ABSTRACT


Maintenance schedules affect power generation units (GU) readiness, and generation schedules impact how often those GUs need to be maintained. Generation and maintenance scheduling (GMS) techniques must consider constraints of both activities at the same time to produce the most efficient schedule.

The compatibility of current published models with the real issues of the Saudi Electricity Company (SEC) is investigated. A new model for generation and maintenance scheduling is introduced. Compared with the most relevant published model, this model considers roughly double the number of technical constraints.

The problem is modeled as a Mixed Integer Linear Program (MILP). A Heuristic is introduced to provide an initial solution for the MILP. Both the MILP and the Heuristic produce excellent schedules. Moreover, the schedules achieved savings in total cost (mostly in fuel consumption), when compared with historic consumption in the SEC’s power plants.

The planning horizon is at least 2 years, and the number of GUs in the studied part of the SEC network is about 150 GUs. For the MILP, a partitioning technique was tested and proved efficient in dividing the huge problems into smaller partitions. The individual solutions are consolidated into one initial starting solution. This results in excellent solutions for the original problem.
Power Generation Integrated Operation and Maintenance Scheduling:
A study of the Saudi Electricity Company

by:
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DEDICATION

After GOD’s will, I am at this point because of the vision of my father, the encouragement of my mother and the support of my wife and my three sons.
BIOGRAPHY

Abdullah Alharbi was born on 9 November 1974 in Jeddah, Saudi Arabia. He graduated as an architect from King Abdul-Aziz University (KAU) in Jeddah 1999. During 1998-2000, he was the technical support unit head at the restoration project of the historical down-town of Jeddah. During 2000-2008, he worked for the Saudi Electricity Company in different construction project management positions. He earned his Masters of Science degree in Industrial Engineering from KAU in 2004. During 2008-2009, he was a senior engineer in the construction of King Abdullah University for Science and Technology (KAUST), Thuwal, Saudi Arabia. During 2009-2011, he was a construction department manager at the KAU, and he joined the faculty of KAU as a lecturer in the Industrial Engineering Department. Abdullah is married to Suzan and has three sons, Musaed, Muaaz and Maan.
ACKNOWLEDGMENTS

Dr. Thom J. Hodgson, I’d like to say that he was the best thing happen to me during my academic experience at NC State University. I consider myself lucky to have such a unique person. Yes, he is going to read this, but I wouldn’t forgive myself if I finished this document without mentioning how humble he is, cooperative, patient, sincere and dedicated to educating others. Thom, in short, is the up-to-date person with a personality from a different era. I am not surprised when I see all students share this opinion with me.

I must admit that I was lucky also to have such smart committee members, which made idea sharing easier than expected. Even their small points of views made differences, and help me to achieve the research goal. Their encouraging words and positive impressions meant so much to me, and helped me more than what they thought.

In the other part of the world, I’d like to thank the people in the Operation and Maintenance Planning Department (OMPD) at the head-quarters of the Saudi Electricity Company West Region Branch (SEC-WRB) in Jeddah-KSA. I believe that this research gains its strength because of the valuable information and data they provide to me. Also, the other colleagues in the power plants we visited. Thank you all for your contribution and time you spent with me in this fruitful research.

Suzan, my wife, I cannot describe how patient she was through these years. Thank you is not enough words to be said, her support was part of the investment, and she is now part of the success. I wish that GOD bless this success, and bless our future life together.
TABLE OF CONTENTS

LIST OF TABLES ........................................................................................................... viii
LIST OF FIGURES ......................................................................................................... ix
LIST OF ABBREVIATIONS ............................................................................................. xi

CHAPTER 1

1. INTRODUCTION ........................................................................................................ 1

1.1. Generation units’ operation and maintenance scheduling .................................... 1
1.1.1. Nature of the electric power service field in general ........................................ 1
1.1.2. GMS problem facts and definition .................................................................... 2
1.1.3. GMS problem constraints .................................................................................. 3
  1.1.3-a Maintenance execution constraints ................................................................. 3
  1.1.3-b Crew constraints ............................................................................................. 3
  1.1.3-c Precedence and Integration constraints ............................................................. 3
  1.1.3-d Capacity constraints ....................................................................................... 3
1.2. Power sector in Saudi Arabia ................................................................................... 4
  1.2.1. An overview of SEC ......................................................................................... 4
  1.2.2. The framework of the SEC .............................................................................. 8
    1.2.2-a Generation Sector ......................................................................................... 8
    1.2.2-b Transmission Sector ..................................................................................... 10
    1.2.2-c Distribution Sector ...................................................................................... 12
1.3. The current O&M Scheduling procedures in SEC-WRB ....................................... 13
  1.3.1. The Involved Departments .............................................................................. 13
  1.3.2. Types of maintenance activities ....................................................................... 13
  1.3.3. Scheduling time horizon .................................................................................. 13
  1.3.4. Preparing the O&M master plan ..................................................................... 14
  1.3.5. OMPD Schedule scheme and contents .............................................................. 15
  1.3.6. Scheduling goals, rules, and steps ................................................................... 18
    1.3.6-a Goals .............................................................................................................. 18
    1.3.6-b Rules .............................................................................................................. 18
    1.3.6-c Steps .............................................................................................................. 18
  1.3.7. Notes and observations on the current procedures .......................................... 19
    1.3.7-a Master plan’s resolution and robustness ......................................................... 19
    1.3.7-b Critical review ............................................................................................... 20
1.4. Problem Statement ................................................................................................. 21

CHAPTER 2

2. LITERATURE REVIEW ............................................................................................. 22

2.1. Problem Structures ............................................................................................... 22
  2.1.1. Deregulated Versus Regulated Energy Markets ................................................ 22


2.1.2. Monopoly systems ................................................................................................. 24
2.1.3. Deterministic Inputs Versus Uncertain Inputs ......................................................... 25
  2.1.3-a Uncertain Demand ................................................................................................. 26
  2.1.3-b Uncertain Failure rate ......................................................................................... 26
2.1.4. The GMS problem’s boundaries ............................................................................ 27
  2.1.4-a Large-Scale Energy Management (LSEM) ........................................................ 27
  2.1.4-b Refueling management ......................................................................................... 28
    2.1.4-b-1. Refueling windows ......................................................................................... 28
    2.1.4-b-2. Fuel amount constraints ................................................................................. 28
  2.1.4-c GMS with network constraints ............................................................................ 29
  2.1.4-d GMS and TMS ..................................................................................................... 29
  2.1.4-e The pure GMS problem ....................................................................................... 30
2.2. Model Features .......................................................................................................... 31
  2.2.1. Features of Group 1 and 2 ..................................................................................... 31
  2.2.2. Features of Group 3 .............................................................................................. 32
  2.2.3. Group 4 features .................................................................................................. 35

CHAPTER 3

3. THE MODEL .................................................................................................................. 40
3.1. Modeling the basic problem structure ........................................................................ 40
  3.1.1. GU activities and state definition .......................................................................... 40
  3.1.2. GU states mathematical presentation ..................................................................... 41
3.2. Cost variables and the objective function ................................................................. 43
  3.2.1. Cost variables ....................................................................................................... 43
  3.2.2. Objective function ............................................................................................... 45
3.3. Modeling the problem constraints ............................................................................. 45
  3.3.1. Satisfying Demand ............................................................................................... 46
  3.3.2. Production Limits (Max and Min generation capacities) ....................................... 46
  3.3.3. No generation exceeding max service-hours ......................................................... 46
  3.3.4. Maintenance steps’ sequencing ............................................................................ 48
  3.3.5. Maintenance steps’ duration ............................................................................... 49
  3.3.6. Maintenance manpower constraints ...................................................................... 49
  3.3.7. Maintenance continuity ........................................................................................ 50
  3.3.8. No maintenance before the window allows .......................................................... 50
  3.3.9. Maintenance Season ............................................................................................ 51
  3.3.10. Spinning Reserve ................................................................................................. 51
  3.3.11. Total capacity reserve ........................................................................................ 52
  3.3.12. Minimum operating state, (Up/Down) time ........................................................ 52
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 1.1</td>
<td>SEC-WRB Power Plants</td>
<td>9</td>
</tr>
<tr>
<td>Table 1.2</td>
<td>Preventive Maintenance Scheduling Standard</td>
<td>14</td>
</tr>
<tr>
<td>Table 1.3</td>
<td>GU Planning table example</td>
<td>15</td>
</tr>
<tr>
<td>Table 1.4</td>
<td>GU Planning table items’ description</td>
<td>16</td>
</tr>
<tr>
<td>Table 1.5</td>
<td>Sample of the Maintenance Plan</td>
<td>17</td>
</tr>
<tr>
<td>Table 2.1</td>
<td>Model Features, Groups (1) and (2)</td>
<td>32</td>
</tr>
<tr>
<td>Table 2.2</td>
<td>Model Features Groups (3)</td>
<td>33</td>
</tr>
<tr>
<td>Table 2.3</td>
<td>Model Features Groups (4)</td>
<td>36</td>
</tr>
<tr>
<td>Table 2.4</td>
<td>Compatibility results of Model Features</td>
<td>39</td>
</tr>
<tr>
<td>Table 3.1</td>
<td>GU states mathematical representation</td>
<td>42</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>Model constraints vs model features</td>
<td>53</td>
</tr>
<tr>
<td>Table 4.1</td>
<td>Model size for each Power Plant</td>
<td>55</td>
</tr>
<tr>
<td>Table 4.2</td>
<td>GUs’ basic data</td>
<td>58</td>
</tr>
<tr>
<td>Table 4.3</td>
<td>The maintenance sorting matrix and logic</td>
<td>60</td>
</tr>
<tr>
<td>Table 4.4</td>
<td>GUs’ Availability Matrix (Jeddah-PP)</td>
<td>65</td>
</tr>
<tr>
<td>Table 4.5</td>
<td>The generation sorting matrix (OP1 for Jeddah-PP)</td>
<td>66</td>
</tr>
<tr>
<td>Table 5.1</td>
<td>MILP code experiments</td>
<td>76</td>
</tr>
<tr>
<td>Table 5.2</td>
<td>Heuristic GMS experiment</td>
<td>78</td>
</tr>
<tr>
<td>Table 5.3</td>
<td>Partitioning experiments (JEDDAH-PP)</td>
<td>81</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

| Figure 1.1 | Geographical distribution of the SEC’s branches | 5 |
| Figure 1.2 | Saudi Arabia map (compared with North Carolina’s) | 5 |
| Figure 1.3 | Saudi Arabia Population density map | 6 |
| Figure 1.4 | Land Area Comparison | 7 |
| Figure 1.5 | Population Comparison | 7 |
| Figure 1.6 | Capacity Comparison | 7 |
| Figure 1.7 | Consumption Comparison | 7 |
| Figure 1.8 | The SEC organizational executive structure | 8 |
| Figure 1.9 | The SEC-WRB “connected” Power Plants | 9 |
| Figure 1.10 | Overhead transmission lines map | 10 |
| Figure 1.11 | Future for the overhead transmission lines plan | 11 |
| Figure 1.12 | Generation, Transmission and Distribution mechanism | 12 |
| Figure 2.1 | The GMS problem structures classification | 23 |
| Figure 2.2 | Nature of markets and objectives of the GMS problems | 25 |
| Figure 2.3 | Uncertainty classification | 27 |
| Figure 2.4 | The GMS boundaries refining | 30 |
| Figure 3.1 | Typical GU activities | 40 |
| Figure 3.2 | GU states diagram | 41 |
| Figure 3.3 | Fuel consumption function for GUs 13 to 18 at Makkah-PP | 43 |
| Figure 3.4 | Fuel curve function discretization | 44 |
| Figure 3.5 | Basic concept of the different capacities in the power system | 45 |
| Figure 3.6 | Example of a maintenance cycle | 48 |
| Figure 4.1 | Coding technique: solution process overview | 54 |
| Figure 4.2 | Models difficulty, and solution techniques | 56 |
| Figure 4.3-a | Example of a 2-year horizon | 59 |
| Figure 4.3-b | Example of a GU maintenance scheduling | 59 |
| Figure 4.4 | Maintenance sorting matrix | 61 |
| Figure 4.5 | Illustrative example of two consecutive iterations for two time-periods | 63 |
| Figure 4.6 | Example of maintenance schedule for Jeddah-PP, during YM1 | 69 |
Figure 4.7  Sorting and splitting GUs of Jeddah-PP into 4 parts .................................72
# LIST OF ACRONYMS AND ABBREVIATIONS

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GMS</td>
<td>Generation and Maintenance Scheduling</td>
</tr>
<tr>
<td>KSA</td>
<td>Kingdom of Saudi Arabia</td>
</tr>
<tr>
<td>SEC</td>
<td>Saudi Electricity Company</td>
</tr>
<tr>
<td>PM</td>
<td>Preventive Maintenance</td>
</tr>
<tr>
<td>GU</td>
<td>Generation Unit</td>
</tr>
<tr>
<td>SEC-WRB</td>
<td>the SEC’s West Region Branch</td>
</tr>
<tr>
<td>PP</td>
<td>Power Plant</td>
</tr>
<tr>
<td>ST</td>
<td>Steam Turbine</td>
</tr>
<tr>
<td>GT</td>
<td>Gas Turbine</td>
</tr>
<tr>
<td>LDC</td>
<td>Load Distribution Center (at SEC-WRB)</td>
</tr>
<tr>
<td>OMPD</td>
<td>Operation and Maintenance Planning Department (at SEC-WRB)</td>
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</tbody>
</table>
CHAPTER 1:

1. INTRODUCTION

In this dissertation, the problem of scheduling the generation assignments and maintenance jobs of multiple power generation units, so that the required maintenance standards are met, and the forecasted power demand is met. A unique mixed linear integer program is developed that considers multiple constraints. Heuristics that find very good starting solutions are developed and their efficacy is demonstrated on a real, large scale problem from the Saudi Electricity Company.

Part 1 of this chapter explains the basic ideas of the Generation and Maintenance Scheduling problem (GMS). Part 2 describes the outlines of electric service in the Kingdom of Saudi Arabia (KSA), which is provided by the Saudi Electricity Company (SEC). Part 3 is a detailed description for the current procedures of the GMS processing in the SEC. Part 4 provides the problem statement of this research.

1.1. Generation units’ operation and maintenance scheduling

1.1.1. Nature of the electric power service field in general

In any electric power generation organization, power supply can be viewed through two common known aspects: 1) As a Public and human need; for every governmental, institutional, social, and individual activity in the community. In other words, Demand should be met. And 2) As an Investment; where the revenue from power consumption sales is essential for the organization to maintain profit, survive, and grow to meet Demand. These two aspects are technically reflected in two important parameters to evaluate the performance of any electric company: 1) Service Reliability, (e.g. outage or failure frequency, reserve margins, preventive maintenance implementation); and 2) Financial Standing (major expenditures are fuel consumption, maintenance cost, expansion projects and manpower salaries. Major income is the power sales revenue).
1.1.2. GMS problem facts and definition

Power generation for public services has some special characteristics. Power cannot be stored, it should be generated, transmitted and distributed to customers on a real-time basis. That is why demand forecasting affects all planning activities. Meeting the continuous demand of the network is the first priority for every entity in the system.

It is not a simple process to startup or shutdown a generation unit in a power plant. Coordination between multiple departments, procedures, personnel, and resources is required. This requires time, effort, and money. The overall objective of the GMS problem is to define the best preventative maintenance (PM) schedule, for a specific set of generation units (GUs), within a predefined planning horizon, while satisfying generation demand at the same time. The best Schedule means: the least cost while satisfying the reliability standards (here is where tradeoffs usually happen).

The reliability standard has two levels: 1) At a unit level, a good PM schedule increases the GU’s reliability, and minimizes failure probability, and 2) At a system level, the more GUs taken out of the network for maintenance, the less reliability of the generation network.

Cost means the total plan cost, which includes both Operating and Maintenance costs. Operating cost is the cost associated with fuel consumption for power generation purposes. Producing the same amount of energy using the same group of GUs differs in cost, based on the load level assigned to each GU. GU’s fuel consumption is nonlinearly related to Load level, which complicates the problem.

