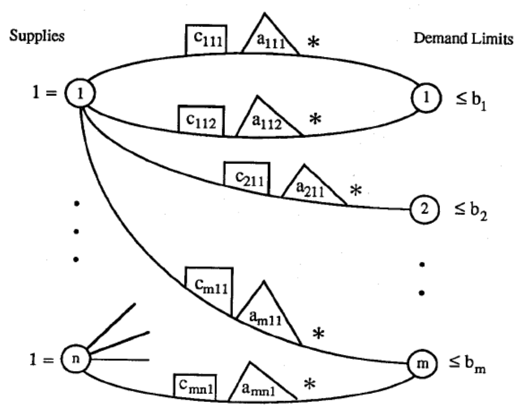

Figure 7 Network Representation of the MGAP

can be considered as an MGAP in which the levels of the units are determined in different periods subject to the living conditions of indoor offices, which provides us constructing a similar graph to the graph of Glover et al. (1979). Figure 8 below shows the graphical representation of our problem where units of HVAC system have four different multipliers represented by H, C, A and VT for heating, cooling, air conditioning and ventilation, respectively, which are used depending on which task units are run.

Why there are four different multipliers is due to the fact that pipelines of the units that are used to heat, ventilate or cool the zones do not necessarily need to be the same, since each unit uses four different mechanisms to do different tasks. Moreover, indices of those multipliers consist of the set of units, levels that are available to the related unit and the zones that the related unit may affect. Another significant notion in the graph is that demand nodes, which are zones, do not necessarily require one unit at all, as they may have different requirements according to the outside temperature and the number of people working in the zone; hence they have to be satisfied at least with their minimum requirements for temperature and air. This difference between our network and Glover's arises from the structure identified in Section 2.4, which is due to the zone specifications like the insulation materials.

Another point is related to the multi-level structure of the units, as supply nodes have to have exactly the same number of arcs going towards each demand node due to the

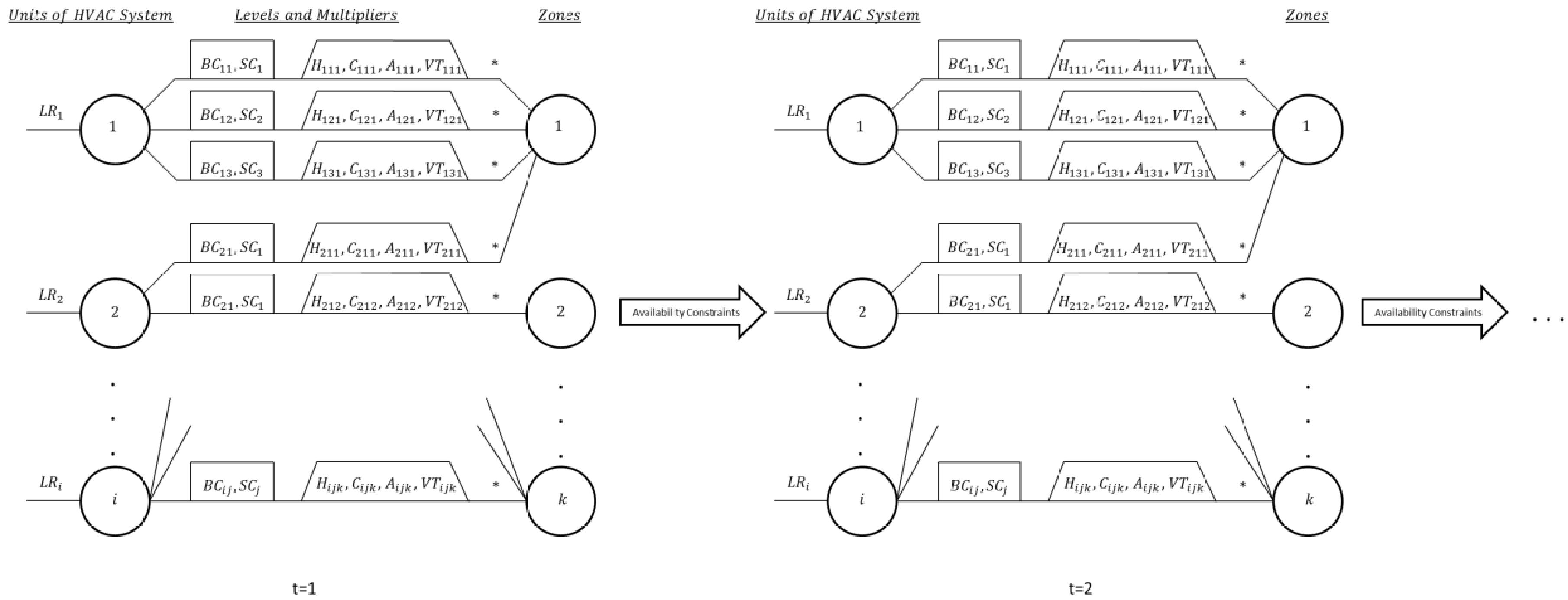

Figure 8 Network Representation of Our Problem

fact that units cannot produce their flow differently for different zones. They only have the ability of running at one level regardless of the zones to which they serve. Costs are enclosed with rectangles and consist of two different components: first is the basis cost of the units, BC_{ij} that changes according to levels of that unit and second is the setup cost, SC, which is a fixed cost that is incurred if the unit starts running at the beginning of that period.

Finally, as we have a multi-period environment, the whole graph actually includes seven joint networks, in which an arc that existed in the previous period may not exist in the next network due to the availability constraints of the running units, which is given in detail below. Moreover, learning effect of each unit, LR_i is shown at the left side of each node. A detailed review of learning effects is considered separately in the following sections.

3.2. Learning Effect

The units that are consuming electricity and providing fresh air and heat to the building can be considered as the resources to be assigned to the zones in different periods with different levels. In this study, resources have the ability to reduce their electricity consumption when they run for the consecutive periods. It is described in Section 2.4 that each unit has its own electricity consumption profile which can be named as their own learning curves (see Figure 6).

One of the first studies on learning curves is done by Wright (1936) where he observes that when the amount of production is doubled, time to produce the next individual unit reduces by a certain rate. He researched an aircraft company and came up with a result that labors had ability to decrease their production time when they produce more units and the rate they decrease their production time could be named as the learning rate. Wright's learning curve, $y = cx^{-b}$, known as log-linear learning curve, defines the cumulative time to produce x units depending on two parameters first of which is the time to produce the first unit, c, and second of which is the learning rate, b.

However, different models have been constructed during the improvement on production processes (Yelle, 1979). Most of the studies have been done on labor learning curves such that by repeating any process the labor starts to produce in lower processing times. The importance of the learning curves is examined in different sectors like automotive,chemical and electronics industries, and in inventory and lot sizing problems (Salameh et al, 1993; Nembhard and Uzumeri, 2000a; Weber and Fayed, 2010; Demeester and Qi, 2005). A recent detailed survey can be found in Anzanello and Fogliatto (2011) that includes different types of learning curve models and their application areas.

Additionally, the learning curves are used for different scheduling and resource assignment problems. Biskup (1999) was the pioneer who uses the learning curves in scheduling environments. Two general categories are introduced for learning curves in scheduling problems: position-based learning curves and sum of processing times based learning effects (Biskup, 2008). Decreasing processing times of parts based on the number of parts processed is considered as position-based learning curves as well as decreasing processing times of parts based on the total time worked on the parts is considered as sum of processing times based learning curves. Researches about learning curves with different objective functions can be found in Baker and Scudder (1990).

In this study, the units of the HVAC system have the ability to decrease their energy consumption when they run for more than one period consecutively. It is because of the fact that the first running period of any unit is the period that not only the unit produces air and heat to the zones, but also organizes its capability according to the zones. In other words, in the first running period of a unit, it firstly starts to determine its optimal capability in order to prepare itself as if it would run as much time as it is capable of, as well as providing air and heat to the zones, which means that units run regarding two main tasks in their first periods. However,in the next period following the first period the units do not need to optimize their future capacity; instead, they only provide air and heat to the zones. It is possible to claim that the units learn how to provide air and heat to the zones after the first period they start running.

There are six different groups to categorize units for their learning abilities (see Table 7 in Chapter 2 above). It is one of the significant tables which helps determining the duration of the periods as well as in giving the idea of machine learning. It is clear that machines’ learning effects are much more rapid and precise than labors, as it is seen from the table that although it lasts longer to learn, time for achieving stable values is as rapid as learning period. No longer than four minutes to sustain stable energy consumption values does not seem realistic and possible for human beings.

3.3. Availability Constraints

Another important concern about our study is that the units have two types of availability constraints. Contrary to most of the researches in which the resources are assumed to run continuously, this study includes resources which cannot run continuously due to the maintenance activities at some proposed times. Since the units have mechanical parts to produce air and heat for indoor offices, they have to be maintained at the proposed periods. Time to maintain a unit would depend on the number of periods the unit has been running. Each unit has two types of availability constraints. The first one consists of maintaining the unit after some consecutive running periods. The second one includes the maintenance of the unit according to the total number of running periods in a day. This second constraint limits the total number of available periods of any unit in a day, whereas units can run immediately after the first type of maintenance is completed. For the first type of maintenance, units have another parameter which describes how long the maintenance activity will take before the unit can start running.