The Power demand always reflects seasonal behavior. For instance, when the planning horizon for this problem is a complete year, the planner can see the whole seasonal cycle of demand. For sure, the time with higher demand is expected to be critical, and the maximum number of the power plants’ GUs (if not all of them) are expected to be ready. This means a fewer number of GUs to be scheduled for PM. The opposite is not always right. The lower demand times of the cycle appear to be a good time for PM activities. However, other limitations and constraints, like GU’s service hours’ records and human resources, could make maintaining the GUs during the maintenance season harder to achieve.
1.1.3. GMS problem constraints

The detailed constraints considered in this research are discussed in Chapter-2 and Chapter-3. The following is a quick brief of global constraints other GMS models usually consider.

1.1.3-a Maintenance execution constraints

Maintenance standards imply many constraints like maintenance duration, type, and timing. For example, some GUs have a maximum limit on production hours. After that, the GU is subject to a PM session. Moreover, this production hour limitation should be taken into consideration when determining the planning horizon for the problem.

1.1.3-b Crew constraints

Technical capabilities, and geographical locations affect cost, time and crew performance. Cost and maintenance time for a GU will be different among maintenance crews. The same crew will have a different cost to maintain two different GUs. Crew constraints can also limit the number of units that can be simultaneously maintained by the same crew, (usually one), and the type of GUs that can be maintained by each crew.

1.1.3-c Precedence and integration constraints

There are situations that require the maintenance of some GUs before another. A precedence constraint specifies the order in which maintenance on units should be performed a) in the same Power Plant, and b) in the whole network, if necessary.

There are some integrated parts or components of the generation network which makes it more efficient to perform maintenance on both at the same time. Also, in some cases, performing maintenance for particular GU requires the shutdown of another one.

1.1.3-d Capacity constraints

For any given time-unit in the scheduling horizon, possible GU states are either receiving maintenance, maintained and ready for generation (standing as a backup), in generation (streaming power into network), or out of service (waiting for maintenance).
Since the whole planning activity depends on the expected demand and a reliable reserve margin, capacity constraints usually ensure: 1) covering the expected demand; and 2) satisfying different types of reserve constraints, at every time unit of the schedule.

1.2. Power sector in Saudi Arabia

1.2.1. An overview of SEC

The SEC is the only electric power provider in the KSA. The company works in a production environment, which may be not the optimum for power companies, but represents a type of organization that can be found in growing countries surrounded by development challenges. The SEC provides electric service for all types of customers in the Saudi community. Private sector, public sector, industrial, governmental, residential groups and individuals. All receive power services from the same source. It is a monopoly system, where neither competition nor sharing with other providers exists. The goal is to provide everyone with power service, and to assure that this very vital sector of the community’s infrastructure is carefully dominated, controlled and secured.

The SEC is supported by the Saudi government. About 80% of the company’s shares are owned by the government, the other 20% are owned and traded on the Saudi stock exchange (Tadawul). The Saudi Government does not consider the company as a for profit organization. Besides financial support the company’s projects, the government waives its share of revenues annually. However, the revenues are not yet particularly attractive to professional investors. However, it provides a choice for others who look for secured investments.

The SEC provides power services to 4 geographically distributed branches: Western, Eastern, Central, and Southern branches. Each has its own head-quarters, power plants, and transmission network. This study will concentrate on the largest network, which is the Western Region Branch of the SEC (SEC-WRB). The map in figure 1.1 shows the geographical distribution of SEC branches (service areas) in Saudi Arabia, the map in figure 1.2 shows the 14 governmental principality provinces in Saudi Arabia, compared with the same-scale map of North Carolina, USA. The map in figure 1.3 shows the population density in the 14 principality provinces.
Figure 1.1: Geographical distribution of the SEC’s branches

Figure 1.2: Saudi Arabia (compared with North Carolina’s same-scale map)
Figure 1.3: Population density map (according to each province). The black line shows the borders of SEC-WRB service area.
Figures 1.4–1.7 show the land area, population, generation capacity and power consumption of Saudi Arabia, North Carolina, and the WRB of SEC by the end of 2014 [201] [202].
1.2.2. The framework of the SEC

Figure 1.8 below shows the 13 main activity sectors of the SEC executive board. Each sector has representation in each Head-Quarters of the four regional networks of the SEC. Three sectors can be referred to as strategic activity sectors because they represent the core business of the company, which are generating electrical energy, transmitting it through the power network, and distributing power to the consumers.

![SEC Organization Sectors Diagram]

Since the concentration in this research will be focused on the operations related to these 3 sectors, brief descriptions in relative to their activities will follow in next pages.

1.2.2-a Generation Sector.

The main role of this sector is to generate power, and the main assets are the Power Plants (PP). Every PP consists of several generating units (GUs). GUs are different in technology (steam (ST), gas (GT) or combined cycle (CC)), and different in their fuel types, and their manufacturers. A power plant could have different types of GUs. Those differences affect their characteristics: fuel consumption, and maintenance standards.
Figure 1.1 shows the types and current location of every PP in Saudi Arabia. In the western region, there are total of 14 PPs. Those PPs are either geographically, administratively or technically separated from each other. Table 1.1 shows the generation capacity for these PPs. Since many GUs have been upgraded, the last column in the table shows the current capacities reported by the O&M personnel.

Table 1.1: SEC-WRB Power Plants

<table>
<thead>
<tr>
<th>Power Plant</th>
<th># Units in each PP in P.P.</th>
<th>PP Capacity in M.W. in Total</th>
<th>Manuf.</th>
<th>O&amp;M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Connected to the main Transmission Network</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoaiba Steam</td>
<td>14</td>
<td>5,538.00</td>
<td>5,538.00</td>
<td></td>
</tr>
<tr>
<td>Rabigh Steam</td>
<td>6</td>
<td>1,572.00</td>
<td>1,572.00</td>
<td></td>
</tr>
<tr>
<td>Rabigh CC GAS</td>
<td>12</td>
<td>592.00</td>
<td>666.70</td>
<td></td>
</tr>
<tr>
<td>Rabigh CC</td>
<td>3</td>
<td>375.00</td>
<td>392.00</td>
<td></td>
</tr>
<tr>
<td>Rabigh Gas (Extension)</td>
<td>28</td>
<td>1,652.00</td>
<td>1,820.00</td>
<td></td>
</tr>
<tr>
<td>Jeddah 3</td>
<td>35</td>
<td>1,618.00</td>
<td>1,733.90</td>
<td></td>
</tr>
<tr>
<td>Makkah</td>
<td>18</td>
<td>761.88</td>
<td>751.80</td>
<td></td>
</tr>
<tr>
<td>Madinah</td>
<td>9</td>
<td>64.00</td>
<td>67.80</td>
<td></td>
</tr>
<tr>
<td>Taif</td>
<td>6</td>
<td>91.00</td>
<td>106.90</td>
<td></td>
</tr>
<tr>
<td>Yanbu</td>
<td>3</td>
<td>45.00</td>
<td>48.00</td>
<td></td>
</tr>
<tr>
<td>Isolated Power Plants</td>
<td></td>
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<tr>
<td>Tabuk 1</td>
<td>4</td>
<td>64.00</td>
<td>67.80</td>
<td></td>
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<td>Tabuk 2</td>
<td>15</td>
<td>841.86</td>
<td>841.20</td>
<td></td>
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<tr>
<td>Duba</td>
<td>9</td>
<td>135.00</td>
<td>162.00</td>
<td></td>
</tr>
<tr>
<td>AlWajh</td>
<td>3</td>
<td>45.00</td>
<td>54.00</td>
<td></td>
</tr>
<tr>
<td>Total Load Capacity</td>
<td>13,597.16</td>
<td>14,035.30</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Ten PPs are linked to the main network in the SEC-WRB region, representing 92% of the generation capacity. The other 4 PPs are isolated from the network, and usually are remotely located next to small cities.

Figure 1.9: The SEC-WRB “connected” Power Plants
1.2.2-b Transmission Sector

In the SEC-WRB, PPs are connected to main power transmission lines network, streaming high voltage electricity into it. The main function of this network is to distribute energy to demand points, and to allocate the demand to the PPs. With the PPs’ capacities in one pool, stable and continuous power service to consumers can be more assured.

For the 4 PP’s separated from the main network, power is generated and distributed locally using significantly smaller separated transmission grids. The SEC has plans to connect as many PPs and networks as possible, to improve system reliability. They are already working on connecting the four regional networks. Figure 1.9 shows the SEC-WRB’s current connected PPs and networks. Figure 1.10 shows the KSA-wide network, and Figure 1.11 shows the future connection projects planned.

Figure 1.10: Overhead transmission lines map.
Figure 1.11: Future for the overhead transmission lines plan.
1.2.2-c Distribution Sector

Different sizes of transformers convert the high-voltage current into mid-voltage and then low-voltage current. They are connected to every building or consumer facility. The small transformers, underground power cables and the electricity meters at each building are the main technical assets of the Distribution Sector.

This sector deals with customer services, power sales, local network expansion and maintenance. They own and run sales offices, low-voltage maintenance facilities and spare parts warehouses. The top management of this sector represents the SEC at any external negotiation, interaction or decision-making situation in the community.

Figure 1.12 illustrates the mechanism of generating, transmitting and distributing power services at SEC-WRB. The two objects (OMPD) and (LDC) will be explained shortly.
1.3. The current O&M Scheduling procedures in SEC-WRB

1.3.1. The involved departments
Two units of the SEC-WRB are involved in generation and maintenance scheduling procedures. These units were presented as two objects in Figure 1.11.

1- First unit is the Load Distribution Center (LDC). The LDC’s main function is to monitor the overall network on a real-time basis. Also, Future demand forecasting is one of the most important outputs of the LDC for both long-term and short-term power demand.

2- The second unit is the Operation and Maintenance Planning Department (OMPD), located in the SEC-WRB’s head-quarters at Jeddah. In coordination with O&M planners in each PP, the OMPD is concerned with setting up and monitoring the execution of generation and maintenance plans. The OMPD takes into consideration the expected demand information received from the LDC.

1.3.2. Types of maintenance activities
There are 3 types of maintenance activities in the SEC: 1) Preventive maintenance, according to the standards, 2) Corrective maintenance, (to rectify failures), and 3) Maintenance projects, which includes upgrades or major changes in the GUs.

The GMS is concerned with preventive maintenance (PM). It is a deterministic model of which job activities must be performed for every GU as per its manufacturing manual. There are PM scheduling standards for every GU, and they differ according to the GU’s technology, manufacturer, and fuel type, (see table 1.2).

1.3.3. Scheduling time horizon
The OMPD produces the schedule annually. The one year usually starts with the coming one maintenance season (winter) with the one peak-generation season (summer) following it. The rapid growth of both demand and generation capacity couldn’t allow for a reliable schedule with a longer planning horizon.
1.3.4. Preparing the O&M master plan

The planning specialist in the OMPD receives next year’s demand from the LDC, and starts preparing the master GMS plan for the coming year in coordination with the O&M planners in each PP. This GMS is a monthly time-unit plan. It considers both generation and maintenance activities, and they call it the Operational plan (see Table 1.3). Another Maintenance plan is prepared simultaneously, which is only concerned with the maintenance activities, covers the whole year, and shown in weeks. It illustrates the type of maintenance, the starting time and the expected duration for each GU subject to maintenance (See table 1.5).
1.3.5. OMPD Schedule scheme and contents

The GU’s Planning Table is prepared in Excel. There are 185 tables representing the 185 GUs distributed among the 14 PPs. Each excel sheet represents one PP, and has all the GUs in that PP stacked above each other on the sheet. Table 1.3 is an example of GU #8 in Makkah PP. There are 18 GUs in that PP. The SEC planners walk through those tables manually, trying to satisfy the generation of demand, and to schedule the right preventive maintenance activities.

Table 1.3: GU Planning table example

<table>
<thead>
<tr>
<th>U #</th>
<th>S.F.C</th>
<th>Generation</th>
<th>Fuel Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.4011</td>
<td>263.334,000</td>
<td>87,016,780</td>
</tr>
<tr>
<td>2</td>
<td>0.4075</td>
<td>19,405,000</td>
<td>8,467,022</td>
</tr>
<tr>
<td>3</td>
<td>0.4037</td>
<td>0.2030</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0.3095</td>
<td>0.3092</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0.2873</td>
<td>0.2873</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>0.2873</td>
<td>0.2873</td>
<td>0</td>
</tr>
<tr>
<td>7</td>
<td>0.4270</td>
<td>0.4270</td>
<td>0</td>
</tr>
<tr>
<td>8</td>
<td>0.4246</td>
<td>0.4246</td>
<td>0</td>
</tr>
<tr>
<td>9</td>
<td>0.4203</td>
<td>0.4203</td>
<td>0</td>
</tr>
</tbody>
</table>

Horizontally, column (A) is the GU ID, column (B) lists the technical planning items, column (C) shows last year readings of each planning item listed in (B), the 12 columns (D to O) represent the 12 months in the next year of the O&M plan, and column (P) calculates the planning items’ totals for the whole year plan. Vertically, specifically in column (B), the 16 technical planning items are described in Table 1.4.
<table>
<thead>
<tr>
<th>#</th>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Capacity</td>
<td>GU generating capacity, according to operations’ records in megawatts.</td>
</tr>
<tr>
<td>2</td>
<td>Service Hrs</td>
<td>The planner manipulates the number of service hours assigned to the GU each month. The lower limit of this field is zero, and the upper limit is the Available Hours each month (see field # 4).</td>
</tr>
<tr>
<td>3</td>
<td>Starts</td>
<td>The number of Start-ups in the month (bringing the GU from shut-down to generation). In some GUs, the Start-up process has an equivalent service hours’ factor (which is not equal for all GUs).</td>
</tr>
<tr>
<td>4</td>
<td>Avail Hrs</td>
<td>The Available Hours is the number of hours the GU will be available to generate each month. The lower limit is zero, and the upper limit is the number of days/month times 24. What mostly affects this number are the maintenance activities requiring the GU to be out of service.</td>
</tr>
<tr>
<td>5</td>
<td>Eq. S/H</td>
<td>The Equivalent Service Hours, is simply the summation of the planned generation hours in field #2 added to the equivalent service hours caused by the Start-up. [Eq. S/H (#5) = Service Hr. (#2) + (Starts (#3) X Start-up factor)]</td>
</tr>
<tr>
<td>6</td>
<td>S/H S. OH</td>
<td>This is the cumulative service hours since the last major overhaul for this GU. When the planner manipulates the generation service hours assigned for this GU in field # 2, the field is automatically changed.</td>
</tr>
<tr>
<td>7</td>
<td>Starts S.OH</td>
<td>This is a monitoring field that calculates, the number of start-ups since the last major overhaul.</td>
</tr>
<tr>
<td>8</td>
<td>Eq. S/H S.Oh</td>
<td>The equivalent service hours since the last major overhaul. [EQ. S/H S.Oh (#8) = S/H S. OH (#6) + (Starts S.OH (#7) X Start-up factor)]. This field affects the whole scheduling process. The planner monitors the GU service hours between the previous and the next major overhaul, and decides when to schedule the GU for PM activities.</td>
</tr>
<tr>
<td>9</td>
<td>S/H S. C.</td>
<td>The number of service hours since commissioning (since the GU first brought into service). This figure is never set back to zero.</td>
</tr>
<tr>
<td>10</td>
<td>Starts S.C.</td>
<td>The number of start-ups since GU commissioning (brought into service). This figure is never set back to zero.</td>
</tr>
<tr>
<td>11</td>
<td>Eq. S/H S.C.</td>
<td>Equivalent service hours since GU commissioning, (brought into service). [EQ. S/H S.C.(#11) = S/H S.C.(#9)+ (Starts S.C.(#10) X Start-up factor)]. This field is important to decide when to schedule the GU’s Turbine for overhaul maintenance. It is helpful to monitor the overall GUs performance. This figure is never set back to zero.</td>
</tr>
</tbody>
</table>
### Table 1.4: Continued

<table>
<thead>
<tr>
<th>#</th>
<th>Item</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>GOF</td>
<td>Gross output factor is the average load to be assigned to the GU, as a percent of total capacity. (% of Capacity (#1))</td>
</tr>
</tbody>
</table>
| 13 | Service Factor | Percent of service hours relative to the total month hours  
[Service Factor= % (Service Hr. (#2) / (month days X 24H))] |
| 14 | SFC         | Specific fuel consumption. The average fuel consumption rate, in (tons/hr). This rate changes non-linearly with the generation load (GOF in field #12). |
| 15 | Generation  | The total Energy generated by the GU each month, equals the number of service hours (#2) multiplied by the gross output factor (#12) multiplied by the GU’s capacity (#1).  
[Generation = Capacity X Service Hr. X GOF]. |
| 16 | Fuel Cons   | The total fuel consumption in the month, equal to the total generation multiplied by the fuel consumption factor.  
[Fuel Cons = Generation (#15) X SFC (#14)]. |

### Table 1.5: Sample of the Maintenance Plan

<table>
<thead>
<tr>
<th>Month</th>
<th>No.</th>
<th>Type</th>
<th>Use</th>
<th>Description</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Legend:**
- T: Turbine Major/Overhaul
- C: Generator Major/Overhaul
- Q: Generator Rewinding
- A: Annual Inspection
- O: Operation
- S: Oil Change
- D: Dispersal Change
- C: Control System
- T: Transformer
- P: Power Plant
- M: Minor Inspection

**Filler Notes:**
- **#2:** 1405
1.3.6. Scheduling goals, rules, and steps

The planner’s mission can be stated as a set of goals the plan should achieve, a set of rules and constraints, and some steps to be executed.