Adiri et al. (1989) were the first to study the problem in which a single machine has unavailability situations in certain intervals. It is proved that the problem is NP-hard and can be solved by Shortest Processing Times (SPT) algorithm with a maximum error bound of 1/4. Liao and Chen (2003) study the similar problem with a in maintenance scheduling policy. The problem allows resources to be maintained at several times ignoring how many times they have been maintained in previous periods, which seems much more similar to the problem addressed in this thesis, since the first type availability constraints provide the units to run after maintenance until the next possible maintenance. Maa et al. (2010) surveyed several studies grouped according to the environment problems are considered such as flow shop, parallel machine and multi-machine environments. Various sizes of assignment problems with availability constraints are presented, where the problems differ from three aspects, first address the resumable job types, second address the nonresumable job types and third addresses the combination of resumable and nonresumable job types. Complexity of such problems and available solution algorithms are also presented in the study.

The role availability constraints have in this thesis is basically to provide linkages between consecutive periods. Given in Figures 9 and 10 below, units running in period *t* may not run in period *t+1* due to their availability conditions. Thus, number of nodes in two consecutive networks may not be the same as units which need to be maintained would decrease the number of nodes and arcs whereas units which complete their first type of maintenance conditions would increase the number of nodes and arcs. Consequently, this fact affects the complexity of the problem, as the size of the whole network not only depends on the number of zones, units and their levels, but also on whether or not availability conditions would occur.

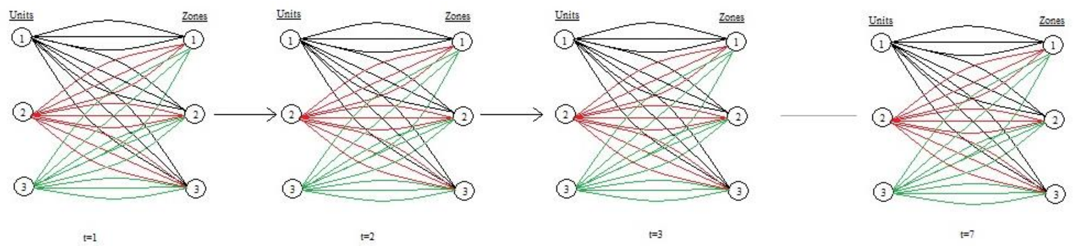

Figure 9 Sample Network without Availability Constraints

For instance, assume a network in which there are three units with three levels and three zones for which all units can produce air and heat. For the first period, there are three supply and three demand points where they are connected with 27 arcs to each other given in Figure 9. Assume that there is not any availability constraint for any unit which leads the network to the same nodes and the same arcs for the next periods and all networks will be same. Therefore, the whole network will have 42 nodes and 189 arcs in total.

Now assume that the first unit has a first type constraint where it has to be maintained for the next period if it runs in current period and would be available for running after the period it is maintained. For the first period, network would be the same with the first period in Figure 9. The difference comes out when it comes to a point that the decision has to be made for the first unit which may lead the network towards two different paths. If the first unit has run in the first period, size of the network for the second period decreases to a network consisting of five nodes (two units and three zones) and 18 arcs in contrast to the condition that the first unit has not run in the first period and consequently the network of the second period stays the same with the first period. For the third period, there are still two paths to select first of which is the same with the network in the first period and second of which is the same with the network in the second period consisting of five nodes.

Illustration for the condition that availability constraints exist is given in Figure 10 below. Consequently, the whole network includes 72 nodes and 297 arcs, which show that even for very small environments, availability constraints increase the size of the problem considerably.

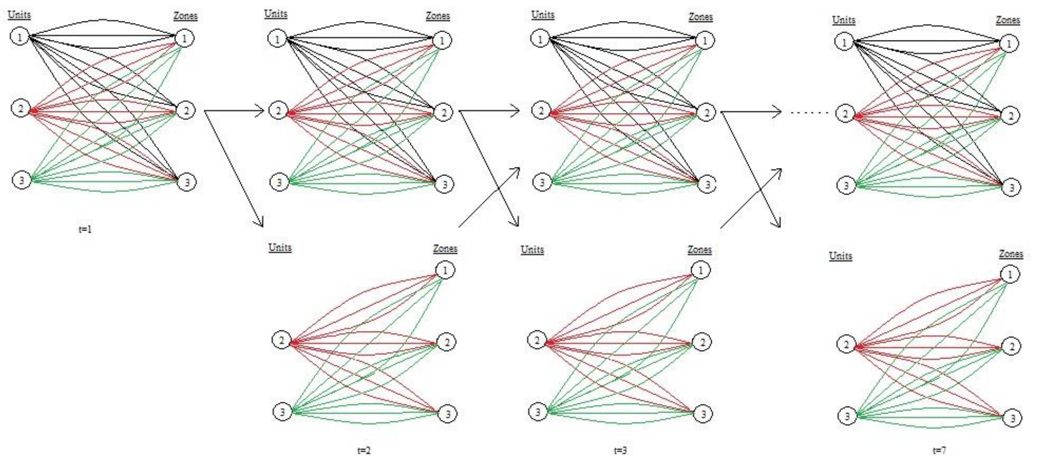

Figure 10 Sample Network with Availability Constraints

As far as it is researched in the literature, no paper is available considering all concepts studied in this thesis. Although there are limited number of researches that combine two pods of the tripod such as multilevel assignment with availability constraints and scheduling with learning effects, it is found that there is not any research including all three characteristics. Thus, a new mixed-integer mathematical model is introduced in which all specifications of the HVAC system are considered and it can be named as multilevel assignment problem with learning effects and availability constraints (MGAP-LA).

CHAPTER 4

MATHEMATICAL MODELLING OF THE PROBLEM

The problem addressed in this study can be formulated as a multilevel generalized assignment problem, where assignments that determine running levels of the units of the HVAC system through a planning horizon would be made in order to decrease the total electricity consumption of the HVAC system regarding both learning ability and availability conditions of the units while meeting the requirements of the users about air and temperature in offices. In this chapter, we discuss the assumptions we made in order to alleviate the complexities inherent in the problem environment. Then we provide the formulation of the problem as a multilevel generalized assignment problem with learning ability and availability constraints (MGAP-LA). Finally we present our data collection and parameter estimation methods we used in preparing the parameters required by the MGAP-LA.

4.1. Assumptions

Before explaining the structure of the MGAP-LA model, it would be better to present several assumptions we made in the formulation of the problem. The first assumption is based on a basic thermodynamic principle that every material, creature or human being in an environment spreads out heat to the environment where they live. Therefore, not only the outside temperature, , but also people in the environment and all the equipment and machinery that run in the same environment have an impact on the indoor temperature that people actually feel. Moreover, body temperature of a person should be 36.5^{o} Celsius in natural conditions, and human bodies react in several ways to adapt its inside temperature in dynamic conditions, having an impact on indoor temperature in the offices. However, we assume that the only determining factor for the indoor temperature is the outside temperature and the insulation levels of the zones, since it does not seem realistic that body temperatures, equipment temperatures or other factors can be measured instantly and then involved in the problem formulation.

Another assumption is related to the maintenance times of the units. Almost half of the operations required in the maintenance of the units depend on the performance of the employees, and therefore the maintenance time is not deterministic. Additionally, the company does not manage any kind of training programs which may help technicians keep the maintenance times in a standard way. However, a time study to determine the characteristic of several maintenance operations is out of the scope of this study, hence it assumed that maintenance times and time to failures are deterministic and known by the company.

Still another assumption is made regarding the relationship of consecutive periods in the planning horizon in terms of air and temperature effects. As it is known that heat is a concept that is transferrable from one place to another in several ways, temperature in offices is likely to change due to the existing temperature in the previous periods. However, based on the claims of the meteorology offices indicating that changes in three-hour periods is not significant, it is assumed that changes in the outside temperature would have a more remarkable effect on the indoor temperatures and air quality than the existing temperature; hence we ignore the impact of the existing temperature of the previous period. Based on this assumption, it can be considered that consecutive periods are related with each other regarding only the availability constraints, which means that other possible factors of the previous period like the existing temperatures, refurbishments or equipment renewals do not have an impact on the temperature and air quality of the next period.

The last assumption above can be seen as an obstacle to achieve higher performances in energy consumption. Assume that our solution proposes to run several units for a certain zone to heat to acceptable degrees in a certain period and the temperature of the next period is exactly the same as the temperature to which the units heat the zone in this period. Actually, there is no need to run the same units again as the indoor temperature has already provided the required temperature between the boundaries, and it leads us to run fewer units in the next period, which helps to reduce the electricity consumption. However, in order to simplify the problem complexity, it is assumed that changes in temperature in each period is triggered only by the outside temperature, and changes in air quality in each period is triggered only by the number of people at the beginning of the period in the zones.

4.2. The Mathematical Model

It is explained in Chapter 3 that origin of the model we propose comes from the basics in Laguna's classic MGAP model. However, we add two main constraints to the MGAP in order to be able to represent the real life environment better in the model. Furthermore, we change the demand and supply definitions. In the MGAP the demands of the problem are defined as the agents that process the tasks defined as the supplies of the problem via the efficiency levels defined as the arcs of the problem (see Figure 7 in Chapter 2). However, in our MGAP formulation, we define the demand points as zones that are not actually part of the decision variables, as the decision variables are determined by the running levels of the units. Apparently, each demand node has two different requirements or service levels: the first requirement occurs when the zone requires heating or cooling while the second occurs when the zone requires air conditioning or ventilation. This is because of the legislation announced by the Ministry of Working and Social Security in 1973 and reorganized in 2012 (The Republic of Turkey, The Ministry of Working and Social Security, 1973; The Republic of Turkey, Ministry of Working and Social Security, 2012). According to the regulations, indoor offices in commercial buildings have to be provided fresh air and convenient temperatures where level of fresh air is measured by the amount of oxygen and temperature is measured by the Celsius degree. Based on the last regulations, fresh air in the offices has to be provided at a level between 1.5 kg/m^3 and 3 kg/m^3; and the level of temperature provided in the offices has to be between 19^o and 22^o.

MGAP-LA assures that every zone requirement is satisfied based on the working principles of the HVAC system. It is explained in Section 2.4 that HVAC system has the ability to stop delivering air and heat to an area in a zone if the area does not require air or heat, although the system continues delivering air and heat to the other areas of the same zone. Thus, we propose independent constraint sets for the four requirements of the zones at least two of which would be redundant, because heating and cooling cannot be provided at the same time and similarly air conditioning and ventilation cannot be provided at the same time.

Another important aspect of our MGAP-LA formulation is related to the learning effects of the units of the HVAC system. It takes 97% of the units between 94 minutes and 122.5 minutes to learn and lower their energy consumption; and only 6 of the units lower their electricity consumption after running 151.5 minutes, while the average total time to stabilization is 118.7 minutes (see Table 7 in Chapter 2 above). Due to the fact that values of average time to stabilization and length of the time periods are close to each other, we build our model considering the base electricity consumption of the units as the energy values when they consume at their stable condition. To reflect the learning effects of the units in the MGAP-LA model, we use learning rates of the units as the multipliers which increases the energy consumption of a unit in the period it starts running.

The mathematical model for the MGAP-LA is as follows:

Notation	**Definition**
Sets	
I	Set of units of the HVAC system, $I = \{1, \dots, 204\}$
J	Set of levels of the units of the HVAC system, $J = \{1, \dots, 6\}$
K	Set of zones, $K = \{1, \dots, 629\}$
T	Set of periods, $T = \{1, \dots, 7\}$
V_i	Set of maximum levels of units i, $i \in I$ (Note that every unit has a different number of running levels)
MINUNI	Set of units that have to be run even if the building is at its minimum capacity $\subset I$
Parameters	
BC_{ij}	Base energy consumption of unit i at level j
LR_i	Learning rate of unit i
CO_{ij}	CO_2 emission released to nature by unit i at level j
SC_j	Setup energy consumption of units at level j
H_{ijk}	Heating effect of unit i at level j to zone k

C_{ijk}	Cooling effect of unit i at level j to zone k
A_{ijk}	Air conditioning effect of unit i at level j to zone k
VT_{ijk}	Ventilation effect of unit i at level j to zone k
B_i	Maximum number of consecutive periods unit i can run
P_i^1	Number of periods to maintain unit i
P_i^2	Maximum number of periods unit i can run in total
CEL_t	Outdoor temperature of period t
E_{kt}	Number of people in zone k in period t
D_k	Insulation level of zone k
F_k	People's effect of zone k
$MAXCO$	Maximum level of CO_2 the building can release to nature

Decision Variables

x_{ijt} $\begin{cases} 1, \text{if unit } i \text{ runs at level } j \text{in period } t \\ 0, \text{o.w.} \end{cases}$

y_{ijt} $\begin{cases} 1, \text{if unit } i \text{ starts running at level } j \text{ in period } t \\ 0, \text{o.w.} \end{cases}$

<u>MGAP-LA</u>

$$\text{Min } \sum_i \sum_j \sum_t [y_{ijt}(SC_j + BC_{ij}LR_i) + x_{ijt}BC_{ij}] \quad (5)$$

s.to

$$\left(1 + \sum_{i\in I} \sum_{j\in V_i} x_{ijt}H_{ijk}\right)CEL_tD_k \geq 19\,, \quad \forall t \in T, \forall k \in K \quad (6)$$

$$\left(1 - \sum_{i\in I} \sum_{j\in V_i} x_{ijt}C_{ijk}\right)CEL_tD_k \leq 22\,, \quad \forall t \in T, \forall k \in K \quad (7)$$

$$\left(1 + \sum_{i\in I} \sum_{j\in V_i} x_{ijt}A_{ijk}\right)E_{kt}F_k \geq 1{,}5\,, \quad \forall t \in T, \forall k \in K \quad (8)$$

$$\left(1 - \sum_{i\in I} \sum_{j\in V_i} x_{ijt}VT_{ijk}\right)E_{kt}F_k \leq 3\,, \quad \forall t \in T, \forall k \in K \quad (9)$$

$$\sum_{j\in V_i \,|\, j\geq 2} x_{ijt} = 1\,, \quad \forall i \in MINUNI, \forall t \in T \quad (10)$$

$$\sum_{i\in I} \sum_{j\in V_i} x_{ijt}CO_{ij} \leq MAXCO\,, \quad \forall t \in T \quad (11)$$

$$\sum_{j\in V_i} x_{ijt} = 1\,, \quad \forall i \in I, \forall t \in T \quad (12)$$

$$x_{ij1} \leq y_{ij1}, \quad \forall i \in I, j \in V_i | j \geq 2 \quad (13)$$

$$\sum_{j\in V_i|j\geq 2} x_{ijt} - \sum_{j\in V_i|j\geq 2} x_{ij(t-1)} \leq \sum_{j\in V_i|j\geq 2} y_{ijt}\,, \quad \forall i \in I, \forall t \in T | t \geq 2 \quad (14)$$

$$\sum_{j\in V_i} y_{ijt} \leq 1, \quad \forall i \in I, \forall t \in T \quad (15)$$

$$M\left(\sum_{b=t}^{t+B_i-1}\sum_{j\in V_i\,|\,j\neq 1} x_{ijb} - B_i\right) \leq \sum_{c=t+B_i}^{t+B_i+P_i^1-1} x_{i1c} - P_i^1, \quad \forall i \in I, \forall t \in T \qquad (16)$$

$$\sum_{j\in V_i\,|\,j\neq 1}\sum_{t\in T} x_{ijt} \leq P_i^2, \qquad \forall i \in I \qquad (17)$$

$$x_{ijt}, y_{ijt} \in \{0,1\}, \qquad \forall i \in I, \forall j \in J, \forall t \in T \qquad (18)$$

In the MGAP-LA model (5-18) above, the objective function (5) is the minimization of the sum of setup energy consumption and operating energy consumption of the units, where the setup energy consumption is due to two components: the first occurs whenever units start to run and the second occurs because of the learning principle that units start to decrease the energy consumption after the period they start to run. The values of the index j represent the state of the unit (i.e. the level of the unit) where it is defined to be *1* if the unit is shut down or under maintenance, and defined to be greater than *1* (higher values) when the unit is running. Higher values of the level indicate that the units would deliver air and temperature more intensively resulting in higher electricity consumption.

Constraints (6)-(9) provide the thermal and air conditioning of the zones and as it is explained above at least one of the thermal-related constraints 6 and 7 would be redundant; similarly at least one of the air conditioning-related constraints 8 and 9 would be redundant. For instance, assume that there is a zone *k* which is at 18^{o} indoor temperature meaning that it requires 1^{o} to be heated for a period and there is only one unit *i* with one level which can deliver temperature to zone *k* with heating effect of 20% and cooling effect of 30%. In this case, decision variable x_{ijt} for unit *i* with its first running level would take the value of *1* which makes the zone reach 21.6^{o} at the end of the period where the 7th constraint in this case seems that zone *k* would be 12.6^{o}. It is the principle of the HVAC system to prevent zones both heating and cooling simultaneously, that is why constraint 7 would be redundant in this case.

Constraint (10) guarantees that the units which have to be run even if the building is in its minimum capacity would run. Constraint (11) prevents the facility from exceeding the amount of CO_2 released to nature regarding the emission management regulations. Constraint (12) guarantees that each unit can only run at one certain level in each period including being off. Constraints (13) and (14) provides setup energy consumption to be taken into account for a unit that is not running during period $t - 1$ and starts running at period t. Constraint (15) guarantees that units can only cause setup electricity consumption, if any, at only one level which is similar to constraint (12). Constraints (16) and (17) are the availability constraints of the units where constraint (16) ensures that any unit i running for B_i consecutive periods would shut down and maintained for the next P_i^1 periods. Similarly, constraint (17) ensures that units cannot run for more than the maximum number of available periods (P_i^2 for unit i) in total. Finally, constraint (18) defines integrality constraints of the decision variables.

4.3. Data Collection and Estimation

There are 16 different parameters in the model to be determined where 14 of these can be obtained directly from their own sources while two of these are not sufficiently precise to be used directly. Data for electricity consumption values, first and second type availability constraint values, learning rates and CO_2 emission values of the units of the HVAC system can directly be gathered from manuals provided by the supplier of the system. Moreover, data for the percentages that the units can affect the zones within two hours have been obtained from the softwares used in the automation center of the company. To determine the exact values of these effects, all units have been run for two hours separately and data have been collected for each unit during running time. As each unit has four different mechanisms (heating, cooling, air conditioning and ventilation) for each zone they can affect, data collection has been held four times for each unit where each replication corresponds to a different mechanism.