1.3.6-a Goals:

1) **Satisfying Demand** is the most recognizable result by the end user, and the main goal of the company.
2) **Providing PM on time**, to avoid losing the manufacturing warrantees, increase the GU’s reliability, and to maximize the GU’s availability during the summer season.

1.3.6-b Rules:

1) The summer peak-generation season starts in May and ends in October. Maintenance activities should not be scheduled during this period.
2) Planners give priority to the GUs with higher service hours’ records to be maintained, to reduce the failure probability during summer.
3) Every GU has two main components, Turbine and Generator. Turbine maintenance steps follow the standards described in Table 1.2. Generators need only major overhaul (MO) every 50,000 service hours. Planners usually schedule the MO for both turbine and generator in the same time.
4) Each PP must have a minimum number of GUs in the generation stage, even if other PPs can cover the demand. This is to secure the service for local areas, and to balance the voltage levels in the network’s overhead lines.

1.3.6-c Steps:

1) Using the GUs planning tables (like Table 1.3), the planner uses his experience to decide which of the GUs needs to be maintained this year, and which can be delayed until next season. And then he distributes GUs’ maintenance among months without specifying what time during the month.
2) The planner distributes the generation service hours, vertically among the GUs in each month (Columns D to O), and horizontally among the months for each GU (Field # 2). In vertical, for each month, the planner makes sure that the total generation of the PP meets the needed generation assigned by LDC for this PP. In horizontal, the planner makes sure that the plan is compatible with maintenance standards.
3) The relationship between the gross output factor GOF (Field #12) and the specific fuel consumption SFC (Field #14) is non-linear. This makes it difficult to assure efficient schedules for the PP, and impossible for the entire network. The planner sets the GOF and SFC to the averages from last year’s records, and then adds 5% to 8% depending on the expected demand growth forecasted by the LDC. This addition varies depending on if new GUs were introduced to the network or not. Until he finishes his final master O&M plan, controlling fuel consumption is not his primary goal.

4) It takes 2 months from starting data collection from PPs, until finishing the first version of the O&M plan. And at least 2 months to coordinate between headquarters and O&M planners in all PPs.

1.3.7. Notes and observations on the current procedures

1.3.7-a Master plan’s resolution and robustness

The resolution of the O&M master plan is in hours among months. The gap between the two scales of time-units (hours to months) weakens the robustness of the plan for both operations and maintenance activities.

For maintenance; the plan tells the amount of time the GU is unavailable for generation (or available for maintenance) during the month, shown in hours only, but it doesn’t state which time within the month.

For generation; since demand differs from week to week, the generation load for each GU will vary. The looseness of the GUs’ service-hour availability means that the results of generation load and fuel consumption cannot be estimated accurately. The planner can do nothing but use average load levels (GOF #12) and fuel consumption (SFC #14). Using those averages on large batches of service hours (which can reach 744 hours/month) reduces the master plan functionality.

To overcome maintenance issues, as previously noted, another plan for maintenance scheduling is designed simultaneously with the O&M master plan. This appears like a reasonable procedure, but in fact, the existence of two plans makes decision making more difficult, and requires more coordination. To overcome the power variations, continuous
follow-up between the LDC, OMPD and O&M planners in each PP is conducted throughout the year on a monthly, weekly and daily basis. In a daily routine, the LDC issues a prediction for the next 24 hour energy demand in hourly units, sends it to the OMPD planner at headquarters to compare the generation data, and then updates each PP to execute its assigned portion of energy.

1.3.7-b Critical review

- Decision of which GUs to be maintained this year and those transferred to next year is taken by vision and experience. This experience should be translated into a numerical constraint that can model and standardize this filtering procedure.

- Maintenance cost is not considered during the planning stage, and there is no estimation for that total cost accompanied with plan issuance.

- Human resources are not considered. If any PP has a shortage in maintenance manpower, OMPD either transfers technicians from other PPs (for additional cost) or uses outsourced contractors (even more expensive).

- The plan only estimates the amount of fuel consumption, with no consideration for the cost of different types of fuel. This, in addition to the uncertainty of maintenance cost, results in a master plan without a total cost. These figures can help management to compare between plans, and to make other strategic decisions. The SEC, for sure, does estimate the O&M costs annually, but it is not part of this planning procedure.

- The planner concentrates on the generation and maintenance of one PP at a time. This scale makes it relatively impossible to do any scheduling trade-offs in generation assignments or human resources between PPs.

- From a scheduling and planning point of view, numerical indicators related to availability, spinning reserve, idle stages, or maintenance capacities can efficiently assess the final plan. These indicators should be considered during the planning process.
1.4. Problem Statement

The final expected output of this research is to develop a mathematical problem-solving procedure for the GMS. As an Integrated GMS scheduling tool, its characteristics should reflect the real case in the SEC as accurately as possible, in a challenging time frame. Characteristics are technical and financial in nature, and expected to achieve but not limited to the following:

1. The maximum coverage for consumption demand,
2. The minimum total cost, for both generation and maintenance,
3. The most accurate reliability measurements, according to predefined constraints.

Various measurements that can be applied for both generation and maintenance. One of the expected outputs of this research is to investigate the current SEC’s criteria for O&M.

Constraints can be obtained from the SEC’s procedures, from other similar companies in the field, or from previous literature.

This problem-solving tool should be coded as a computer program, to make it more accurate to use than the current traditional planning procedure. In the following, Chapter-2 will compare the SEC with previously investigated GMS models. Chapter-3 will introduce a mathematical model for the SEC. Chapter-4 presents the research solution methodology. Chapter-5 demonstrates the experimental results. Chapter-6 concludes the research findings and future challenges.
CHAPTER 2:

2. LITERATURE REVIEW

Basically, the GMS problem is expected to result in one major output, which is a timely plan of when to maintain the GUs, when to run them, and at what level of load for each time unit during planning horizon. From there, the problem objectives and constraints start to widely vary. This problem has been well researched. Research differs according to either the problem structure, or the modeling features.

In the first section of this chapter (2.1. Problem Structures), different environments of the GMS are categorized, and how the Saudi Electricity Company (SEC) fits in each categorization. The second section (2.2 Modeling Features) concentrates on problem constraints. Appendix I contains a summarized table of the 98 papers surveyed.

2.1. Problem Structures

Variances of administrative, financial and technical production conditions are reflected mathematically either in the main objective of the problem, or among the various constraints. “It is however difficult to define a typical organization because several structures are possible”, Froger et al. [101]. In general, variances between the GMS structures can be classified in several ways. For example; Energy markets, Network components, Data type and other characteristics influence the overall problem objective and constraints.

2.1.1. Deregulated Versus Regulated Energy Markets

The top view in the energy market environments can be categorized as: Regulated markets and Deregulated markets. The difference between them is administrative in nature, but ultimately creates major differences in performance standards, which are reflected in the GMS problem structures.

The common concept of deregulated energy is that it is an open market. Any supplier can enter and provide services to customers. Neither price nor market share are limited or controlled by higher authorities (governments). Competition in this type of market is the main factor that controls decision making. That is why when a problem like GMS is to be tackled in this atmosphere, the common main objective is to maximize profit.
Papers describing deregulated markets explain the role of three major parties; the generation companies (GENCOs), the transmission companies (TRANSCO), and the independent system operator ISO. The ISO is responsible for ensuring the social and economic welfare of the market while keeping the system safe, and ensures the smooth running of the system in terms of reliability and security [101].

Billinton and Abdulwhab [07] discussed the fact that in a deregulated utility environment, system capacity shortages can be created by a lack of coordination in scheduling generating unit maintenance among service providers. This can be avoided by having the GMS solved and managed by the ISO. The objective in scheduling preventive maintenance should be to ensure that the resulting risk does not exceed a predetermined acceptable level.

CONEJO et al. [19], (as an example of other papers listed in Appendix I), proposed a model to solve the GMS problem in a deregulated market. The challenge was to maximize the providers’ profits which conflicts with the reliability objective of the ISO. The paper proposed a three-step procedure. Step 1: formulate and solve the problem maximizing reliability. Step 2: reformulate and solve the problem maximizing profit for each producer. Step 3: coordinate,
using revenue-neutral incentives/disincentives, between the ISO and each provider to find acceptable solutions.

Between 1998 and 2000, Marwali & Shahidehpour [52-56], presented 5 papers which tried to solve different combinations of generation, transmission and maintenance scheduling in deregulated markets. Later in 2002, Shahidehpour et al. [91] published a book that touched a wide range of market operations in electric power systems. More details about this type of market components and interactions can be found.

A regulated market usually is a production environment where the governing bodies have more control of market characteristics like pricing or even market share. Taking into consideration that energy services depend on three main activities (generation, transmission and distribution) the government may own and control the transmission network, and leaves the generation and distribution sales open for competition.

A regulated market provides a more stable competitive environment. When a planning problem like the GMS is considered, the common objectives are to minimize the cost, and to maximize reliability. The wholesale prices and market shares may be fixed.

Since regulated systems sometimes allow for more than one provider to exist, the best field for investors is generation. Instead of tackling the customer services issues, running a power plant stands as a more reliable investment with less problems. There will be one customer, which is the regulation authority. More time and space will be available to concentrate on the investment objectives within the technical scope of energy production.

The GMS problem in the regulated environment had been tackled by many papers. Some selected ones will be given a more concentrated review in the Section 2.2.

2.1.2. Monopoly systems

Monopolies are a more controlled version of a regulated market. Political aspects, an unattractive market, or other reasons usually play a rule in producing such an environment.

In monopoly systems, there is no fear of losing market shares. The main goal of such organizations is to maintain some certain levels of reliability while aiming to minimize cost. This is the exact case in Saudi Arabia as a regulated production environment, where the SEC
represents a typical monopoly organization providing power service for all types of consumers. Papers that solve the GMS problem can have one of three types of objectives; maximizing reliability, minimizing cost, or reliability and cost multi-objective models.

Figure 2.2 shows the number of papers that solved the GMS problem in the deregulated and regulated markets. Papers dealing with the regulated markets are classified according to their objective functions, and the SEC case is identified in both classifications.

Figure 2.2: Nature of markets and objectives of the GMS problems solved in the literature.

*There are 40 Papers that have the same objective and market nature of the SEC*

### 2.1.3. Deterministic Inputs Versus Uncertain Inputs

The uncertainty of GMS problems mainly presents in the sudden failure of GUs, unpredicted increases in demand, or maintenance resource shortages, which result in being unable to adhere to the maintenance schedule. These undesirable events were dealt with by a remarkable quantity of papers. Probabilistic researches mostly considered one of the first two points; the effect of probabilistic demand or GU failure rates. But they are never considered together. The 40 Papers obtained from figure 2.2, are classified in figure 2.3 according to their data input types. 22 papers among them have deterministic scheduling inputs.
2.1.3-a Uncertain Demand

The probability that the power consumption is going to be higher than expected usually called the loss of load probability (LOLP). Planners tend to consider this probability when they have unreliable data, or resource shortage expectations. Papers considering stochastic inputs of GMS in regulated markets assumed different scenarios of (LOLP), and then tried to satisfy demand in each one of those scenarios [3, 9, 10, 12, 13, 37, 39, 40, 43, 50, and 64].

2.1.3-b Uncertain Failure rate

Because breakdowns can be unexpected, some papers presented a forced outage rate (FOR) as the probability of a unit’s failure (GU breaks down). Many papers considered a fixed percentage of the capacity to represent FOR, this may unrealistically elevate the unsupplied energy cost, which many papers considered. [6, 7, 17, 31, 36, 38, 41, 51, 59, 63, and 70]

Modeling uncertainty is an attempt to reflect the real production environment through scheduling process. It is important to note that generation planners in the field usually consider several common types of operating reserve methodologies. Those types can be used at different levels of generation process [203-205], and determined according to the organization policies, so as to be ready for any uncertain incident. In fact, capacity reserve methodologies tend to convert the uncertain inputs of the problem into deterministic ones. These deterministic inputs are just the technical performance standards the organization has set for itself and is committed to follow.

In the SEC, and during scheduling process, LOLP and FOR are not considered probabilistically. There is no cost for unsupplied demand, and sudden failures are treated only through the SEC’s predictive or corrective maintenance policies as needed. Planners are asked to satisfy the forecasted demand, schedule appropriately programmed maintenance, and to follow the company’s reliability standards for operating reserve. More details of the operating reserve policy of the SEC can be found in (section 1.3.2-e), and (section 3.2.3 & 3.2.4).
Among the 40 Papers that have the same objective and market nature of the SEC, 22 papers have deterministic scheduling inputs.

2.1.4. The GMS problem’s boundaries

Most of the constraints explained in this section (2.1.4) are not applicable to the SEC’s model investigated in this research, but mentioned here to give an idea of the dimensions and limits the GMS problem can have, and to compare the situation at the SEC with other literature. The reader can find a comparison summary in part (2.1.4-e) of this section.

Interactions the generation, transmission and distribution sectors, with suppliers and contractors can affect the planning process. Those interaction limits should be defined to draw the boundaries of the GMS problem.

2.1.4-a Large-Scale Energy Management (LSEM)

The French Operational Research and Decision Support Society ROADEF, jointly with the European Operational Research Society EURO proposed a challenge problem in 2010. They introduced the ROADEF/EURO challenge called “A large-scale energy management problem with varied constraints” [301]. Which was a very large-scale GMS problem.

Their problem considers a system that contains almost every type of thermal power generation. Multiple types of fuel (nuclear, coal, fuel oil and gas) are considered. Various constraints, regarding safety, maintenance, logistics and plant operation are also considered. It must lead
to production programs with minimum cost. Twenty-six senior research teams and another 17 junior teams participated in the ROADEF/EURO challenge.

The objective is to plan the production and refueling of the generating system while minimizing the overall expected cost of non–nuclear plants and the refueling costs of nuclear plants. The problem was proved to be NP-hard by Godskesen et al. [39].

2.1.4-b Refueling management

Fuel management, or Refueling, can create significant constraints in the GMS problem. Porcheron et al. [98] solve the LSEM problem as two dependent sub-problems: 1. determining a schedule of plant outages for maintenance and refueling, and 2. determining an optimal production plan to satisfy demand (multiple scenarios generated, and then solve for the quantity of energy to produce at each plant in each time unit for each scenario).

2.1.4-b-1. Refueling windows

Sometimes refueling activities can only be performed when a GU is off-line. Anghinolfi et al. [03] considered two types of power plants: power plants that can be refueled while operating, and power plants that need to be shut down for refueling and ordinary maintenance (typically nuclear plants). In this research, all the GUs in the SEC network are of the first type.