Outside temperature values are obtained regularly by the company from the Turkish State Meteorological Service (TSMS) which is the official organization of the government to collect data and forecast future weather conditions. The data includes hourly temperature, humidity and air mixture values, and TSMS sells only five-day-period data due to rapid change of weather conditions. Moreover, number of people in the zones can be estimated from the values gathered in the automation center. Because of the company’s data security procedures and principles, exact values cannot be displayed in the thesis. However, idea behind data collection relies on the toll gates around the facility, and any entrance or exit is recorded online in the software in the automation center whenever people swap their ID cards; thus the company has the ability to estimate the people density in the facility in different time periods like hours, days or weeks. Having more than 100 toll gates all around the facility and in the buildings brings the advantage of analyzing each flat and each zone separately, where reporting and estimating those numbers are sort of clauses in tenant agreements provided by the company to tenants.

There are only two types of data, which are insulation levels and people's effects of the zones, to be estimated, since they may have been demolished or deteriorated in recent years. Although data about these are given by the design and construction company (Ceylan Construction, 1998), they are not reliable and coherent due to long years passed since the facility was commissioned officially.

Table 8 Insulation Materials and Their Specifications

Zone Specification	Ground Clearance	Sunlight Position	Insulation Material	Old Insulation Level	New Insulation Level
Office Space up to 5 people per m^2	Basement to 5th floor	Direct	*	75.0 %	73.0 %
Office Space up to 5 people per m^2	Basement to 5th floor	Indirect	**	80.0 %	76.0 %
Office Space up to 10 people per m^2	6th. Floor to 15th floor	Direct	**	80.0 %	79.0 %
Office Space up to 10 people per m^2	6th. Floor to 15th floor	Indirect	***	82.5 %	82.0 %
Office Space up to 20 people per m^2	16th Floor to 29th floor	Direct	**	82.5 %	81.0 %
Office Space up to 20 people per m^2	16th Floor to 29th floor	Direct	***	87.5 %	87.0 %
Office Space up to 20 people per m^2	16th Floor to 29th floor	Indirect	****	90.0 %	87.0 %
Conference Halls and Meeting Room	Other	Indirect	*	75.0 %	70.0 %

It is mentioned in Section 2.4 that each zone has a different insulation material according to its position towards sunlight and ground clearance. General policy for usage of materials depending on the zone type and other specifications are given in Table 8 above.

There are eight different categories for insulation levels and each level was designed according to their design specifications. The first 5 floors of the facility are designed to be warmest with compact spaces where low quality materials were used generally, although there are some workspaces that were built with moderate quality materials due to their sunlight positions. The next 10 floors' insulation materials are more resistant against outside-inside weather changes and each floor was designed specifically according to its sunlight position. Insulation specification of the rest of the buildings is much more related with their clearance to the ground, since the height becomes a key factor for designing of workplaces higher than 60 meters. Thus, those floors were categorized into three groups and their levels differ from 82.5 % to 90 % where the highest levels were especially used for VIP rooms and Presidents Office at the top of the towers. Moreover, other buildings like conference halls, meeting rooms and refectories were designed more cost-effectively in order to keep construction costs as low as possible because of the fact that those places were planned as spaces that would be utilized less frequently.

During the past years, since no people lived in the buildings and extra refurbishments and replacements were made during redesigning and commissioning phases, insulation levels have deteriorated and hence values given in Table 8 are not reliable anymore. Therefore, data have been collected and analyzed to determine new percentages of levels so that more realistic values could be used in the MGAP-LA model. Data for the levels have been collected via sampling where five different times of different days are determined randomly in order to compare outside temperatures against indoor temperatures; and average rates of indoor values over outside values have been used for the new levels. Reorganized insulation levels (new levels) are presented in the last column of Table 8 above.

Another estimation has been done for the data collected to determine people's air effects of zones. One of the service levels to be provided by the company to the end users is the amount of oxygen per cubic meter in the offices in order to prevent people from kinds of air-quality related diseases like asthma. The values determined by the government agencies are as follows: air mix should include at least 1.5 kg/m^3 of oxygen and at most 3.0 kg/m^3 of oxygen in the offices (The Republic of Turkey The Ministry of Working and Social Security, 1973; 2012). As it is common in most of the commercial buildings, fresh air is directly absorbed from the nature and it is delivered through the facility by pipelines where there are some filtration and refining tasks processed before delivering.

As volume of each zone is known by the company and all data are gathered to count the number of people in the zones, a regression analysis has been done in order to determine the relationship between zone volume and its reflection to the amount of

Table 9 People's Effects of the Zones

Zone Specification	Ground Clearance	Zone Volume	Pipeline Efficiency	Zone Effect
Office Space up to 5 people per m^2	Basement to 5th floor	300-350 m^3	**	15.0 %
Office Space up to 5 people per m^2	Basement to 5th floor	351-450 m^3	***	11.0 %
Office Space up to 10 people per m^2	6th Floor to 15th floor	300-350 m^3	*	18.0 %
Office Space up to 10 people per m^2	6th Floor to 15th floor	351-450 m^3	***	11.5 %
Office Space up to 20 people per m^2	16th Floor to 29th floor	450-550 m^3	**	14.5 %
Office Space up to 20 people per m^2	16th Floor to 29th floor	551-650 m^3	**	13.0 %
Office Space up to 20 people per m^2	16th Floor to 29th floor	651-800 m^3	***	22.0 %
Conference Halls and Meeting Room	Other	500-950 m^3	***	26.0 %

oxygen where the independent variables are the volume of the zone and the number of people in the zone, and the dependent variable is the amount of oxygen. Although it cannot be detailed in the text due to data security principles of the company, Table 9 above indicates the effects of the zones where the groups of zones are the same as those in Table 8.

The zone effect values given in Table 9 are used in the model as the multipliers of the number of people in the zone in a period, providing the air requirement of the zone in a meaningful manner. According to the values in the table, zone's air effect can be considered high when the zone is smaller and have poor efficiency values, while it can be considered low when it has larger volumes and better efficiency values. However, zones in the last two rows of the table do not behave in a similar manner, since they have primarily different perceptions. Supplementary buildings are built to be used whenever a meeting or conference demand occurs, which means that their utilization values are low compared to other zones in the building. Even if they are built with very efficient pipelines, their size prevents achieving low electricity consumptions when an event is held by the company. Moreover, although the VIP rooms and Presidents Office have been built using high quality materials and first class engineering, large areas in the zones affect the general approach mentioned above in a different way.

CHAPTER 5

THE TABU SEARCH ALGORITHM

Having modelled our problem as an extension of the multilevel generalized assignment problem (MGAP), now we propose a tabu search algorithm to be able to solve the real-life size problems in reasonable computational times. MGAP is considered a variation of the generalized assignment problem (GAP), in which agents can execute tasks at different efficiency levels with different costs.

In this chapter we first discuss the approaches developed to solve the MGAP and then present our tabu search algorithm based on one of the known algorithms by Laguna et al. (1995).

5.1. Solution Approaches for the GAP and MGAP

A large body of literature exists for the classical generalized assignment problem (GAP). Fisher et. al. (1986) prove that the GAP is *NP*-complete. A survey by Cattrysse and Van Wassenhove (1990) which is an old survey provides a comprehensive examination of most of the methods for GAP.

Fisher et.al. (1986) describe a branch and bound algorithm for GAP in which bounds are obtained from a Lagrangian relaxation with the multipliers set by a heuristic adjustment method. Computation times were found to be reasonable in all cases and the branch and bound trees generated had nearly two orders of magnitude fewer nodes than for the available competing algorithms.

Amini and Racer (1995) develop a hybrid heuristic (HH) for solving GAP and conduct a computational comparison with the leading alternative heuristic approaches. HH is designed around the two best known heuristics: Heuristic GAP (HGAP) and Variable-Depth-Search Heuristic (VDSH). Previous performance studies show that HGAP dominates VDSH in terms of solution CPU time, while VDSH obtains solutions of 13% to 300% better quality in a reasonable time.

Lourenço and Serra (2000) present the application of a Max-Min Ant System (MMAS) and a greedy randomized adaptive search procedure (GRASP) to the GAP based on hybrid approaches. A bees algorithm (BA) is proposed by Özbakır et al. (2010) which is adapted to GAP by employing an ejection chain type neighborhood mechanism. The proposed BA is observed to be very effective for solving larger size and tightly constrained GAPs.

Pierskalla (1968) introduce an extended version of the assignment problem with the addition of the third dimension to the problem. He extends the classical assignment problem with the addition of time horizon for a warehouse problem of a distribution firm and presents a solution algorithm. He constructs a tree of feasible solutions including items, locations that items would be assigned to and different time horizons; and seeks for the optimal solution through nodes according to a systematic approach. The algorithm is very similar to the branch-and-bound algorithm where the dual problem at each iteration takes an important role in determining whether it would be better to progress to the next node or to terminate. However, the algorithm does not perform well especially when the optimal solution occurs near the end of the tree, as may be the case with our MGAP problem which has an enormous number of nodes and seven different levels presuming that it is highly likely to find optimal solutions at the last levels.

Since MGAP is a generalization of the GAP, the MGAP is *NP*-hard, and even the problem of determining whether a feasible solution exists is *NP*-complete (Ceselli and Righini, 2006). The first exact algorithm for the MGAP has been presented by Ceselli and Righini (2006) which is a branch-and-price algorithm, based on decomposition into a master problem with set-partitioning constraints and a pricing subproblem that is a multiple-choice knapsack problem.

It can be observed that the MGAP includes a set of knapsack constraints, one per agent that can help in generating simple logical constraints or cuts. Osorio and Laguna (2003) exploit the fact that logic cuts can be generated in linear time and can be easily added in order to strengthen the initial formulation before solving it with a classical branch and bound methodology.

Laguna et al. (1995) was the first to use a meta-heuristic approach to MGAP that is a tabu search algorithm. Ejection chains were in the heart of their algorithm, where different neighborhood movements are defined as changing some decision variables from *0* to *1* in return to changes in some other decision variables from *1* to *0*. They introduce a tabu search algorithm based on such chains and establish a new data set to test their algorithm, which is different from the ones in the literature (Martello and Toth, 1981), since most of the problems generated using the data sets of Martello and Toth had already been solved by the new commercial software packages. They claim that their tabu search algorithm provides better results compared to the other algorithms in the literature, especially for the difficult single-level GAP problem, which is a special form of MGAP with only one level for each agent. They emphasize some other benefits of their algorithm, for example, it does not require any parameter adjustment. They also provide a real-life example of MGAP and solved by their algorithm, although they could not obtain any solution by CPLEX due to the size of the problem.

French and Wilson (2002) introduce two heuristic approaches to MGAP and establish a new upper bound algorithm to the problem. Both heuristics are found to perform well compared to known solution approaches in the literature. In one of the heuristics, they firstly find a feasible solution to the problem by relaxing the capacity constraints and then they proceed to find an integer solution by reallocating the tasks to the agents. The other heuristic includes a kind of regret minimization approach which is the potential loss occurring when the task is not assigned to that agent.Both heuristic approaches are greedy and myopic and do not guarantee to find the optimal solution, however, they provide impressively rapid results compared to some other approaches in the literature. They also introduce an upper bound algorithm which starts with a relaxed solution and tries to improve it by considering the minimum decrease in the objective function when reallocating tasks to other agents. They provide the computational results of their heuristics and upper bound algorithm and compare them against the tabu search algorithm of Laguna et al. (1995).

To the best of our knowledge, there is no paper considering MGAP with availability and learning constraints. Therefore, we introduce a new solution procedure which is a kind of extension to the tabu search algorithm of Laguna et al. (1995). The reason to harness from that paper is that the other approaches are greedy and myopic and do not provide good solutions compared to the solutions of Laguna's approach. We use ejection chains in our algorithm, as in Laguna's heuristic, with various differences by adding the notion of availability constraints, learning effects and time horizon.

5.2. Tabu Search Algorithm

The merit of our solution procedure comes from the idea of having several tabu lists at the same time in order to increase intensification and diversification approaches to achieve high quality solutions as in Laguna's algorithm. However, there are some discriminating features of our algorithm in terms of implementing availability and demand propositions.

5.2.1. Demand Proposition

In Laguna's algorithm, agents have proposed capacities; and hence infeasibilities may occur when the capacities are exceeded. MGAP-LA has a different characteristic in terms of demand nodes in the network, since they are not agents providing some tasks to the agents, but they are expected to be satisfied in such a way that air or temperature needs are fulfilled. Therefore, demand nodes in MGAP-LA have requirements instead of capacities. Then there have to be some changes in the Laguna's feasibility condition when ejection chains are defined in order to implement their algorithm to our problem.

We propose a new variable r_k defining the slack of the requirements of zone k as follows:

$$
\begin{aligned}
r_k = \max\ & \left(TEMP_k^+ - \textstyle\sum_i \sum_j x_{ijk} H_{ijk}\,, 0\right) \\
& + \max\ \left(TEMP_k^- - \textstyle\sum_i \sum_j x_{ijk} C_{ijk}\,, 0\right) \\
& + \max\ \left(AIR_k^+ - \textstyle\sum_i \sum_j x_{ijk} A_{ijk}\,, 0\right) \\
& + \max\ \left(AIR_k^- - \textstyle\sum_i \sum_j x_{ijk} VT_{ijk}\,, 0\right)
\end{aligned} \tag{19}
$$

where $TEMP_k^+$, $TEMP_k^-$, AIR_k^+ , and AIR_k^- can be defined as the percentages of temperature and air requirements of zone k, respectively. Variable that has a plus indicator implies that current condition of the zone is below the boundaries so that the zone has to be heated if it requires heating or air conditioned if it requires air, whereas having a minus indicator implies that the zone is above boundaries so that it has to be cooled or ventilated. The computation of these variables is defined as follows:

$$TEMP_k^+ = \sum_t \frac{19 - CEL_t D_k}{CEL_t D_k} \tag{20}$$

$$TEMP_k^- = \sum_t \frac{CEL_t D_k - 22}{CEL_t D_k} \tag{21}$$

$$AIR_k^+ = \sum_t \frac{1.5 - E_{kt} F_k}{E_{kt} F_k} \tag{22}$$

$$AIR_k^- = \sum_t \frac{E_{kt} F_k - 3}{E_{kt} F_k} \tag{23}$$

Attention should be paid to the “zero” value of r_k meaning that zone k is satisfied, whereas positive values of r_k requires other units to start running or other increased levels of already running units to be satisfied. Moreover, we define a new variable that shows the degree of infeasibility of a solution. Let x be a solution to MGAP-LA that satisfies all constraints but does not necessarily meet the requirement constraints of the zones (Constraints 7-10). Then, the degree of infeasibility of a solution, $v(x)$, gives the algorithm the chance of jumping into the infeasible region whenever it gets stuck in the feasible region. $v(x)$ is defined as follows:

$$v(x) = \sum_k r_k \tag{24}$$

5.2.2. Availability Proposition

One of the most important components of our problem is the availability constraints of the units of the system. While making ejection chains, these constraints are to be controlled together with the constraint related with CO_2 emissions of the units. In order to satisfy these constraints, in each iteration of the algorithm, a binary variable is kept for each unit, which is defined to be *0* when constraints are satisfied related to that unit and *1* when they are not, and it has to be provided that the sum of all records has to be zero, which means that all of the availability constraints of the units are satisfied.

Another variable, b, is used to track CO_2 emission levels of the building. This is the variable which is defined in the same way as r_k is defined; however the indices of components generating b are independent of zone variables this time. b is the slack of CO_2 emission of the units and it is defined as follows:

$$b = CO - \sum_i \sum_j \sum_t x_{ijt} CO_{ij} \quad (25)$$

5.2.3. Ejection Chains

Aspiration to achieve reduced objective function values are searched for by the ejection chains in our algorithm. Table 10 below presents the possible chains that might occur at each iteration and the feasibility conditions which are kept for choosing the best chain.

Table 10 lists the candidate moves in each iteration. There are three main groups for ejection chains as single, double and circular, where single chains are kind of changes in which nodes are searched in the same period: double chains are kind of changes in which different periods may be resources for changes of different nodes and circular chains are kind of changes in which opposing nodes are changed from both the same and different periods. For each type of ejection chains, there are two feasibility conditions, first of which is related with air and temperature requirements of zones and second of which is related with total emission building releases to

Table 10 Ejection Chains and Feasibility Conditions

Type		Leaving Arc	Entering Arc	Feasibility Condition – 1 (Demand)	Feasibility Condition - 2 (CO_2)
Single	a	(i_1, j_1, t_1)	(i_1, j_2, t_1)	$r_k = 0$ for every k that can be serviced by i_1 at t_1	$b + CO_{i_1 j_1} - CO_{i_1 j_2} \geq 0$
	b	(i_1, j_1, t_1)	(i_2, j_2, t_1)	$r_k = 0$ for every k that can be serviced by i_1 or i_2 at t_1	$b + CO_{i_1 j_1} - CO_{i_2 j_2} \geq 0$
Double	a	$(i_1, j_1, t_1)(i_1, j_1, t_2)$	$(i_1, j_2, t_1)(i_1, j_3, t_2)$	$r_k = 0$ for every k that can be serviced by i_1 at t_1 and t_2	$b + CO_{i_1 j_1} + CO_{i_1 j_1} - CO_{i_1 j_2} - CO_{i_2 j_3} \geq 0$
	b	$(i_1, j_1, t_1)(i_1, j_1, t_2)$	$(i_2, j_2, t_1)(i_3, j_3, t_2)$	$r_k = 0$ for every k that can be serviced by i_1 or i_2 or i_3 at t_1 and t_2	$b + CO_{i_1 j_1} + CO_{i_1 j_1} - CO_{i_2 j_2} - CO_{i_3 j_3} \geq 0$
Circular	a	$(i_1, j_1, t_1)(i_2, j_2, t_1)$	$(i_2, j_1, t_1)(i_1, j_2, t_1)$	$r_k = 0$ for every k that can be serviced by i_1 or i_2 at t_1	$b + CO_{i_1 j_1} + CO_{i_2 j_2} - CO_{i_2 j_1} - CO_{i_1 j_2} \geq 0$
	b	$(i_1, j_1, t_1)(i_2, j_2, t_2)$	$(i_2, j_1, t_1)(i_1, j_2, t_2)$	$r_k = 0$ for every k that can be serviced by i_1 or i_2 at t_1 and t_2	$b + CO_{i_1 j_1} + CO_{i_2 j_2} - CO_{i_2 j_1} - CO_{i_1 j_2} \geq 0$

nature. In order to simplify and decrease the CPU times, not all zones are searched for feasibility, but only zones that have connection with the changing nodes are computed in iterations.