2.1.4-b-2. Fuel amount constraints

If the fuel amount to be used by any individual GU, or group of GU is limited, the generation load assignment will be affected, and the maintenance schedule should be adjusted accordingly. Especially when operation optimization is the goal, load levels of the GU should be considered because it reflects directly on generation efficiency.

Al-Khamis et al. [02] show that for some utilities, contractual obligations limit the amount of fuel burn at a unit may include yearly or monthly maximum and minimum limits. Some power plants have a maximum storage capacity for fuel, Muñoz-Moro & Ramos [61] (Fourcade et al., 1997 [34]; Khemmoudj et al., 2006 [44]) are concerned with planning shutdowns in production to carry out refueling and maintenance operations; in this case the fuel quantity to supply the next period is known in advance and not a problem variable.
2.1.4-c  GMS with network constraints

Network constraints usually refer to the transmission capabilities of the power grid including all network components of overhead lines and transforming stations.

These constraints put some limitations on the network regarding power energy providing ability in certain locations. GMS planners may need to alternate the generation load assignment and generation maintenance tasks between power plants to satisfy the transmission limitations of the network.

Chen and Toyoda [18] and Leou [49] assume that there is a limitation on the capacity of each segment of the transmission lines. In some cases, like the Brazilian system (Silva [68]), the transmission grid causes various bottlenecks due to large distances among the plants and load centers, giving rise to relevant congestion costs. Also, most research assumes that maintenance crews can only perform maintenance for GUs within their power plants, and it can be one unit only at a time period to be maintained.

In the SEC, all power plants are streaming power to the same pool, which is called the Power National Grid (PNG). The Saudi PNG has no limitations relative to transmission capabilities that need to be considered in the GMS, at least not in the near future. In addition, maintenance personnel can be transferred from their base power plants, in order to perform maintenance in other locations, but for extra cost.

2.1.4-d  GMS and TMS

The maintenance of the transmission overhead lines is another maintenance activity in the network that can also affect the transmission capacity of the network. The difference between this concept and the previous one (4-c), is that the transmission maintenance scheduling problem (TMS) may create some temporary issues in the network capacities. The TMS planner designs and reconstructs the maintenance schedule according to the technical inputs of network and the forecasted demand. In this case, coordination needs to exist between the generation and transmission sectors’ planners in order to plan, execute and follow up with the generation scheduling and maintenance activities.

TMS and GMS has been formulated in some research as another boundary level of the GMS problem structure, with another level of constraints. The objectives still varied between
reliability, cost and profit, or a mix of them. Only 5 out of 76 papers considered the TMS problem while solving the GMS [1, 36, 38, 52, and 54]. As previously noted, transmission issues are out of the scope of the GMS planner at SEC.

2.1.4-e The pure GMS problem

In the most common type of GMS problem, 75% of the papers try to solve the pure GMS, where only the generation units’ technical and financial inputs are considered in building the generation and maintenance schedules.

In regard to the problem structure, the pure GMS problem has considered other objectives too. Maximizing reliability, minimizing cost and maximizing profit are the most common objectives. Sometimes, the problems solved consider a multi-objective function.

The pure GMS is the case in Saudi Arabia. The objective is to minimize the total cost of generation and maintenance, combined with reliability control factors. The 22 papers matching the market nature and certainty classification of the SEC (figure 2.3) are refined below (figure 2.4) according to their scope boundaries. There are 14 papers matching the case of SEC. The next section (2.2) will concentrate on the solution methodologies to solve similar problems.

Figure 2.4: The GMS boundaries refining

Out of the 22 papers filtered in figure 2.3, 14 have the same GMS scope as the SEC
2.2. Model Features

For efficient review (the GMS literature obtained from (2.1.4-e)), all possible subjective and objective features of those models have been analyzed, as well as the current procedures of GMS planning at the SEC. These features are sorted into four groups and compared with the situation of the SEC. Tables 2.1, 2.2 and 2.3 illustrate this comparison. Table 2.4 summarizes the findings.

2.2.1. Features of Group 1 and 2

In Table 2.1, group #1, the features commonly agreed on, show that all papers agree on two specific features compatible with the SEC. First, the maintenance duration for any GU is fixed and predetermined. Second, the execution of this maintenance will be continued, not to be interrupted, and the GU will not be considered as part of the total generation capacity until that specific maintenance period is finished.

In Table 2.1, group #2 listed three features that are related to the size and planning horizon. While the 2-year planning horizon will be considered for the SEC’s model, most of the papers considered a one-year (single season) planning horizon and chose weeks to be the time unit. This will give the problem a planning horizon of 52 periods. Lin & Huang [77] select a 5-day time unit, for a planning horizon of one year. They were trying to make the problem more realistic, with a more flexible selection of different schedules.

Although it is known that shorter time-units can increase the computation time exponentially, 2014 Fattahi et al. [30] claim that they are trying to “introduce a new practical GMS for centralized electrical power systems”. The paper considered the planning of operational hours during each week time-unit period (168 hours) in order to schedule maintenance outages for each GU according to its cumulative operational hours. In that case maintenance outages are going to be scheduled in week periods.

Out of all papers reviewed, Fattahi’s model is the most compatible to SEC procedures which will be discussed in part 2-2-3. In this research, scheduling time-units will be in weeks. The number of GUs in the SEC problem is as large as 150 GUs, while the largest application considered in all the other papers reviewed is 60 GUs.
### 2.2.2. Features of Group 3

The features in group #3 represent deeper details of the GMS models. These features can be considered flexible. In other words, even if the feature does not match the SEC model, slight modifications can make it compatible. For example, in (feature#6), most of the papers assumed that all maintenance jobs are to be scheduled and completed during the planning horizon. Two papers considered a rolling horizon. Burke & Smith [11] and Digalakis & Margaritis [23] constructed their models such that the planning horizon “wraps-around”, and maintenance jobs can continue at the start of the following planning horizon. Thus, a rolling plan is generated. In the field, consecutive seasons always affect each other. Only these two papers are close to the target model for the SEC, where a multi-season horizon is expected to be solved.
Table 2.2: Model Features Group (3).

<table>
<thead>
<tr>
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<th>F #</th>
<th>Class</th>
<th>Feature:</th>
<th>SEC</th>
<th>Matches</th>
<th>Mismatches</th>
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<td>12</td>
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<tr>
<td></td>
<td>7</td>
<td>model</td>
<td>Operating Cost differ per Unit</td>
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<td></td>
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<td>G</td>
<td>Minimum Load Generation</td>
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<td>4</td>
<td>10</td>
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<td></td>
<td>9</td>
<td>model</td>
<td>GU Maint. Cost can differ per time</td>
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<td>10</td>
<td>M</td>
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<td>0</td>
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<td>8</td>
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<td></td>
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<td>8</td>
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<td></td>
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<td>9</td>
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<td></td>
<td>14</td>
<td>G</td>
<td>Constraint Violation</td>
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<td>5</td>
<td>5</td>
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<td></td>
<td>15</td>
<td></td>
<td>various energy system</td>
<td>Yes</td>
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</table>

1991 [66] No No No Yes NA Yes Penalty F. No
1992 [77] No NA No Yes No No In periods No No Yes
1993 [14] No NA NA No No No NA No No
1995 [47] No No No Yes Fixed In periods Yes Yes Yes
1998 [35] No Yes No Yes Yes NA Yes No No
2000 [11] Yes No No Yes Yes NA No No No
2000 [25] No No No No Yes Fixed No No No
2002 [23] Yes No No Yes NA Yes Penalty F. No
2008 [62] No No No No Yes NA No No Penalty F. No
2011 [46] No Yes No No No NA No No Yes
2011 [65] No No Yes NA No No Yes Fictitious GU Yes
2014 [27] No Yes Yes No No No No No No
2014 [30] No Yes Yes No No Yes No No No
2014 [60] No Yes Yes No Yes No No No Yes

Matches 2 5 4 9 6 0 1 8 8 9
Mismatches 12 9 10 5 8 14 13 6 6 5
Feature-7 consider the variation of generation cost between units. Even within the same thermal-based energy in the SEC, GUs with different technologies consume different types of fuel and generate power with different cost parameters. Moreover, Feature-8 reflects the fact that every GU has a lower generation capacity, this is the common situation in the SEC and many other power generation fields. In feature-9, some papers assumed that maintenance cost can differ per time. The maintenance cost in the SEC model is fixed.

In feature-10, many papers presented the precedence constraint, implying that for a certain two GUs neither can be maintained at the same time, or a fixed sequencing order to maintain one of them before the other one. Although 7 out of the 14 papers had this constraint, it is not common, and inapplicable to the SEC. The GUs in the usual common setup are separated, and maintaining one is totally independent from the other ones.

This means whenever the GUs’ maintenance priority exists, (feature-11), it is more relevant to be evaluated and solved by the proposed model itself. Priority changing with time between GUs according to specific technical parameters. This rotating priority is the real case in the SEC and most of similar fields and it is not common to be fixed.

Feature-12, shows that some papers considered that the GU cannot be scheduled for maintenance outside a specific time window. Some papers proposed a previously fixed window among planning horizon, others proposed the maximum possible window with free allocation, and others just neglected this constraint. This is one of the unique model features of the SEC model. This maintenance window is considered, but it is dynamically changing for each GU separately, according to the amount of generation hours assigned to it.

In feature 13, some models assumed a certain cost for unsatisfied energy demand, or any other model constraints’ violation. Others, in features 14, used a penalty function for such a situation. Saraiva et al. [65] added a fictitious GU to the existing ones in order to model the energy not supplied. This generator will have a large generation cost, so it should only be used as a last strategy to balance the generation with the demand. Also, papers in feature 15 considered an additional supplied energy generated by other sources or systems like hydro or nuclear systems. The power system at SEC is only thermal, and the idea of unsupplied energy demand is a totally unacceptable option.
2.2.3. Group 4 features

The fourth group illustrates the features that have a significant effect on the model. If the feature conflicts with the SEC procedures, the model is incompatible, and cannot satisfy the scheduling objectives.

Feature-16 is an objective function components feature. Although the objective of all papers is to minimize cost, most of them define cost by the summation of operation and maintenance cost, but there were four papers, (Kralj & Petrovic [47], Kovács et al. [46], Saraiva et al. [65], and Charest & Ferland [14]) which tried to minimize maintenance cost only without taking generation cost into consideration.

In cost regards, features 17-18 show that only El-Amin et al. [25] and El-Sharkh [27] considered a non-linear generation cost calculation, depending on the fuel consumption. The first one considers an equation of a second degree with three input variables, and the second one considered the GU heat rate and a continuous fuel cost variable of that specific GU. The rest of the papers only assumed a constant cost per output of generated power ($/MWh), which is not accurate enough for the SEC model. Simply, the GU’s load generation output is non-linear with amount of fuel consumption. In (Feature-19), only Fattahi et al. [30] proposed a model that consider minimum time to change the status of any GU from generation state to shut-down or vice versa. The non-linearity of generation cost, and the minimum Up-and-Down time of GUs are true characteristics applicable for the SEC’s generation procedures.
Table 2.3: Model Features Group (4).

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<th>Yes</th>
<th>Yes</th>
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<td>NA</td>
<td>NA</td>
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<td>[65]</td>
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<td>[60]</td>
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**Group #**

<table>
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<th>Class</th>
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<td>F #</td>
<td>Objctv Cost includes O &amp; M</td>
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<th>16</th>
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<th>Fuel model</th>
<th>model</th>
<th>model</th>
<th>M</th>
<th>M</th>
<th>M</th>
<th>reserve</th>
<th>reserve</th>
<th>M</th>
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**Matches** 9 2 1 1 0 2 3 1 1 0 1 2 8 1

**Mismatches** 5 12 13 13 14 12 11 13 14 13 12 6 13
The SEC network covered in this study contains 7 power plants (PPs), feeding the same pool of the connected overhead line transmission network. But those PPs still must be separated in the model for two reasons. First, a portion of load must be generated from each PP to elevate the voltage and reduce the energy lost in the transmission lines. Second, maintenance crews can be assigned to any GU at any PP other than their base PP (incurring an additional maintenance cost). Moreover, when the maintenance manpower capacity is insufficient, and cannot be provided from other PPs, a more expensive option of outsource contracting is always available and usually utilized by SEC. Accordingly, there is no limit for the number of GUs that can be maintained at the same time, if the generation demand is satisfied by the other streaming GUs.

Features 20-23 show the following: Kralj and Petrovic [47] assumed GUs grouping into PPs without any reflected effect on the model depending on that grouping (which is different). Kovács et al. [46] provide the same grouping and calculate the travel cost of each crew in wind farm energy, but with major variation between their model and any thermal power systems. Mollahassani-pour et al. [60] provided a division by type of power technology, but in the same pool of resources. The model didn’t assume a different maintenance cost per crew, no travel cost considered, and still limited the number of GUs to be maintained in the same time. In a totally different assumption, Lin & Huang [77] had the GUs’ grouped in PPs, to put a limit on the number of GUs under maintenance in each PP. In summary, the case of SEC, with availability of multiple options for maintenance manpower resources with different cost for any GU has never been modeled by any of the surveyed papers.

As previously mentioned, the PM schedules are usually constructed according to the operational load progress of the GU. In the SEC, as explained in Ch 1, service hours are the official planning units for planners. Scheduling the GU for PM depends mainly on standards of cumulative operation hours (Table 1.2, pp 16). Feature-24 shows that Only Fattahi et al. [30] modeled this decision-making procedure, which matches the same procedures in the SEC. Also, his model was the only model that didn’t limit the number of PM activities for any GU in the same planning horizon. If the GU was assigned an amount of generation hours that can make it due for the next PM activity, then it should be scheduled for PM even if it already received a PM activity in the same planning horizon. Those maintenance activities differ in class, time and cost (Table 1.2, pp 16). The idea of having different types of maintenance for
the same GU had never been discussed while solving the GMS, either by Fattahi et al. [30] or any of the surveyed papers (feature 25-26).

Most of the GMS models consider the reserve capacity to overcome the risk of either sudden failures or uncertain demand. Fattahi et al. [30] and Mollahassani-pour et al. [60] furnished the reserve from the excess capacity of the actual running GUs. This is the spinning reserve (also called hot reserve) which is at least equal to the largest running GU’s capacity. Since GUs are spinning, this reserve can be streamed into the network immediately whenever needed. The total reserve is another type of reserve which includes the total capacity of both running and the non-running (ready to be used) GUs. This type is usually calculated as a portion of the demand value, and has been taken in consideration in the rest of the surveyed papers. El-Sharkh [27] and Charest and Ferland [14] didn’t consider the idea of reserve at all. None of the surveyed papers has satisfied both spinning and total reserve together, but it is essential for companies (including the SEC) to satisfy both (features 27 & 28).

Feature-29 shows that Kralj and Petrovic [47] and Lin & Huang [77] made a very essential assumption, that the maintenance activities are preferred to be executed within a specific time season during the planning horizon, only the generation assignment has to be scheduled throughout the whole planning horizon. This is very true in the SEC, and since the scheduling decisions depend on the operational load, any decisions to be taken in this maintenance season are going to affect the next operation season and the following maintenance season, etc. Although Fattahi et al. [30] was the only model that considered the operational load for maintenance decisions, the maintenance in that model was continuously scheduled throughout the planning horizon whenever needed.

Kralj and Petrovic [47] presented an application case study limiting the model to execute maintenance within an interval of 31 weeks out of 52 of the complete year planning horizon. But, the maintenance decisions inside that interval was not affected by what is going on during the rest of the year. Lin & Huang [77] constructed a model and tested it on the Taiwan Power Company system. The plot of output result shows how the model was considering the demand behavior throughout the year, and avoided any maintenance activity during the peak demand months of July and August to satisfy the generation capacity requirements.
As a quick brief for this chapter, more than 90 published papers discussed the GMS modeling during the last two decades. The problem nature of the SEC production environment matches only 14 of them. Critical comparison study for those 14 models versus the technical constraints at the SEC was conducted. The closest model was of Fattahi et al. [30], and only satisfied 15 out of the 29 features that already existed for the SEC’s situation.