First column of Table 10 gives the type of chain and is grouped according to the description above. Second and third columns describe the arc(s) that take(s) value of *0* instead of *1* in return to another arc(s) taking the value of *1* instead of *0* respectively. The last two columns describe the two feasibility conditions which ensure that zone requirements are satisfied and CO_2 emission limit is not exceeded.

Some other parameters should be defined to complete the tabu search algorithm. Every leaving arc, which is determined by some conditions according to cost and infeasibility degree, is recorded in a tabu list, providing the arcs be kept in a shortlist to remain tabu for a proposed period of time. The required number of iterations that arcs should be kept in tabu is defined as follows:

$$tabutime(i_L, j_L, t_L) = z(i)\left(\frac{3}{2} + \frac{\Delta}{2(z(i)-1)}\right) + \frac{I \times J \times T \times \gamma(i_L, j_L, t_L)}{\gamma_{max}} \quad (26)$$

where

$\gamma(i_L, j_L, t_L)$ = number of times that (i_L, j_L, t_L) has been part of an executed move,
γ_{max} = maximum of $\gamma(i_L, j_L, t_L)$ for all i, j and t,
$z(i)$ = number of units that can serve to zones which unit i can also serve,
$\Delta = q(i_L) - q(i_E)$, and
$q(i)$ = The position of the unit i when all units that can ser
can serve, are ordered in descending order of cost to resource ratio.

Three parameters determine the tabu time of a leaving arc. The first parameter is the number of zones that units can serve; the second parameter is the position of the arcs in the rank which is determined by the ratio of the electricity consumption over the sum of the impacts that units have over zones and the third parameter is the frequency of that arc being listed as a tabu move before. We take into account the sum of all impacts that the unit may have over zones, which is the main difference of our algorithm from the formula of Laguna et al. (1995). The merit of such a procedure brings the benefit of utilizing multiple tabu lists for each unit indeed and the length of being tabu for a unit depends on the history of the search. The minimum time that units may remain in tabu list is $z(i)$, which occurs when the leaving arc has the best electricity-impact ratio $(q(i_L) = 1)$ and has never been a tabu move $(\gamma(i_L, j_L, t_L) = 0)$, while the entering arc has the worst ratio $(q(i_E) = z(i))$. Similarly, the maximum time that the unit may remain in tabu list is $2z(i) + IJT$ which occurs when the entering arc has the best ratio, the leaving arc has the worst ratio and the maximum number of being tabu move.

The only thing that should be kept in mind in the execution of the algorithm is to keep the units that have to be run continuously running through the whole process. Therefore, decision variables related to the first level of these units at least would always take on the value of *1*. We keep decision variables that show these units being off, as tabu moves until the end of the algorithm to avoid breaking the constraints about these units.

To initialize the algorithm, a construction algorithm is proposed which is described below.

Initialization

- Set t=0.
- Set a new variable to *0* which is defined to record the total CO_2 emission of the units.
- Set a new binary variable for each unit which is defined to be *1* if maintenance is necessary and *0* if the unit is able to run. Assign *0* to each availability variable.

Step.0 If t=7, stop, otherwise $t \leftarrow t$+1.

Step.1 Assign the first level of all units that have to be run continuously and check whether or not there is a zone requiring air or temperature. If not, go to Step.0; otherwise, go to Step.2.

Step.2 Rank the units that are available and able to deliver air and temperature to the open zones that require air or temperature in ascending order, according to energy consumption values at their first level. Begin to assign the first level of the units from the first order through the last one until no open zone remains. Note that we ignore the unit causing CO_2 emission limitation to be exceeded and assign the next possible unit. Assign *1* to the availability variable of each running unit, add CO_2 emission values of running units to the related variable and increase t by *1*. If there is a unit whose availability variable should be reset to *0*, assign *0* to it and go to Step.0.

The last element of tabu search algorithm is to define *best move* which leads the solution state of the next iteration. As infeasible regions are allowed to be searched in our algorithm, $v(x)$ has an impact on the best move. The procedure implemented in our algorithm is similar to Laguna's, but differs with the additional degree, $b(x)$, which is the consideration of CO_2 emissions. Table 11 below presents the selection criteria of the best move. In each iteration, there are two candidate moves: the first minimizes $Z(x') - Z(x)$ where $Z(x)$ the objective value of the current solution and $Z(x')$ is the objective value of the candidate move; and the second minimizes $v(x") - v(x)$ where $x"$ is the second candidate move. Looking at Table 11, whenever the current solution is infeasible, the next move is the one that minimizes the infeasibility while there are three options..

Table 11 Best Move Selection Criteria

Current Solution	**Candidate - 2 ($x"$)**	**Move**
$b(x) < 0$ or $v(x) > 0$	-	$x"$
$b(x) \geq 0$ *and* $v(x) = 0$	$b(x") < 0$ *or* $v(x") > 0$	x'
$b(x) \geq 0$ *and* $v(x) = 0$	$b(x") \geq 0$ *and* $v(x") = 0$ *and* $Z(x") \leq \tau$	$x"$
$b(x) \geq 0$ *and* $v(x) = 0$	$b(x") \geq 0$ *and* $v(x") = 0$ *and* $Z(x") > \tau$	x'

```
input
    Temperatures; //Outside temperatures of the periods
    #ofPeople; //Number of people in the zones in the periods
    InsulationLevels; //Insulation multipliers of the zones
    HumanFactors; //Human factor multipliers of the zones
    UnitImpacts; //Heating, cooling, air conditioning and ventilation effects of the units
    UnitsElectricityConsumptions; //Electricity consumption of the units in different levels per period
    UnitsCO2Emissions; //CO2 emission values of the units in different levels per period
    UnitsSetupElectricityConsumptions; //Setup electricity consumption of the units
    UnitsType1AvailablePeriods; //Maximum number of periods during which units can serve consecutively before they require first type maintenance operations
    UnitsType1MaintenancePeriods; //Number of periods of the units which is required to make first type maintenance operations
    UnitsType2AvailablePeriods; //Maximum number of periods during which units can serve before they require second type maintenance operations
    SetOfMinimumUnits; //Set of units that have to be run continuously
set
    //assign the solution found by construction algorithm as the incumbent solution
    S_incumbent ← ConstructInitialSolution( ) ;
    //check if the construction solution is feasible or not
    if(CheckFeasibility(S_incumbent))
        S_best ← S_incumbent ;
    else
        S_best ← infinity ;
    end
    TabuList ← ∅;
while (StoppingCriteria( ))
    //assign the solution selected according to Tables 10 and 11 as the candidate move
    S_candidate ← NeighborhoodSelection( S_incumbent, TabuList);
    //calculate the tabu time of the leaving solution and add it to the tabu list
    TabuList ← AddMoveToTabuList(S_incumbent, TabuTime_{S_incumbent}) ;
    S_incumbent ← S_candidate ;
    if(CheckFeasibility(S_incumbent))
        if(ObjValue(S_incumbent) ≤ ObjValue(S_best))
            S_best ← S_incumbent ;
        end
    end
    //remove the moves whose tabu time is finished
    TabuList ← RemoveFromTabuList( ) ;
end
return(S_best);
```

Figure 11 Pseudocode of the Tabu Search Algorithm

If the second candidate move is infeasible, the algorithm is to remain in the feasible region, thus x' is selected. If not, a threshold value, τ, would be identifier to determine the next move, where x'' is selected as long as the objective value of x'' does not exceed the threshold value. If the threshold value is exceeded by x'', then x' is selected. Threshold value is defined by the first objective value of the last time the algorithm entered the feasible region, while it is reset to the objective value of the starting solution after $i \times j \times t$ non-improving iterations to re-allow the algorithm to jump into infeasible region. The merit of such threshold is to allow for non-improving moves within the feasible region.

Pseudocode of the algorithm regarding all the specifications explained above is given in Figure 11. All parameters are given as inputs to the algorithm and the algorithm begins with the solution found by the construction algorithm. It is checked if the solution with the construction algorithm is feasible in order to define the best solution. Objective value of the best solution is defined as the solution of the construction algorithm if the solution satisfies the four feasibility conditions. First condition is that all zones have to be served at their minimum requirements, while the second condition is that the total CO_2 emission value should not exceed the maximum value allowed, and the third condition is that all units have to be maintained according to their two types of availability constraints; finally the fourth condition requires that units that have to be run continuously are assured to be run at their first level at least for all periods. If this solution of the construction algorithm does not satisfy the feasibility conditions, objective function value of the best solution is defined to be infinity since we study a minimization problem.

The algorithm, then, searches for better solutions by exploring the neighborhood solutions of the incumbent solution regarding the criteria given in Tables 10 and 11, and a candidate move is defined as the new best solution if it satisfies the feasibility conditions and has an objective function value less than the existing best solution. The last incumbent solution is added to the tabu list with its specific tabu time (see formula 26) after the algorithm moves to a new solution, while the solutions whose tabu time is finished are deleted from the tabu list. Finally the algorithm terminates whenever the stopping criterion defined is reached.

CHAPTER 6

COMPUTATIONAL RESULTS

We test our tabu search algorithm against several algorithms in the literature. As the problem we address is somehow different from the existing MGAP in the literature, we had to generate different problem instances. Laguna et al. (1995) and French and Wilson (2002) utilized from the comparisons they did against general assignment problems defined and solved by Martello and Toth (1981) via considering the number of lot sizes as *1*, which is the index k for their problem, thus they reduce the problem to two dimensions.

First of all, we compare our algorithm against the optimal solutions by using two different data sets which are defined in a similar manner to Martello and Toth (1981), and Laguna et al. (1995). Table 12 below presents the structure of the data sets we use to test our algorithm. Since we have four different multipliers associated with the zones that can be delivered by certain units, as ascending cost values according to levels, setup cost values, availability parameters and external variables of temperature and number of people in zones, all of which are not considered in the other papers, we cannot use exactly the same distributions as in the other studies. Therefore we use similar distributions, where the number of zones that each unit can serve (air and temperature) is estimated based on the $Integer\ Uniform\ [\ 1, k\ ]$. For the first set of test environment, number of zones is defined to be 100 for each replication and zone numbers are assigned to units randomly avoiding that there is not any zone that cannot be served by any unit. Then, another parameter associated with zones is used to test the efficiency of the algorithm in the problems that include different number of zones.

To test the efficiency of the algorithm, we generate 27 different problem instances with 20 replications each, in which the number of units, levels and periods are defined as 5, 10 or 15, respectively. All parameters are estimated separately for each replication and we change only one variable at a time. Then we compare the results of our algorithm obtained from 540 problem instances in total against the optimal results..

A 2.40 GHz i5 computer with 4GB RAM and Windows 7 is used while testing the algorithm. The mathematical model is coded in IBM ILOG CPLEX Studio 12.5 and the tabu search algorithm we propose is coded in Java. Table 13 below shows the efficiency of the proposed algorithm over 540 problem instances with the first data set, where the stopping criterion for each problem instance is 100,000 iterations.

Table 12 Test Data Type - I

Variable	Data Structure
$H_{ijk}, C_{ijk}, A_{ijk}, VT_{ijk}$	$\in Uniform\ [\ 0, 1\ ]$
BC_{ij}, CO_{ij}	$= 411 - 100\frac{\sum_{k \mid H_{ijk}+C_{ijk}+A_{ijk}+VT_{ijk}>0} H_{ijk}+C_{ijk}+A_{ijk}+VT_{ijk}}{value\ of\ k\ that\ can\ be\ delivered\ by\ unit\ i} + Uniform\ [\ -10, 10\ ]$
SC_j	$\in Uniform\ [\ 1, 50\ ]$
LR_i	$=$ (value of k that can be delivered by unit i) $\times Uniform[\ 0, 0.025\ ]$
B_i	$\in Integer\ Uniform\ [\ 1, t/2\ ]$
P_i^1	$\in Integer\ Uniform\ [\ 1, t/2\ ]$
P_i^2	$= B_i + Integer\ Uniform\ [\ 1, t/2\ ]$
CEL_t	$\in Uniform\ [\ -5, 35\ ]$
D_k	$\in Uniform\ [\ 0, 1\ ]$
E_{kt}	$\in Integer\ Uniform\ [\ 0, 50\ ]$
F_k	$\in Uniform\ [\ 0, 1\ ]$

Looking at Table 13 below, we end up with 484 optimal solutions out of 540 solutions, which correspond to 89.62% of all problem instances. The average deviation from optimality is approximately 0.4% on the average, which seems to be a substantially high performance for our algorithm. However, performance of the algorithm may be increased by trying a higher number of iterations as the stopping criterion or different kinds of stopping criteria, like terminating the algorithm after a defined number of iterations without improvement, which would probably lead to shorter solution times, since our stopping criterion allows our algorithm to continue even if there is not any improvement after a certain number of iterations below 100,000. However, solution times are insignificant for our algorithm and it takes less than 10 seconds to solve problems in the current testing environment.

Table 13 Results with Test Data Type - I

% deviation from optimality		
	Average	0.004
	Maximum	0.081
CPU Times to Optimality obtained from CPLEX (seconds)		
	Average	12.382
	Maximum	874.650
Number of Optimum Solutions		484

One of the significant features of our algorithm is observed while analyzing the results grouped by variables in Table 14 below. As it can be seen from the table, higher number of units would give better results in terms of optimality, which decreases to 0.1% from 0.7% in average deviation from optimality corresponding to 86% improvement, whereas performance growth is 67% with the changes in the number of levels. However, the number of periods does not necessarily affect the quality of the objective function values of our algorithm. Moreover, the CPU times do not follow a standard pattern while increasing the value of the variable from 5 to 15. The number of optimal solutions found reaches 169, when the number of units of

Table 14 Results Summarized by Variables with the Test Data Type – I

	Number of units, i			Number of levels, j			Number of periods, t		
	5	10	15	5	10	15	5	10	15
% deviation from optimality									
Average	0.7	0.4	0.1	0.6	0.4	0.2	0.4	0.4	0.4
Maximum	8.1	7.1	7.0	8.1	7.1	7.1	8.1	7.0	7.3
CPU Times to optimality obtained from CPLEX (seconds)									
Average	0.148	7.338	29.661	0.392	11.722	25.032	0.660	11.183	25.303
Maximum	8.790	196.000	874.650	9.610	547.180	874.650	26.510	756.367	874.650
Number of Optimal Solutions	153	162	169	152	165	167	160	161	163

the HVAC system is increased to 15 units. While the number of levels increases to 15, the number of optimal solutions increases to 167; and while the number of periods increases to 15, the number of optimal solutions increases to 163. Considering the solution time to optimality, higher number of units cause an increase in solution times much more than the number of levels and the number of periods do, whereas the algorithm accomplishes better objective function value when the size of the problem increases overall.

Our algorithm is also tested using another set of 20 problem instances for each environment, where the number of zones ranges from 200 to 500 and the number of units, levels and periods are defined to be 15 each. Table 15 below shows the results listed according to different sizes of the zones.

Table 15 Results Grouped by the Number of Zones with the Test Data Type I

	Number of zones, *k*			
	200	300	400	500
% deviation from optimality				
Average	0.7	0.9	1.0	1.6
Maximum	9.4	9.9	10.2	11.3
CPU Times to optimality obtained from CPLEX (seconds)				
Average	2.490	16.870	135.470	218.750
Maximum	34.510	97.840	1,154.730	3,784.120
Number of Optimal Solutions	17	16	13	11

It may easily be seen that larger instances, which are actually not so large due to the number of decision variables but number of zones increases the complexity of problem, take significantly more time to solve optimally, and the number of zones slightly affects the solution quality of the algorithm.

Laguna et al. (1995) introduce a different data set, where multipliers are estimated based on a proposed probability variable. Type – II data set for our algorithm is generated by using a structure which is similar to Laguna's one. Table 16 below presents how multipliers and cost variables are estimated according to that structure, where all other variables are in the same form as defined in the previous data type. It is shown by Laguna et al. (1995) and French and Wilson (2002) that it becomes even harder to solve the problems when multipliers are not from a uniform distribution . Table 17 below shows the results obtained in solving the ten problem instances with the number of units, levels and periods ranging from 5 to 15 and the number of zones being 100.

Table 16 Test Data Type-II

Variable	Data Structure
$H_{ijk}, C_{ijk}, A_{ijk}, VT_{ijk}$	$= \begin{cases} \frac{ln(\,Uniform(\,0,1\,]\,)}{10}, \text{with probability } p \\ 0, \quad \text{with probability } (1-p) \end{cases}$
BC_{ij}, CO_{ij}	$= \frac{1000}{\frac{\sum_{k \mid H_{ijk}+C_{ijk}+A_{ijk}+VT_{ijk}>0} H_{ijk}+C_{ijk}+A_{ijk}+VT_{ijk}}{value\ of\ k\ that\ can\ be\ delivered\ by\ unit\ i}} - 10 \times Uniform\ [\,0,1\,]$
All other variables are estimated with the same distribution defined in Type – I	

Table 17 Results with Test Data Type – II

		p		
		1.00	0.75	0.50
% deviation from optimality				
	Average	0.7	0.7	0.9
	Maximum	8.7	9.0	9.7
CPU Times to optimality obtained from CPLEX (seconds)				
	Average	11.039	19.348	43.467
	Maximum	764.043	919.101	1,542.027
Number of Optimum Solutions		237	230	228

Results in Table 17 indicate that our algorithm also performs well with such data structures in terms of CPU times. However, quality of the results considering optimality is not much above our expectations; however, the results do not turn out to be poorer compared to the results given in Tables 13 and 14 in terms of solution quality. We have achieved 237 optimal solutions out of 270 problem instances corresponding to 88%, when the probability variable equals 1; 230 optimal solutions corresponding to 85% when the probability variable equals 0.75; and 228 optimal solutions corresponding 84% when the probability variable equals 0.5. Similarly, Table 18 below presents the performance of our algorithm when the number of zones range from 200 to 500 with the test data structure defined in Table 16 above. When it comes to different ranges of zones, our algorithm also behaves in a similar manner as it does as shown in Table 15 above.The solution times increase while the solution quality of the algorithm slightly decreases, and the average CPU times of the solutions get even higher with the rising number of zones as reported in Table 18.