Table 2.4: Compatibility results of Model Features.

<table>
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<tr>
<th>Year</th>
<th>Ref #</th>
<th>Literature</th>
<th>Features Satisfied</th>
<th>Out of 29</th>
</tr>
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<td>[77]</td>
<td>Lin &amp; Huang</td>
<td>7</td>
<td>23%</td>
</tr>
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<td>2011</td>
<td>[46]</td>
<td>Kovács et al. (2011)</td>
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<td>29%</td>
</tr>
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<td>2011</td>
<td>[65]</td>
<td>Saraiva et al. (2011)</td>
<td>5</td>
<td>16%</td>
</tr>
<tr>
<td>2014</td>
<td>[27]</td>
<td>El-Sharkh (2014)</td>
<td>12</td>
<td>39%</td>
</tr>
<tr>
<td>2014</td>
<td>[30]</td>
<td>Fattahi et al. (2014)</td>
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<td>52%</td>
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<tr>
<td>2014</td>
<td>[60]</td>
<td>Mollahassani-pour et al. (2014)</td>
<td>10</td>
<td>32%</td>
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CHAPTER 3

3. THE MODEL

The first part of this chapter analyzes how the system works. The second part formulates the constraints. The third part states the objective function components.

3.1: Modeling the basic problem structure

3.1.1: GU activities and state definition

Figure 3.1 describes the regular operational rules of a typical generation unit (GU). It works like a time-scale of service-hours record, each hour of operation assigned to the GU counts towards its next preventive maintenance step. \((h_i)\) is the GU’s service hour counter, counting from zero to a maximum of \((U_{hi})\). \((L_{hi})\) and \((U_{hi})\) are the lower and upper bounds of service hours defining the maintenance window time-frame for each GU. The GU can receive preventive maintenance whenever the counter reaches to the lower window value of \((L_{hi})\). No more generation is allowed after the GU reaches the upper limit \((U_{hi})\). This process repeats itself after every preventive maintenance (PM) step, once the GU receives the due PM step, the step counter is set to zero again.

Figure 3.1 and Figure 3.2 show the different possible states for any GU. (R) is when the GU is in the ready state for generation. (On) is the generation state. (W-R) indicates the state where the GU has entered the maintenance window but can still be used for generation. (W-On) means the GU is generating, but inside the window. (Off) means the GU has exceeded its service hour limit, is turned off, and waiting to receive preventive maintenance, and (PM) is when the GU is receiving preventive maintenance (this state can exist any time after \((L_{hi})\)).

Figure 3.1: Typical GU activities.
3.1.2: GU states mathematical presentation

To simplify the model structure, three main variables will be used. \((x_i)\), \((m_i)\) and \((w_i)\) represent the Generation, Maintenance, and Window mode, respectively. Each variable of them can take on of the following values:

\[
x_{i,t} = \begin{cases} 
1, & \text{GU}(i) \text{ is generating at time } t \\
0, & \text{GU}(i) \text{ is not generating at time } t 
\end{cases}
\]

\[
m_{i,t} = \begin{cases} 
1, & \text{GU}(i) \text{ is recieving PM at time } t \\
0, & \text{GU}(i) \text{ not recieving PM at time } t 
\end{cases}
\]

\[
w_{i,t} = \begin{cases} 
2 & \mathbf{h}_i \geq U_{h_i} \quad (\text{GU's maximum service hours consumed}) \\
1 & U_{h_i} \geq \mathbf{h}_i \geq L_{h_i} \quad (\text{GU is inside the Maintenance window}) \\
0 & L_{h_i} \geq \mathbf{h}_i \quad (\text{GU didn't reach Maintenance window yet})
\end{cases}
\]

The combinations of the possible values of these variables can generate 12 different states for each time \(t\). To eliminate interference, three constraints are formulated to keep the six fundamental states consistent, and to exclude the unneeded states:

a) Operating and Window:

\[
x_{i,t} + w_{i,t} \leq 2 \quad \forall i \in I, t \in T 
\]

No generation after reaching max service-hours limit.

b) Operating vs Maintenance:

\[
x_{i,t} + m_{i,t} \leq 1 \quad \forall i \in I, t \in T 
\]

Generation and Maintenance cannot occur in same period.
e) Maintenance and Window:

\[ w_{i,t} \geq m_{i,t} \quad \forall i \in I, t \in T \] (3.3)

No maintenance allowed before GU enters the maintenance window.

Using the above constraints, the following table can be constructed and the corresponding six states of the GU can be independently defined:

**Table 3.1: GU states mathematical representation.**

*Interference constraints, Basic variables, and the six different states of a GU*

<table>
<thead>
<tr>
<th>( x_i )</th>
<th>( m_i )</th>
<th>( w_i )</th>
<th>( r_i )</th>
<th>( g_i )</th>
<th>( wr_{i,t} )</th>
<th>( wg_{i,t} )</th>
<th>( f_i )</th>
<th>( pm_{i,t} )</th>
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</table>

\( r_i = \begin{cases} 1, & x_i = 0, m_i = 0, w_i = 0, \\ 0, & \text{otherwise} \end{cases} \)

\( g_i = \begin{cases} 1, & x_i = 1, m_i = 0, w_i = 0, \\ 0, & \text{otherwise} \end{cases} \)

\( wr_{i,t} = \begin{cases} 1, & x_i = 0, m_i = 0, w_i = 1, \\ 0, & \text{otherwise} \end{cases} \)

\( wg_{i,t} = \begin{cases} 1, & x_i = 1, m_i = 0, w_i = 1, \\ 0, & \text{otherwise} \end{cases} \)

\( f_i = \begin{cases} 1, & x_i = 0, m_i = 0, w_i = 2, \\ 0, & \text{otherwise} \end{cases} \)

\( pm_{i,t} = \begin{cases} 1, & x_i = 0, m_i = 1, w_i \geq 1, \\ 0, & \text{otherwise} \end{cases} \)

\( (0,0,0) = R: \) set of Ready to operate GUs,

\( (0,0,1) = WR: \) set of ready to operate or to be maintained GUs,

\( (0,0,2) = G: \) set of generating GUs,

\( (0,1,1) = WG: \) set of generating GUs, that can be stop for maintenance,

\( (1,0,0) = Off: \) set of Off-line GUs, (IDLE-GUs), that needs to be maintained, and

\( (1,0,1) = PM: \) set of GUs receiving preventive maintenance.
3.2: Cost variables and the objective function

3.2.1: Cost variables

There are two major cost variables in the problem: 1) the total generation cost, i.e., the amount of fuel consumption; and 2) the maintenance cost, i.e., the resources utilized in the maintenance schedule.

Figure 3.3: Fuel consumption function for GUs 13 to 18 at Makkah-PP.

Figure 3.3 shows how the amount of fuel consumption is nonlinearly related to the load level. To linearize the problem, the load-fuel function is discretized into independent values for each GU (from min-load to max-load, i.e., 30% to 100%). Each load level \( l \) has a deterministic amount of fuel consumption \( F \), and represents an independent cost variable. The smaller the difference between those levels, the more number of variables and the larger the problem model becomes. Choosing the right resolution is essential, to balance between solution’s accuracy and feasibility.

In this research, the resolution of each load-step value represents a 5% increment of the GU capacity, see Figure 3.4 for an example GU. For any given GU \( i \), at any given time \( t \) The model will be limited to choose only one load level \( l \) out of the GU’s levels. For our case study at the SEC-WRB network, the 5% resolution is sufficient. For example, the GU shown in Figure 3.3 from Makkah-PP has the capacity of 60 MW, which is one of the largest gas
turbine GUs among the SEC-WRB’s network. The 5% of its capacity equals to 3 MW, this 3 MW is less than 0.4% of Makkah-PP’s capacity, and about 0.02% of the total network capacity, which is considered a good scheduling resolution.

Moreover, because of the nature of continues fluctuation in the power consumption at any power grid, the GU productivity always affected, and these load levels are usually averages of the actual load-generation. However, the resolution of this discretization process is totally up to the planner.

When the main MILP model solve the problem assigning GUs for maintenance and others for generation, it is possible to run another LP model with higher resolution (say 1% levels increment) only for the GUs that assigned for generation. The goal is to redistribute the generation load assignments among the running GUs more efficiently when possible. This experiment was tested in this research. With higher accuracy solution, more savings were found, but not much significant. The second LP is smaller and easier than the original one, and the solution time was faster.

Figure 3.4: Fuel curve function discretization.
The second cost is maintenance. This cost differs according to the nature of problem and the company’s policies. In the SEC’s case, since we are dealing mostly with preventive maintenance which is going to be performed sooner or later, we consider the manpower cost only, assuming that parts and equipment costs are fixed. SEC has its own maintenance crews on its employee payroll. The cost is either the cost increment of transferring a team from their base PP to other PP, or the cost of outsourced contractors, when the maintenance load is greater than the in-house capacity.

3.2.2: Objective function

Since the objective is to minimize the total cost consisting of both generation and maintenance, objective function is the following:

\[
\text{Min } \sum_{t=1}^{T} \sum_{i=1}^{I} F_{i,l,t} + M_{c_{i,r,s,t}}
\]

\( F_{i,l,t} \) Fuel cost associated by using GU\((i)\) at the generation level \((l)\), during time \((t)\).

\( M_{c_{i,r,s,t}} \) Maintenance cost increment, caused by using resource \((r)\) to perform maintenance step \((s)\), for GU\((i)\), during time \((t)\).

3.3: Modeling the problem constraints

The basic different capacities in the system usually follow either the regulator or the service provider (the company). Figure 3.3 illustrates the global concept behind each one of those capacities.

![Figure 3.3: Basic concept of the different capacities in the power system.](image1)

Figure 3.5: Basic concept of the different capacities in the power system.
3.3.1: Satisfying Demand

Total output power from all units in generation mode must satisfy demand:

\[ \sum_{i=1}^{I} g_{i,l,t} + wg_{i,l,t} \geq D_t \quad \forall t \in T \]  \hfill (3.5)

where:

- \( D_t \): the total demand at time \((t)\).
- \( g_{i,l,t} \): unit’s generating power on load \((l)\), at time \((t)\).
- \( wg_{i,l,t} \): unit’s inside its’ maintenance window, and generating power on load \((l)\), at time \((t)\).
- \( T \): Total time horizon.

3.3.2: Production Limits (Max and Min generation capacities)

Generated output of each GU has minimum and maximum limits.

\[ x_{i,t} \cdot P_{i,max} \geq l_{i,t} \geq x_{i,t} \cdot P_{i,min} \quad \forall i \in I, t \in T \]  \hfill (3.6)

where:

- \( x_{i,t} \): GU \((i)\) is in generating state at time \((t)\)
- \( P_{i,max} \): The maximum generation capacity of GU\((i)\). \((GU rating)\)
- \( P_{i,min} \): The minimum generation capacity of GU\((i)\). \((minimum turbine speed effect)\)
- \( l_{i,t} \): Load generating level of unit \(i\) at time \(t\).

3.3.3: No generation exceeding max service-hours

If GU \((i)\) reached to its upper limit of service hours \((Uh_i)\), it cannot be used for generation before receiving the due step of preventive maintenance. This rule was programed under four assumptions to consider four different cases:

**a)** The first assumption is that if the GU never received any PM during the planning horizon. In this case:

\[ Sctr_{i} + \sum_{s=1}^{MS} \sum_{k=0}^{t} Sh_{i,k} - Mh_{i,s,k} \leq Uh_i \quad \forall i \in I, t \in T \]  \hfill (3.7)

- \( Sctr_i \): Step-Counter for GU \((i)\), is the service-hours record value at schedule starting point.
- \( MS \): Max number of PM steps considered in the schedule.
- \( Sh_{i,k} \): Service-hours utilized by operating GU \((i)\), at time \((k)\).
**Mh\(_i,k\):** Service-hours renewed by executing PM-step \((s)\), for GU \((i)\), at time \((k)\).

**Uh\(_i\):** Max number of hours GU \((i)\) can be operated before the next PM step is needed.

**b)** The second assumption; if the GU received at least the first PM step. In this case the previous constraint will be loose, and the following constraint will be tight:

\[
S_{ctr_i} + \sum_{s=1}^{MS} \sum_{k=0}^{t} Sh_{i,k} - Mh_{i,s,k} \leq 2 \cdot Uh_i \quad \forall i \in I, t \in T  \tag{3.8}
\]

Note that \(Mh_{i,k}\) differs:

\[
Mh_{i,k} = \begin{cases} 
    Uh_i & \text{if PM was executed by time } k \\
    -Uh_i & \text{if PM was executed after time } k
\end{cases}
\]

**c)** The third case is to control the service hours after the last executed PM step, (whichever that step is). In this case:

Assuming \(mt\) is the time-period when the PM step is executed, then \(MS^*\) is the number of steps after that:

\[
\sum_{s=1}^{MS^*} \sum_{t=mt}^{T} Sh_{i,t} + Mh_{i,s,t} \leq 2 \cdot Uh_i \quad \forall i \in I, t \in T  \tag{3.9}
\]

\(Mh_{i,s,t}\) takes one of following:

\[
Mh_{i,s,t} = \begin{cases} 
    -Uh_i & \text{for any } t = mt \\
    Uh_i & \text{for any } t > mt
\end{cases}
\]

**d)** The last case is that if the GU received any two consecutive PM steps, the maximum possible service hours between them must be limited. Assume that \(mt1\) is the time of the earlier PM step, and \(mt2\) is the time of later PM step:

\[
\sum_{t=mt1}^{mt2} Sh_{i,t} + Mh_{i,t} \leq 3 \cdot Uh_i \quad \forall i \in I, t \in T  \tag{3.10}
\]

\(Mh_{i,t}\) takes one of following:

\[
Mh_{i,t} = \begin{cases} 
    Uh_i & \text{for any } t = mt1 \\
    Uh_i & \text{or } t = mt2 \\
    0, & \text{otherwise}
\end{cases}
\]
3.3.4: Maintenance steps’ sequencing

The system has four different maintenance cycles, A, B, C and D. Each GU follows one of these cycles according to its manufacturing standards. The LP model always searches for the cheapest options. Two constraints are introduced to assure those steps are scheduled in the right order.

a) No steps repeated: Once a PM step performed, it couldn’t be repeated.

\[
\sum_{t=1}^{T} m_{i,s,t} \leq Mdu_{i,S} \quad \forall i \in I, t \in T, s \in MS \quad (3.11)
\]

\( m_{i,s,t} \) : Status of PM step (s), for GU (i), at time (t). (1 if executing, 0 if not).

\( Mdu_{i,S} \) : Standard duration of PM step (s), for GU (i).

\( MS \) : Max number of PM steps considered in the schedule.

![Figure 3.6: Maintenance Cycle “C”, Example of the maintenance cycles in the power system.](image)

b) Correct sequencing: at any time, the model should recognize the right sequence of maintenance steps.

\[
\sum_{t=1}^{T} \left( \frac{Q}{Mdu_{i,S}} \right) \cdot m_{i,s,t} - \left( \frac{Q}{Mdu_{i,(s+1)}} \right) \cdot m_{i,(s+1),t} \quad \forall i \in I, t \in T, s \in MS \quad (3.12)
\]

\( m_{i,s,t} \) : Status of PM step (s), for GU (i), at time (t). (1 if executing, 0 if not).

\( Mdu_{i,S} \) : Standard duration of PM step (s), for GU (i).

\( MS \) : Max number of PM steps considered in the schedule.
3.3.5: Maintenance steps’ duration

Since maintenance duration is deterministic. To assure this rule, a maintenance duration index was introduced ($Midx$). The index is a series of elements equal to the number of time-periods in the planning horizon. There is a specific series for every duration ($tu$). The elements are arbitrary numbers, generated to satisfy the following:

$$\sum_{t=k}^{k+tu} Midx_t, tu = 0 \quad \forall tu \quad (3.13)$$

$tu$: Maintenance duration. ($tu \in TU$, $TU = \{2, 3, 4, ..., (max \ standard \ duration)\}$)

$Midx_t, tu$: The value of the maintenance duration index of duration $tu$, at time $t$.