Table 18 Results Grouped by the Number of Zones with Test Data Type – II

	% deviation		CPU times obtained from CPLEX (seconds)		
$(p;k)$	Average	Maximum	Average	Maximum	Number of Optimal Solutions
(1.00; 200)	1.0	9.6	9.064	67.471	8
(1.00; 300)	1.6	10.9	26.291	167.034	8
(1.00; 400)	1.9	12.4	211.631	1,597.730	8
(0.75; 200)	1.1	9.8	10.104	68.011	8
(0.75; 300)	1.5	11.6	30.147	275.410	7
(0.75; 400)	2.1	13.0	213.465	1,941.002	8
(0.50; 200)	1.0	9.9	9.940	58.000	7
(0.50; 300)	1.9	12.7	41.201	417.653	7
(0.50; 400)	2.7	23.1	207.072	1,937.854	7

We also test the performance of our algorithm for larger problem instances, where the number of units range from 100 to 200, the number of levels range from 3 to 5, the number of periods range from 5 to 10 and the number of zones range from 300 to 400. However, the optimization software is not able to solve these problem instances optimally, therefore we have fixed the CPU times to 600 seconds for both CPLEX and Java in order to be able to compare the results. Table 19 below displays the comparison of the larger problem instances in which variables are estimated by using the data structure given in Type – II (Table 16). It can be observed that our algorithm finds better objective values for the seven problem instances out of eight instances, where the difference between the results obtained for the only problem instance in which our algorithm had a worse objective value is only 0,41% (problem (1.00; 200, 5, 5, 400)).

The final test is applied over a real life problem to see how our algorithm works on the data collected through the last 14 months records of the building studied in this thesis. Total electricity consumption of the building has been recorded since 2010; however, card swapping system, which keeps the logs of transactions whenever people swap their personnel or visitor ID cards on the readers to pass across the digital toll gates, was installed in October, 2011. Therefore, we can only test our algorithm with the data collected for the number of people in the zones after that installation. Table 20 below presents the comparison between the real electricity consumption, where all units are run at their highest levels for 24 hours/7day, and the objective values of our algorithm which was run for 600 seconds for every single day of the whole period. The column showing the total estimated electricity consumption values is obtained by summing up the electricity consumption of the days of each month. The last column shows the average numbers of units running for each day.

Looking at the table, it can be claimed that our algorithm could reduce the electricity consumption by 15.1 %, which corresponds to approximately 630,000 TL per annum, when it is compared to real electricity consumption values that have been invoiced already to the company by the energy distributor company of the region. The impact of such a reduction could have been a 5 % reduction in the overall service charges.

Moreover, another improvement could have occurred over the number of running units. Tabu search algorithm shows that running only 156 units in average per day could have been adequate to satisfy the requirements of zones. As we know that there are some units that have to be run continuously within the facility and if we disregard them, improvement in the number of units running could decrease to 144 units,

Table 19 Results for Larger Problem Instances

$(p; i, j, t, k)$	Number of Decision Variables	Objective Value	
		Tabu Search Algorithm	CPLEX
(1.00; 100, 5, 10, 300)	10,000	2,067,880.822	2,408,031.093
(1.00; 200, 5, 5, 400)	10,000	3,219,912.005	3,206,710.366
(1.00; 200, 3, 10, 300)	12,000	4,769,117.314	5,006,209.652
(1.00; 200, 5, 10, 400)	20,000	4,329,703.523	4,881,279.272
(0.50; 200, 5, 5, 300)	10,000	3,179,381.869	3,544,337.884
(0.50; 200, 3, 10, 400)	12,000	2,291,914.219	2,318,263.723
(0.50; 100, 5, 10, 400)	10,000	1,700,331.093	1,897,410.690
(0.50; 200, 5, 10, 300)	20,000	3,009,752.199	3,486,880.301

Table 20 Comparison of Real Consumption Data and Tabu Search Algorithm Solutions

Month	Real Consumption	Tabu Search Solution	Reduction (%)	Number of Units Running
Nov.11	1,006,654.8	799,770.8	20.6	136
Dec.11	1,096,492.6	981,109.5	10.5	151
Jan.12	1,079,712.1	994,857.2	7.9	156
Feb.12	1,116,740.5	913,054.6	18.2	147
Mar.12	1,132,466.3	967,164.3	14.6	149
Apr.12	1,111,603.8	851,759.1	23.4	139
May.12	1,299,725.4	1,061,944.5	18.3	174
Jun.12	1,318,107.0	1,016,476.7	22.9	156
Jul.12	1,428,935.0	1,211,930.0	15.2	181
Aug.12	1,296,386.0	989,967.8	23.6	149
Sep.12	1,200,255.0	1,088,247.6	9.3	177
Oct.12	1,113,536.0	1,063,671.9	4.5	173
Nov.12	1,048,869.0	1,009,247.5	3.8	153
Dec.12	1,034,784.6	881,540.7	14.8	145
Total	16,284,268.1	13,830,742.3	15.1	156

which means that 25 % of the units had run idle to provide air and temperature requirements. Reduction in the number of units running may help the company reduce its spare parts inventory and labor cost as well. Staff and spare parts inventory have been kept regarding all units of the system. Reduction in the number of units running may lead the company to reduce its inventory and staffing cost, as it becomes useless to hold much inventory and staff for the idle units. It may also affect the maintenance schedule of the units, where almost half of the time of the technicians and specialists in the company are spent to perform the maintenance work of these units. Therefore, even reducing the number of total units by one may have substantial effects on the performance of the in-house employees.

CHAPTER 7

CONCLUSION AND FURTHER RESEARCH ISSUES

In this study, a recent topic related to energy efficiency has been discussed and a new approach has been proposed. Growing demand on resources and increasing population of the world encourage people to find better ways to consume available resources. Organizations are also one of those components that should take proper actions to reduce resource consumption in order to decrease their costs and carbon foot prints as well. Energy efficiency applications have been used for the last decades, where the main principle is to create more sustainable environments that consider needs of the future generations without increasing the costs. Reducing total energy consumption without decreasing the outcomes is the aim of such applications as well. Residential buildings, commercial buildings, manufacturing facilities and non-residential buildings are important key elements of energy consumption that can easily implement energy-efficient solutions. In order to incorporate scientific approaches with such a trendy topic, we introduce a new multilevel generalized assignment model with learning consideration and availability constraints (MGAP-LA), which reduces the electricity consumption of a facility, where all resources consuming electricity could be measured by automated meter-reading equipment and can be scheduled by the automation systems.

The model we propose is a specific implication of the well-known generalized assignment problem with some differences. Addition of a new set of index to decision variables that creates a multi-level environment is one of the most significant differences between GAP and MGAP, which makes the problem more complex. Moreover, learning machine systems is another approach used in this study in order to reflect the real world building specifications in the model. The set of availability constraints of the system, providing that the machines are not allowed to run during some time periods when they have to be maintained to run again properly, is the other aspect of our problem. Additionally, we consider CO_2 emission of the buildings to prevent exceeding the defined limits, which is an emerging area all around the world and there has been several guidelines and legislation on the topic.

We, then, propose a new tabu search algorithm, where we utilize ejection chains, to solve this complex problem and test our algorithm in different ways. According to these test results, our algorithm comes up with a high performance in terms of both CPU times and solution quality. We also test our algorithm with the real data, belonging to the headquarter of The Union of Chambers and Commodity Exchanges of Turkey, We find out that total electricity consumption could be decreased by 15% in average regarding the outside temperature and the number of people living in the facility.

Although we achieve a high level of performance with th proposed algorithm, there is still room for improvement in this area. It is the machine availability constraints that we consider in our model; however, there are some other binding criteria to maintain the systems such as staff and inventory. It may lead to more holistic approaches if scheduling issues of staff can be involved in the model. Similarly the inventory levels of spare parts may be considered to accomplish more realistic and integrated solutions. Moreover, ability to get the online data of temperature and number of people who live in the building embedded into model may increase the accuracy of the problem solution, since currently we can only use the future predictions for the weather conditions and the number of people.

Another improvement opportunity is related with the availability constraints of the units of HVAC system. As we introduce the problem environment, HVAC system has several types of units that have different conditions on their maintenance schedule, where some of the units require even four hours of maintenance, and some of them do not need any maintenance at all and can run continuously for two years. Due to the complexity and the size of the problem, we only solve problems within a day period. Increasing the time horizon of the problem may lead the organization to find more realistic solutions in which maintenance schedule of the units can be defined more properly.

Another opportunity to improve the approach is related to the assumptions we had to make in order to reduce the problem complexity. It may be possible to find better, that is more accurate, results if all factors affecting the indoor temperature, apart from only the outside temperature, like the existing temperature (previous period's temperature), equipment and machines in the environment and body temperatures of people are considered in the problem. Improving the model so as to include all aspects in the environment would probably help researchers obtain more realistic solutions as a result of a more holistic approach.

It is also possible to increase the performance of the tabu search algorithm by trying several parameters and termination criteria. We only define our stopping criteria as a certain number of iterations and a limited time in order to simplify the procedure. However, calibration of the parameters like stopping criteria, aspiration criteria and threshold value is likely to have significant effects on the results in the subject of tabu search methodologies (Glover et al., 1993). Comparison of several parameters and determining the best set of parameters would lead researchers to achieve better performing algorithms.

We show that there are always innovative approaches to manage resources apart from changing the type of resources or introducing new products to market. Energy efficiency is becoming a phenomenal issue that every human being should hammer on it as we do not have any other world to live. Therefore, it will always be on top of the emerging lists and provide people room to improve.

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