For any maintenance decision during the planning horizon, the following must be true:

$$\sum_{t=1}^{T} m_{i,s,t} \cdot Midx_{tus} = 0 \quad \forall i \in I, t \in T, s \in MS \quad (3.14)$$

$m_{i,s,t}$: Status of PM step ($s$), for GU ($i$), at time ($t$). (1 if executing, 0 if not).

$Midx_{tus}$: Maintenance duration index for duration ($tu$) needed for step ($s$).

3.3.6: Maintenance manpower constraints

Constraints related to maintenance crews are following.

a) Technical capabilities: Teams are different, not all of them are qualified to perform some maintenance activities, even among different steps for the same GU.

$$f_{c,i,s} = \begin{cases} 1, & \text{if PM step (s), for GU (i), can be performed by team (c).} \\ 0, & \text{if team (c) cannot perform this particular PM step.} \end{cases}$$

$$\sum_{t=1}^{T} m_{i,s,c,t} \cdot (1 - f_{c,i,s}) \leq 0 \quad \forall i \in I, c \in C, t \in T, s \in MS \quad (3.15)$$

$m_{i,s,c,t}$: Status of step ($s$), for GU ($i$), by team ($c$), at time ($t$). (1 if executing, 0 if not).

b) Team handling capacity: every team can handle only one GU at a time.

$$m_{i,s,c,t} \leq 1 \quad \forall i \in I, c \in C, t \in T, s \in MS \quad (3.16)$$

$m_{i,s,c,t}$: Status of step ($s$), for GU ($i$), by team ($c$), at time ($t$). (1 if executing, 0 if not).

Outsourced contractors’ capacities ($cn$) can be previously determined, (say $cns$):

$$m_{i,s,cn,t} \leq cns \quad \forall i \in I, t \in T, s \in MS \quad (3.17)$$

$m_{i,s,cn,t}$: executing step ($s$), for GU ($i$), by the contractor at time ($t$). (1 if yes, 0 if not).
### 3.3.7: Maintenance continuity

This constraint assures two important rules:

**a) Maintenance continuity:** If a maintenance step was started, it should be continued until finished. It cannot be canceled or interrupted.

**b) Preventing teams’ interference:** If a team or contractor started a maintenance step, it cannot be replaced with another team until the job is finished (because the model could try to replace them when cheaper resources are available).

To solve this, assume $Q$ as a positive arbitrary number (say 100). $Q_t$ is the value of $Q$ at time $(t)$, and can take one of the two following values:

$$Q_t = \begin{cases} 
-Q, & \text{if } t = mt_{i,s,c} \\ 
\frac{Q}{(Mdu_{i,s} - 1)}, & \text{otherwise}.
\end{cases}$$

$$\sum_{t=mt_{i,s,c}}^{mf_{i,s,c}} m_{i,s,c,t} \cdot Q_t \leq 0 \quad \forall i \in I, c \in C, s \in MS$$

$m_{t_{i,s,c}}$: Starting time of PM-step $(s)$, for GU $(i)$, by team $(c)$.

$mf_{i,s,c}$: Finishing time of PM-step $(s)$, for GU $(i)$, by team $(c)$.

$m_{i,s,c,t}$: executing step $(s)$, for GU $(i)$, by the contractor at time $(t)$. (1 if yes, 0 if not).

### 3.3.8: No maintenance before the window allows

The maintenance window constraint states that the maintenance of GU $(i)$ can start if and only if its cumulative service-hours $(hi)$ exceed its maintenance-window lower limit of service hours $(Lhi)$. This can be managed in two different cases:

**a) The first case is the maintenance window before the first PM-step for.** Step (1) can be started for GU $(i)$, at time $mt_{i,1}$, if the following constraint valid:

$$Sctr_i + \sum_{t=1}^{mt_{i,1}-1} Sh_{i,t} \leq Lh_i \quad \forall i \in I, t \in T$$

$mt_{i,1}$: Scheduled time-period to start maintenance step $(1)$ for GU $(i)$.

$Sctr_i$: Step-Counter for GU $(i)$, is the service-hours record value at schedule starting point.
\( Sh_{i,t} \): Service-hours utilized by operating GU (i), at time \((k)\).

\( Lh_i \): Min number of hours GU (i) should be operated before receiving the next PM.

b) The second case is to manage the window between any two consecutive PM-steps. In this case, assume that \( m_{t_1} \) is the starting-time for the earlier PM step, and \( m_{t_2} \) is the starting-time for the later PM step, the following should be true:

\[
\sum_{t=m_{t_1}}^{m_{t_2}} Sh_{i,t} \geq Lh_i \quad \forall i \in I, t \in T \tag{3.20}
\]

3.3.9: Maintenance Season

During the planning horizon, the model needs to recognize the maintenance season (no maintenance performed outside the maintenance season), because all the human and generation resources are prepared to meet the rapidly escalating demand.

\[
\sum_{t=1}^{M_{1}} m_{i,t} + \sum_{t=M_{0}}^{T} m_{i,t} = 0 \quad \forall i \in I \tag{3.21}
\]

\( M_{1} \): Maintenance season starting time.

\( M_{0} \): Maintenance season ending time.

3.3.10: Spinning Reserve

The marginal capacities (not being used) out of the running generating units must be able to cover the largest running unit’s capacity, (called Hot Reserve):

\[
\sum_{i=1}^{l} [(g_{i,t} + w g_{i,t}) \cdot (p_{i}^{max} - l_{i,t})] \geq SR_{t} \quad \forall t \in T \tag{3.22}
\]

where:

\[
SR_{t} = \max \{p_{i}^{max} : \forall i, x_{i,t} = 1\} \tag{3.23}
\]

\( SR \): minimum spinning reserve value out of the generating units at time \((t)\).

\( p_{i}^{max} \): The maximum generation capacity of GU(i). (GU rating)

\( l_{i,t} \): Load generating level of unit \(i\) at time \(t\).
3.3.11: Total capacity reserve

Total reserve DR_t is a percentage of the total demand D_t at time (t). The percentage follows the regulator’s rules or the company’s policy, and is considered out of the total available GUs’ capacities (called Cold Reserve):

\[
\sum_{i=1}^{l} (g_{i,t} + w_{i,t} + r_{i,t} + w_{i,t}) \cdot P_{i}^{\text{max}} \geq D_t + DR_t \quad \forall t \in T \tag{3.24}
\]

where:

- \(g_{i,t}\): GU(i) is generating power, at time (t). (0 or 1)
- \(w_{i,t}\): GU(i) is inside the maintenance window, and generating power at time (t). (0 or 1)
- \(r_{i,t}\): GU(i) is ready for generation at time t. (0 or 1)
- \(w_{i,t}\): GU(i) is inside the maintenance window, and ready for generation at t. (0 or 1)
- \(P_{i}^{\text{max}}\): The maximum generation capacity of GU(i).
- \(DR_t\): Total capacity reserve at time t, according to demand.

3.3.12: Minimum operating state, (Up/Down) time:

If GU(i) started generating at time (t), it should continue running for at least a minimum amount of time.

\[
\left(\frac{-Q}{2}\right) \cdot (x_{i,t} + x_{i,(t+up+1)}) + \sum_{k=t+1}^{k=t+up} \left(\frac{Q}{up - 1}\right) \cdot x_{i,k} \leq Q \quad \forall i \in I, t \in T, up = 1,.., Mup \tag{3.25}
\]

- \(Q\): random positive number. (say 100).
- \(x_{i,t}\): Generation state, (1) if GU (i) was operating at time (t), (0) otherwise.
- \(Mup\): Minimum GU generation time (Up-time).

In the Down-time case, if a GU was shut-down, it cannot be re-operated before a specific amount of time (\(dn\)):

\[
\left(\frac{-Q}{2}\right) \cdot (x_{i,t} + x_{i,(t+dn+1)}) + \sum_{k=t+1}^{k=t+up} \left(\frac{Q}{dn - 1}\right) \cdot x_{i,k} \geq -Q \quad \forall i \in I, t \in T, dn = 1..Md_n \tag{3.26}
\]

Here:

- \(Md_n\): Minimum GU offline time (Down-time)
Regarding the comparative study for the SEC procedures and previous models’ features discussed in Chapter-2, Figure 3.5 below illustrates where the current model’s constraints satisfy each one of those features.

Table 3.2: Model constraints vs model features.
CHAPTER 4

Solution Methods

The initial attempt to solve the generation and maintenance scheduling problem (GMS) was coding the mixed integer linear programming model (MILP), from Chapter 3, and solving the model using LP solver programs. The coding technique is explained in section 4.1. Since models’ sizes varied according to the size of the power plants (PP) or the network, difficulty to solve the large models require more helpful techniques. A heuristic solution (in section 4.2), and a partitioning experiment (in section 4.3) are introduced to generate solutions for the GMS. (see Figure 4.2).

4.1: Coding technique

4.1.1 Overview

Initially, the basic technical raw data for each generation Unit (GU) in the system is prepared in Excel files. Coding was done using MATLAB. The function of the code is to read the GUs’ input data from the Excel files, and then to construct the GMS problem as an MILP model. Then the code calls the solver (GUROBI) to execute the model. The solver continues working until either optimality or the time-limit reached. When the solver finishes, the code translates the results into a final GMS plan and presents the output schedule in Excel. (see Figure 4.1).

![Figure 4.1: Coding technique: solution process overview.](image)

4.1.2 Model size

The code defines the model cost variables to construct the objective function, and then starts generating the model constraints in groups. The number of constraints in each group varies according to the type of constraint and the raw data inputs of each GU. Table 4.1 shows a comparison of the model size of each individual PP in these experiments.
There are two versions of the code, one deals with Gas-Turbine GUs, and the other deals with Steam-Turbine GUs. However, models with both types of GU’s are straightforward. This is the main goal of the research: solving the whole network containing two different technologies in one integrated model.

Table 4.1: model size for each Power Plant

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<th>TAIF</th>
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</table>

1. Demand satisfaction
   - 728
   - 1248
   - 728
   - 936
   - 1976
   - 3744

2. Service Hrs Limits
   - 0
   - 3950
   - 3934
   - 5893
   - 13800

3. Maintenance Logic
   - 12
   - 22
   - 286
   - 256
   - 525
   - 1136

4. Maintenance Window
   - 0
   - 5390
   - 5390
   - 6263
   - 14988

5. T. Reserve _ Excld Mi
   - 104
   - 104
   - 104
   - 104
   - 104

6. Spinning Reserve
   - 280
   - 1040
   - 0
   - 0
   - 1717
   - 3536

7. Total Constraints
   - 4070
   - 7555
   - 12194
   - 12489
   - 22220
   - 43573

8. Model Size
   - 16 k X 4 k
   - 30k X 7.5k
   - 13k X 12k
   - 20k X 12k
   - 45k X 22k
   - 110k X 44k

4.1.3 Code application

During the first trials, the code was applied on each power plant (PP) separately. Starting with the basic constraints, and then adding more constraints to the model step by step. The results of those experiments are illustrated in detail in Appendix 2. The solutions took too long, and the optimality gap increased, as the model size increased. It was observed that model difficulty can be divided into 3 levels. easy, medium and hard, (Figure 4.2).
4.1.3-a: Easy models:

Two types of PP models are easy to solve. First, is the steam-turbine PPs, because there are no service hour limitations, and the preventive maintenance must be executed annually. The PM decision is deterministic, and it is just a matter of producing a well-coordinated GMS plan. A second type of easy model is a small gas-turbine PP where the number of GUs is less than 10. All types of constraints are applicable. The model limits are 20k variables and 12k constraints. Such models are solves in less than 5 minutes. Example PPs are: Shoaibah ST, and Madinah GT. See Appendix 2 for experiment details.
4.1.3-b: Medium difficult models:

Gas-turbine PPs in the range of 15 to 20 GUs can be considered medium difficult models. Solution time for such model can take up to 60 minutes, with less than a 2% optimality gap. Makkah PP is the best example of this type. This particular PP consists of 18 gas-turbine GUs, and the model size is 45k variables and 22k constraints. See Appendix 2 for experiment details of this PP.

4.1.3-c: Hard models:

Jeddah Gas-turbine PP which consist of 34 GUs can be considered a hard model. The original code worked on this model for 24 hours, and still was not able to solve it. This raised the need for additional solution techniques. Two techniques were introduced to generate initial solutions, so Gurobi could start from that initial solution. A heuristic solution and a partitioning technique were developed and tested. Gurobi was able to read those solutions, assessing the accuracy of each solution, testing compatibility with model’s constraints and then start solution improvement. This whole new process was able to solve this hard problem with less than a 1.6% gap within 45 minutes.

4.2: Heuristic GMS technique

The goal of this heuristic is not to attempt optimality, but rather to create a valid solution that satisfies the constraints of the GMS MILP model (chapter-3 and section 4.1). The fundamental logic considers the traditional goals that planners consider while constructing the GMS. For example, maintenance activities are expected to be executed for the maximum possible number of GUs in order to increase system reliability. Table 4.2 represents the basic GUs’ data needed to start the heuristic (the example is the Jeddah-PP).

The heuristic constructs a GMS schedule for the gas-turbine GUs over a two-year planning horizon. It starts by constructing the maintenance schedule, then constructing the GUs’ availability matrix according to their maintenances schedules. The availability matrix works as a base line to design the generation schedule (unit commitment).
Table 4.2: GUs’ basic data. 1) GUs ID#. 2) GU preventive maintenance (PM) cycle type. 3) PM cycle length (in steps). 4) PM step length (hours). 5) Service hours record at planning time. 6 & 7) PM step ID and duration this year (8 & 9) for next year. 10) Hours record in this PM step. 11) Hours available in this PM step. 12) Weeks available in this PM step.

<table>
<thead>
<tr>
<th>GUID</th>
<th>Cycle ID</th>
<th>Cycle Length (#Steps)</th>
<th>Step Length (S. Hrs)</th>
<th>Srv. Hrs Record</th>
<th>This year</th>
<th>Next year</th>
<th>Service Hours</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Stp idx Mdu_1</td>
<td>Stp idx Mdu_2</td>
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<td>4 7</td>
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<td>4,793</td>
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<td>3 1</td>
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<td>4 7</td>
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</table>
The heuristic works according to the following steps:

1) Divide the planning horizon into years, (here, there will be Y1 and Y2)
   a. Each year contains two seasons: maintenance season and generation season,
      Y1 ==> Y1M, Y1G. and Y2 ==> Y2M, Y2G. (see Figure 4.3-a)
   b. Later, for each GU, the year is divided into two operation periods:
      1. Operation period 1 (OP1), for each GU, is the time before receiving maintenance.
      2. Operation period 2 (OP2), for each GU, is the time after receiving maintenance.
         (See Figure 4.3-b).

Figure 4.3: a) example of a 2-year horizon, with 20 periods per year, 10 with maintenance and 10 with no maintenance. b) example of GU to be maintained during periods 6 to 8.

2) Construct the maintenance plan for the first maintenance season (Y1M):
   a. Construct the GUs’ maintenance sorting matrix (see Table 4.3). Rows represent GUs, and:
      1. Column-1, the available generation hours for each GU.
      2. Column-2, the generation capacity for each GU,
      3. Column-3, the GU consumption rate (at 100% load), and
      4. Column-4, the GUs ID#.
5. GUs with service hours’ records that didn’t reach the maintenance window, and cannot reach the window before the end of maintenance season Y1M. Those GUs are to be eliminated from this matrix. (Example: GUs #5 and #34 in Jeddah PP, See Table 4.3).

Table 4.3: Columns 1 to 4: The maintenance sorting matrix. Columns a to d; the logic behind step 2.5.

<table>
<thead>
<tr>
<th>Available Weeks</th>
<th>Capacity Mw / Hr</th>
<th>Consum. ton / hr</th>
<th>GU ID#</th>
<th>Max (weeks)</th>
<th>Maint W. = 70%</th>
<th>(a) - (1)</th>
<th>(b - c + Mdu) - 26</th>
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<td>-21</td>
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</table>
b. Start (left-side) scheduling, (early periods of the maintenance season):

1. Find the IDLE-GUs: GUs that reached their maximum service hours, and cannot be used before receiving maintenance. (in Table 4.3, GUs# 9, 29, and 33, are examples from Jeddah-PP).

2. For time-period 1 in Y1M, schedule IDLE-GUs for maintenance, considering the largest capacity GU first, and using the least cost team. Continue scheduling those GUs until they finish or until reaching the maximum number of teams in period-1 (see schedule in Figure 4.4).

3. In time-period 2, (and so the next time-periods), if there are still more IDLE-GUs and available maintenance teams, schedule IDLE-GUs using the same priority in 2-b-2. If there are IDLE-GUs, and no maintenance team available, go to the next period. If there are no more IDLE-GUs, (Left-Side) Scheduling step is done.

c. Start (right-side) scheduling, (from the last period of the maintenance season):

1. Use the matrix constructed in 2-a, to sort GUs by their maximum available generation hours in the first column, then by the largest capacity in column-2, then by the least fuel consuming GU in column-3. Part of this sorting matrix for Jeddah-PP example is shown in figure 4.4, and the schedule in Figure 4.5 illustrates the application of these steps.

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<td>Consum. ton / hr</td>
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</table>

Figure 4.4: Maintenance sorting matrix.

2. The first GU in this order, which has the maximum available generation hours, is to schedule for maintenance in backward order starting with the last day in YM1 and
using the least cost available maintenance team (Example: as in Table 4.4, GU#3 has the max-available weeks, with maintenance duration of 3 time-periods as in Table 4.2, starting from the last day in YM1, which is day 26, will be scheduled for maintenance at time periods 24, 25 and 26).

3. Whenever scheduling GUs for maintenance, the capacity of the other GUs available for generation in that period must satisfy demand and reserve for that period, otherwise stop and go to the previous period.

4. Go to the next GU in the matrix, and repeat steps 2 and 3. If you reach the maximum possible number of GUs in the same period, (either because of team availability or capacity limitations), go to the previous period, check maintenance possibility and repeat steps 2 and 3.

5. In the case of an inadequate number of maintenance teams, add a contractor, and try to add them to the schedule (following steps from 2-c-1). If one contractor is not enough, add contractors as needed, until scheduling all possible GUs, without sacrificing Demand.

6. The maintenance schedule for this season will be finished whenever all the GUs in the matrix (from 2-a) are scheduled, or the maximum number of scheduled GUs during the maintenance season is limited by demand.
Figure 4.5: Example of maintenance schedule for Jeddah-PP, during YM1.
3) Constructing the GUs’ Availability Matrix:
   a. For each GU, the number of available operating time-periods is the result of dividing the available service hours by the length of every period (week = 24*7 = 168 hr.). The availability matrix shows the available service time-periods (weeks) for each GU over two parts of the planning horizon. See Table 4.4.
   b. The 1st part of the availability matrix represents OP1 in two columns. The first column shows the current available number of periods that the GU can operate before the scheduled maintenance date (from period-1, to the last period before receiving maintenance). This figure depends on the service hours record of each GU.
   c. The 2nd column for OP1 defines max-t for each GU as the last probable generation time-period before the date the GU’s scheduled maintenance should start. This is the last chance to consume current availability of each GU, and it is possible that max-t is less than the actual availability of the GU, (for example, GU#3 and GU#32 in Table 4.4).
   d. Two types of GUs should have zeros (0) during OP1. The 1st type is the current IDLE-GUs (which was described in 2-b-1). The 2nd type is the GUs that were not scheduled for maintenance in this season (like in 2-c-6 for GU#5 and GU#34). These GUs will be utilized during OP2 only.
   e. The 2nd part of the availability matrix represents OP2 in two columns also. The 1st column shows the GU’s availability, which could be one of two cases. Case-1, if the GU was scheduled for maintenance during Y1M, its availability will be the maximum possible generation periods as per standards. Case-2, if GU will not receive maintenance during Y1M season. In this case, GU’s availability will be stated according to the current service hour records.
   f. The 2nd column for OP2 defines min-t for each GU. For case-1 GUs, min-t is the first possible generation time-period after receiving scheduled maintenance. For case-2 GUs, min-t is the first time-period in the planning horizon (week-1). No GU can be scheduled for generation during OP2 before it’s min-t date.
Table 4.4: GUs’ Availability Matrix (Jeddah-PP).

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4) Constructing the generation plan:

a. **Scheduling for the first stage (OP1):** The 1st step is to prepare the generation sorting matrix for OP1. In column-1, GUs should be sorted according to their availabilities during OP1, with maximum first, then sorted in column-2 by the maximum capacity first, then in column-3 by the minimum fuel consumption rate first, then in column-4 by the earliest max-t first, and the last column represents the GU ID#. See Table 4.5.

Table 4.5: The generation sorting matrix (OP1 for Jeddah-PP).

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b. The generation scheduling horizon at OP1 stage starts from the first period in the planning horizon (which is currently week-1 in Y1), until the last $\text{max}$-$t$, which is the last period of OP1 for all GUs (this will be week-25 for GU#31 and GU#32. See Figure 4.5, Table 4.4 and Table 4.5).

c. The process of generation job assignment works in iterations, solving for one week (time-period) in each iteration. For each time-period (t), three figures are to be considered; Power Demand ($D_t$), Spinning Reserve ($SR_t$) which is at least equal to the size of the largest running GU, and the total capacity of the assigned GUs ($G_t$). $D$ is previously known, $SR$ starts as (0), and changes according to the selection of GUs, and $G$ also starts at (0) and increases as a cumulative figure. The iteration objective is to cover the demand plus the spinning reserve with the minimum number of GUs ($G_t \geq (D_t + SR_t)$).

d. At each iteration, do the following: take the first GU in the generation sorting matrix and assign it for generation assuming using the maximum GU capacity, update the $SR_t$ and the $G_t$ figures, and check the validity of the capacity condition ($G_t \geq (D_t + SR_t)$). If the condition is not valid yet, assign the next GU and check again. If it is valid, stop, and go to the next iteration.

e. If all available GUs in this iteration were used, and the condition in 4-d still not satisfied, stop, and go to the next iteration (this lack of capacity is to be solved during the OP2 scheduling stage).

f. Before starting the next iteration ($t+1$):
   1. Reduce every assigned GU’s availability in column-1 by (-1),
   2. Exclude GUs that reached its OP1 horizon (GUs with $\text{max}$-$t < t+1$),
   3. Sort the matrix again according to the same rules in (4-b). This will update the GUs’ order for the next iteration.
   4. Start ($t+1$) iteration, follow the same steps at 4-d and 4-e. An illustrative example is shown in Figure 4.6 for two consecutive iterations.

g. Generation scheduling for stage-1 will be finished if the iteration of the last time-period in the OP1 horizon was completed (week-25 in this example), or if the generation availability at OP1 for available GUs had been totally consumed.
h. **Scheduling for the 2nd stage (OP2):** Use the same structure as 4-a to construct the generation sorting matrix. Differences will be in column-1 and column-4, which represent the GUs’ availability and \( \text{min-}t \) during OP2 respectively.

i. Column-4 \( \text{min-}t \) does not affect GU’s priority sorting directly. However, for each time-period (t), the GU would be considered for scheduling only if it is already inside the OP2 horizon, (only GUs that satisfy \( \text{min-}t \geq t \)).

j. The generation scheduling horizon at this step starts from the earliest time-period in OP2, (in the current example, this will be week-1, see Figure-4.5), until the last period in the planning horizon (which is week-52 in Y1).

k. In regard to the three figures (\( D_t \), \( SR_t \) and \( G_t \)), keep using the last update from the OP1 stage.

l. For each time-period iteration, start with the capacity check (\( G_t \geq (D_t + SR_t) \)), and schedule GUs for generation whenever needed, following the same steps as 4-d, e, and f.

m. Generation scheduling for stage-2 will be finished if the iteration of the last time-period of Y1 was completed (week-52 in this example).

n. If the generation availability at OP2 for each GU had been totally consumed, and still not satisfying demand, this scheduling process is infeasible.

o. Translate the remaining GUs’ availabilities at Y1 to the starting record for Y2.

5) **Constructing the GMS for the second year:**

   a. Maintenance plan for the second maintenance season (Y2M) is to be constructed following the same steps explained in (2).

   b. Define the OP1 and OP2 for the second year, and construct the availability matrix following the same steps as in (3).

   c. Construct the generation plan, following the same steps as in (4).

6) Since the total capacity of the GUs assigned generation at each time-period is greater than demand, the GUs can be processed by a simple heuristic distributing the load by the minimum consumption GU first. Also, as fuel consumption rates are non-linear, the process can be accomplished using a simple mathematical model to attain better efficiency.
With the GUs’ maintenance jobs scheduled and assigned to maintenance teams from steps (2) & (5), and all generation loads assigned to GUs in step (6), the GMS is finished.

Figure 4.6 shows an illustrative example for two consecutive iterations of generation assignment. In iteration-1, capacity of the first 8 GUs (426 MW) is able to cover demand (400 MW). However, the excess of 26 MW cannot cover the spinning reserve of (60 MW), so the 9th GU is added. In iteration-2, the sorting order of GUs #23 and #28 is flipped because their availability reserve changed after iteration-1 assignment. This example assumes the same demand for both time-periods, but the real application always carries more fluctuating demand, which means more dynamic unpredicted changes in the generation sorting matrix.

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<td>45</td>
<td>60</td>
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<tr>
<td>34</td>
<td>39.8</td>
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</tbody>
</table>

Figure 4.6: Illustrative example of two consecutive iterations for two time-periods.
4.3: Partitioning technique

4.3.1 Preface

The inputs to the GMS problem are interactive in nature. In the end, it is a distribution process for generation demand and maintenance jobs. The partitioning technique objective is to divide the original problem into smaller problems. The major consideration here is that the solutions of the new smaller problems should not conflict with each other, so they can be consolidated into one global solution. The function of this consolidated solution is to create a jump start for the MILP code to be able to solve the hard models (section 4.1.3). The contribution of this partitioning technique becomes more significant as the problem gets larger. In other words, beside the size of the MILP itself, as more PPs and service areas of the network are included in the model, more the need for partitioning arises.

The partitioning technique was necessitated by the failure of the MILP to solve Jeddah-PP model. Jeddah-PP has GUs and maintenance teams double that of Makkah-PP. The MILP code was able to solve the Makkah-PP model in less than 60 minutes, and was not able to find a single solution for Jeddah-PP in more than 24 hours. Many partitioning experiments were performed to divide Jeddah-PP either by GUs, capacities or technologies into 2, 3, and 4 parts. In each case, there was a failure. Finally, a successful partitioning technique was found.

4.3.2 Partitioning methodology

The main concept is to split the GUs in separate parts, considering the GUs’ service-records and maintenance requirements. Then, the maintenance teams’ capability to maintain each GU is considered. Lastly, to distribute demand to each part. When the MILP solves each part separately, it should be possible to consolidate the different solutions in one major schedule without conflict, and then to use that schedule as a starting solution for the original problem. The technique works as follows:

1) The number of partitions is to equal the number of maintenance teams. There are 4 teams in Jeddah-PP, so there are 4 parts.

2) The next step is to distribute the GUs to the partitions. Do the following:
a. Calculate the total durations of possible maintenances for each GU. Since 3 steps are considered in Jeddah-PP, those 3 maintenance durations are summed for each GU, call it MD$_i$.

b. Sort the GUs according as follows:
   
i. The GU that has the largest total maintenance time is first (max MD$_i$).
   
ii. Ties in max MD$_i$s sorted by the minimum available service-periods first. (number of periods the GU can operate before reaching the IDLE-GU state).

   iii. Ties in (i) and (ii), are sorted by the largest duration of the first maintenance step in the planning horizon.

   iv. If still tied (which is possible), sort by ID#.

c. Fix the sequence for the partitions (i.e., 1-2-3-4). Assign the first GU in order to the first partition, and the next GU to the next partition, etc. Continue until the last GU is assigned.

3) Because of technical capabilities, some maintenance teams cannot provide service for some GUs. Generate a capability matrix comparing the number of GUs that each team is able to maintain, (here, it will be a 4X4 matrix).

4) Start with the team that can maintain the smallest number of GUs among all GUs in the PP. Assign this team to the partition containing the largest number of GUs the team can maintain. Continue the process, assigning teams to partitions.

5) In each partition, an open-source of contractors are added. The MILP cost-minimizes, so it will solve the problem using as few contractors as possible, avoiding costs.

The major concept is to separate the GU’s based on an integrated decision between their generation capabilities and maintenance requirements. In the worst case, teams can be replaced with contractors, and then existing teams can be introduced in the final stage.
<table>
<thead>
<tr>
<th>GU ID#</th>
<th>Availability</th>
<th>1st maint.</th>
<th>Mdi</th>
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<td>1308.068</td>
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<td>6000</td>
<td>5834.88</td>
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<td>6000</td>
<td>5021.23</td>
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<td>U # 22</td>
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<td>4115.97</td>
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<td>8000</td>
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</tr>
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<td>U # 23</td>
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Figure 4.7: Sorting and splitting GUs of Jeddah-PP into 4 parts.
CHAPTER 5
5. SOLUTIONS RESULTS

5.1 Structure of experiments

All the experiments in this research were based on a planning horizon of 2 years, starting with the maintenance season of 2008-2009, and ending with the summer (peak generation) season of 2010.

Experiments used the actual conditions of the generation units (GU) by the end of Oct-2008 in 6 different power plants (PP). The gas-turbine (GT) PPs were TAIF-PP, MADINAH-PP, MAKKAH-PP and JEDDAH-PP. The steam-turbine (ST) PPs were SHOAIBAH-PP and RABIGH-PP. Table 5.1 shows details of the PPs: the number of GUs, maintenance teams and contractors, and the capacity of Each PP at that time.

The rule of the maintenance window is applied for GT-GUs as follows: a GU is eligible to receive preventive maintenance if it was operated at least 70% of the max service hours since the last preventative maintenance. However, ST-GUs must be maintained annually, regardless of the generation record during the year.

The actual amount of power generated by each PP at that 2008-2010 planning horizon was set as the demand for that PP. Two objectives for this: first, to test the model’s ability to satisfy the same demand within the given constraints; and second, to test the model’s ability to produce more efficient (least cost) schedules compared with the actual PPs’ performances.

CPLEX and GUROBI solvers were used to solve the MILP. It was noticed that CPLEX can find the first solution faster than GUROBI. However, after finding the first solution, GUROBI was more efficient during the solution improvement process. In regard to their final solutions, differences were not significant.

The model’s constraints were revised after each experiment, resulting in a final version that is able to solve the problem in challenging times. Most of the experiments were set with 2-hour solving times. The model was considered solved when the final solution has less than 2% optimality gap. The coming sections carry more detail of the MILP running times with each experiment.
5.2: MILP code

The first part of Table 5.1 shows information about each PP experiment. The first 2 PPs are the ST-PPs of RABIGH and SHOAIBAH. It is shown in the second part of Table 5.1 that a significant portion of model’s constraints are not applicable, especially all types of service-hours constraints. This makes the ST-PPs’ models smaller than GT-PPs’ models, and faster in both construction and solving. In fact, optimality was reached when some constraints were disabled for testing purposes (e.g. Spinning Reserve constraints).

Both RABIGH-PP’s and SHOAIBAH-PP’s models were constructed in less than 12 minutes, and solved in less than 30 minutes. In RABIGH-PP’s case, the 1st solution was found in 5 seconds, with a 4.4% optimality gap, the best solution was found in 12 minutes, and had an optimality gap of 0.15%. The final solution schedule consumed about 50 million liters of fuel more than actual performance of this PP.

To verify this extra consumption, the actual performance was examined, and it was found that many constraints were violated in actual performance. Both spinning-reserve and total-reserve were not satisfied in most of the planning horizon’s time periods, this may be justified because other PPs in the network can secure this reserve. In this experiment, the PP was considered isolated. Moreover, at least 4 GUs received maintenance one month outside the maintenance season, and at least 6 GUs received maintenance in the same time, which is more than the number of maintenance teams in RABIGH-PP (2 teams). In addition, those maintenances took more than the standard maintenance durations. The cost of those extra maintenance resources was not provided, so the comparison between both schedules was not possible.

In SHOAIBAH-PP, the first solution was found in 55 seconds, with 1.98% optimality gap. The best optimality gap was 0.53%, reached in less than 8 minutes. Compared to the actual performance, the MILP solution schedule saved at least 217 million liters of fuel, during the 2-year planning horizon (1.8% of actual consumption).

The rest of the PPs in Table 5.1 are GT-PPs of TAIF, MADINAH, MAKKAH and JEDDAH-PP, arranged ascendingly by their number of GUs and total capacity. TAIF-PP is the smallest. The MILP was able to solve TAIF-PP’s model in less than 5 minutes, with an optimality gap of 0.9%. The final solution consumed 3 million liters of fuel more than the actual records (1.2% more than actual consumption). Again, the actual records were checked, and many constraint
violations were found. At least 3 GUs received maintenance outside the maintenance season, at least 3 GUs received a major-overall (MO) maintenance before reaching to the MO’s standard maintenance sequencing, and at least 2 GUs exceeded their service-hours limitation and were operated without receiving the standard preventive maintenance steps.

In MADINAH-PP, the 1st solution was found in less than 4 minutes, and the best solution (with 0.4% optimality gap) was reached in less than 5 minutes. Compared with actual records, the best solution schedule saved more than 31 million liters of fuel, (3.7% of the actual consumption).

MAKKAH-PP’s model represents a good example of the medium-size PPs. The MILP was given 2-hours limit to run, and it took the solver 33 minutes to find the 1st solution with 22% optimality gap. The best optimality gap reached during solution time-limit was 1.6%, and the output schedule saved about 242 million liters of fuel (8.9% of the actual consumption).

JEDDAH-PP was a real challenge. It took the MATLAB 1 hour to construct the MILP model longer than any other model. The solver ran for more than 24 hours without finding a solution. Inputs of model and constraints were examined many times to find out if there was any technical reason. Finally, the need of a starting solution was expected to be the best alternative. Constraints checking with actual records was mentioned when we have more expensive schedule only. In other cases, constraints were also violated, but no need to mention.

The above MILP schedules for all PPs utilized the maintenance teams very efficiently. During the 2-year Planning horizon, and Out of 22 maintenance jobs in SHOAIBAH-PP, only 1 job was assigned to an outsourced contractor. It was also one job out of 17 maintenance jobs in Makkah-PP. Never used a contractor for Madinah-PP and TAIF-PP. And in Jeddah-PP, it was 6 jobs assigned to a contractor out of 54 jobs.
<table>
<thead>
<tr>
<th>Power Plant name / Type</th>
<th>SHOAIBAH ST</th>
<th>RABIGH ST</th>
<th>TAIF GT</th>
<th>MADINAH GT</th>
<th>MAKKAH GT</th>
<th>JEDDAH GT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Code stage</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max. Maint. Steps / Horizon</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># of GUs / Teams / Cont.</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Planning Horizon</td>
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</tr>
<tr>
<td>W % =</td>
<td></td>
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</tr>
<tr>
<td>D % =</td>
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<td>0</td>
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<td>256</td>
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<td>245</td>
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<td>1,285</td>
<td>1,445</td>
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<td>Feasible</td>
<td>Feasible</td>
<td>Feasible</td>
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<td>TF</td>
<td>MO - 4</td>
<td>MK - 4</td>
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Table 5.1: MILP code experiments
5.3 Heuristic GMS results

The heuristic GMS technique was developed to find a starting solution, and was tested to provide feasible solutions for JEDDAH-PP MAKKAH-PP and MADINAH-PP. Table 5.2 shows the 3 experiments of JEDDAH-PP. The 1st experiment is the failed execution of the MILP. The 2nd experiment is the heuristic GMS. The 3rd experiment is the one which GUROBI used the heuristic solution as a starting solution for the original MILP.

The heuristic GMS solution for JEDDAH-PP was evaluated by GUROBI to have a 3.2% optimality gap. The heuristic schedule saved about 407 million liters of fuel during the given planning horizon (6.3% of the actual performance). The heuristic took about 10 seconds to produce a schedule for JEDDAH-PP. When GUROBI started from the heuristic solution, it was given a 1-hour time limit. The best solution had a 1.59% optimality gap, and saved 457 million liters of fuel (7.1% of actual consumption).

For MAKKAH-PP, the heuristic GMS achieved a savings of 49 million liters less than actual fuel consumption. Although this is about 190 million liters more than the pure MILP schedule for MAKKAH-PP mentioned above, heuristic GMS still proved full constraint validity in less than 10 seconds.
Table 5.2: Heuristic GMS experiment

<table>
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<th>Solver</th>
<th>Power Plant name / Type</th>
<th>Code stage</th>
<th>Experiments Inputs</th>
<th>Solver</th>
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<th>Code stage</th>
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<td>JEDDAH GT</td>
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<td>H-GMS to Code</td>
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<td>35 GUs / 4 T 2 C</td>
<td>35 GUs / 4 T 2 C</td>
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5.4 Partitioning results

5.4.1 Model construction

In this experiment, both the total reserve and spinning reserve constraints are be disabled. The purpose is to model constraints that mimic the actual situation of JEDDAH-PP during that period. The non-existence of those reserves in that time is justified as it was secured by other PPs of the network. Since the MILP already proved capability to solve models with full technical constraints (for JEDDAH-PP and other PPs), and the purpose here is to test the partitioning and solution combining process, this will allow a fair comparison between actual performance and this experiment.

The partitioning technique (explained in Ch-4.3) was programmed in MATLAB. After dividing the PP’s inputs, and each partition has its own demand, GUs and maintenance resources, the MATLAB code started to construct the MILP model for each separate partition.

The bottom part of Table 5.3 shows that the MILP construction time for JEDDAH-PP’s full-problem model was 53 minutes. When it was divided, total time to construct all of the 4 partitions was less than 14 minutes.

5.4.2 MILP solving process

The partitioning experiment was designed to be conducted using 2 different methods, the time-limit-solution method and the 1st-feasible-solution method:

1) In the time-limit-solution method, GUROBI is given a limited time (10 minutes) to solve the MILP for each partition. The best output schedule of each partition is consolidated into one solution, to be used by GUROBI as a start for JEDDAH-PP. The consolidated solution produced a schedule that saved about 480 million liters of fuel (7.5% of actual consumption), with a 2.1% optimality gap. Next, GUROBI was given 40 minutes to solve the full model using this solution as a starting point. GUROBI was able to reach a solution with 0.53% optimality gap. The final solution saved about 566 million liters of fuel (8.8% of actual fuel consumption. With 15 minutes to construct partitions’ models, 10 minutes to solve each partition, and 40 minutes for MILP solution improvement, the whole time-limit experiment was conducted within a 95-minutes time frame.
2) In the \textit{1}\textsuperscript{st}-\textit{feasible-solution} method, GUROBI is programed to stop once it finds a feasible solution. The solutions are collected into one solution, and used as a starting solution for the full model of JEDDAH-PP (in this case with a 10.5\% optimality gap). There were no savings in the consolidated solution. The schedule consumed about 74 million liters (1.2\% more than actual consumption). GUROBI was given a 40-minute time limit, and was able to reach to a solution with a 0.52\% optimality gap. This final solution saved about 567 million liters of fuel (8.8\% of actual fuel consumption). The difference here is that GUROBI was able to find the first feasible solution in less than 1 minute for each partition. The whole experiment of the \textit{1}\textsuperscript{st}-\textit{feasible-solution} was conducted within a 60-minute time frame.

For overall comparison purposes, the heuristic GMS technique was also used to solve the same (non-reserve constrained) model. The heuristic output schedule was used in the MILP model for the same constraints, and GUROBI was given 1-hour time limit to improve the schedule. Final schedule saved 557 million liters (8.7\% of actual consumption), and optimality gap reduced from 3.2\% to 0.69\%. 
Table 5.3: Partitioning experiments (JEDDAH-PP)

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**Optimality Gap Tracking**

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CHAPTER 6:
CONCLUSION AND DISCUSSION

6.1 GMS significance

Maintenance schedules affect the generation units (GU) readiness, and generation schedules impact how fast the GUs need to be maintained. The generation and maintenance scheduling (GMS) techniques consider constraints of both activities at the same time to produce the most efficient schedule.

In the Kingdom of Saudi Arabia (KSA), the government owns the major share of the Saudi Electricity Company (SEC). The SEC was and is still supported by the government. This makes the main objective of this work to be secure and reliable power service for the community. Now, the financial policies of the KSA are going through revolutionary changes which will move the country toward a more efficient operations (The Saudi 2030 Vision). Implementation of the GMS centralized decision system is expected to result in a remarkable financial savings for both generation and maintenance.

29 technical characteristics were identified from the generation and maintenance activities in the SEC’s power plants. The published models of the GMS were explored. The closest model to the SEC system satisfied 16 out of these 29 characteristics. The mathematical model proposed in Chapter 3 of this research satisfies all 29 characteristics.

One of the most important differences between this model and all previous models is that this model considers the effect of generation assignment on accelerating the GU’s need for the next preventive maintenance step. This dynamic relationship and all other constraints were modeled in a mixed integer linear program (MILP), constructed using MATLAB, and solved using GUROBI.

6.2 GMS experiments

The steam turbine power plant (ST-PP) models were solved in less than 10 minutes, regardless of model size. For gas turbine power plants (GT-PP), the sizes of the models generated and
their solution times are exponentially increasing as the number of GUs and the number of maintenance resources increases. For instance, the smallest model generated is for TAIF-PP, with 6 GUs and 1 maintenance team. That model has 13k variables and 12k constraints, and is solved in less than 5 minutes. In comparison, MAKKAH-PP has 18 GUs and 2 maintenance teams, size of the model is 45k variables and 22k constraints, and takes about an hour to solve. JEDDAH-PP has 35 GUs and 4 maintenance teams. The model has 110k variables and 44k constraints. GUROBI ran for 24 hours and the model never found a feasible solution, unless the heuristic GMS or the partitioning technique was used.

The main objective of the heuristic GMS developed in this research was intended to provide a feasible starting solution for the MILP models. However, the heuristic generated solutions for JEDDAH-PP and MAKKAH-PP that were actually more efficient than the historic performance of these PPs. The heuristics were very fast (taking less than 10 seconds) in providing schedules that consumed less, and satisfied all the constraints and characteristics noted earlier.

A partitioning technique was developed also to provide a feasible solution for starting the MILP. The technique was tested using two different methods: Time-Limit-Solution and 1\textsuperscript{st}-feasible-Solution. The 1\textsuperscript{st}-feasible-Solution method proved to be the fastest technique among all experiments, and it provided the most efficient schedule for the JEDDAH-PP experiment. It is conjectured that the partitioning technique will be the most efficient methodology for solving large multi-PP networks.

Multiple PP experiments in this study, especially for JEDDAH-PP, proved that the size of model, number of GUs and maintenance resources were not the only reason for the model to be difficult. Exploring the input data structure of the GUs in JEDDAH-PP was helpful to understand the critical GUs situations that caused the model to be more difficult. The partitioning dealt with those critical points and solved that complicity.

Experiments conducted in this research covered only 6 PPs of the SEC network, with a total capacity of 8.8 Giga Watt, during 2008-2010 (Data availability was the main constraint). The total savings for those PPs (individually experimented) in that time was about 1 million cubic tons of fuel. Knowing that the total generation capacity of the SEC now is around 55 GW, (more than 6 times the capacity of the PP’s studied), and the power demand in KSA now is
almost 180% of what it was in 2008. These facts give an indication that fuel savings could reasonably exceed 10 times the savings achieved in this study.

It is commonly agreed on that the GUs’ capacities can differ according to weather conditions like temperature and humidity. The current model can consider those variations and the GUs generation capacities can be entered for each time-period separately.

### 6.3 Model deliverables

Schedule accuracy, efficient consumption, and fast schedule production are the main features of the MILP code. When the preliminary scheduling experiments were presented to the planners of the SEC, they showed a remarkable interest in how it works. Instead of spending time and effort coordinating between the PPs and the load distribution center (LDC), these efforts can be directed toward improving data collection and the schedule implementation processes.

The greatest challenge that weakens the reliability of current planning procedures is when a GU failure occurs (or any other forced change in the schedule). Because of time limitations, the probability of having a new updated and efficient GMS is low. The new MILP can provide a fast updated and efficient schedule in less time.

Furthermore, this tool has the capability to fix any inputs if needed. For example, if specific maintenance projects are already committed to or under way, the MILP can take those event as permeant and find out the most efficient schedule compatible with them.

The current MILP can go further than the GMS application. It can be used as a decision-making tool. Many scenarios can be simulated to compare alternatives, like new generation capacities, new maintenance team allocation, etc.

The current model can be used to study and evaluate some of the generation and maintenance standards. For example, using the current resources, multiple experiments can be conducted to study the effect of maintenance window length, to find the length that has the best effect on both reliability and costs.
6.4 Future work

The current model can be expanded to contain the transmission inputs, (e.g. voltage control among the transmission overhead-lines network). It is important to consider power loss along the network. In the SEC, this task is being done now by the LDC.

Combined cycle (CC) modules are rarely used in the current network, (only 3 modules in RABIGH-PP), but it is very efficient in regard to fuel consumption. Modeling the GMS of the CC-GT using the current MILP is possible, but not included in this research. It needs further modeling analysis.
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Note: References from 01 to 98 are the previous published models. References starts at 101 are the review papers. And the official sources and web-based links start at 201.


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91


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93


APPENDICES
APPENDIX 1: Literature classification detail

The following tables list all previous GMS publications, which were classified throughout Chapter -2. The cells shaded in light-green, are the models that match the problem nature at the SEC, and were detailed studied in section 2.2.

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## APPENDIX 2: Experiments details,

### (SHOAIBAH-PP)

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<th>GUROBI</th>
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### 1 Demand satisfaction
- 1248

### 2 Service Hrs Limits
- 0

### 3 Maintenance Logic
- 22

### 4 Maint. Resources
- 2080

### 5 Maintenance window
- 0

### 8 Min Up/On time
- 0

### 8.1 Min. Down-Time
- 0

### TOTAL CONTRAINTS
- 4156

### Result File
- 6,075,791,811

### % GAP
- 2.0%
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| **1** Demand satisfaction     | 728        | 728        | 728        | 728        |
| **2** Single Slowness Cost    | 624 Y      | 624 Y      | 624 Y      | 624 Y      |
| **3** Demand Satisf           | 104 Y      | 104 Y      | 104 Y      | 104 Y      |
| **2** Service Hrs Limits      | 0          | 0          | 0          | 0          |
| **3** Type-1                  | NA         | NA         | NA         | NA         |
| **4** Type-2                  | NA         | NA         | NA         | NA         |
| **5** Type-3                  | NA         | NA         | NA         | NA         |
| **6** Type-4                  | NA         | NA         | NA         | NA         |
| **3** Maintenance Logic       | 12         | 12         | 12         | 12         |
| **4** Min. Starting Times     | 12 Y       | 12 Y       | 12 Y       | 12 Y       |
| **5** No repeating            | 0 Y        | 0 Y        | 0 Y        | 0 Y        |
| **6** Sequencing              | 0 Y        | 0 Y        | 0 Y        | 0 Y        |
| **7** Duration                | 0 Y        | 0 Y        | 0 Y        | 0 Y        |
| **5** Maint. Resources        | 1716       | 1716       | 1716       | 1716       |
| **1** Feasibility             | 0 Y        | 0 Y        | 0 Y        | 0 Y        |
| **2** Interference            | 312 Y      | 312 Y      | 312 Y      | 312 Y      |
| **3** Maintenance window      | 0          | 0          | 0          | 0          |
| **4** First Step Window       | NA         | NA         | NA         | NA         |
| **5** Between Steps           | NA         | NA         | NA         | NA         |
| **6** Total Reserve Excl Mi   | 104        | 104        | 104        | 104        |
| **7** Spinning Reserve        | 0          | 0          | 280        | 280        |
| **8** Min Up/Down Time        | 0          | 0          | 512        | 512        |
| **9** Min. Down Time          | 0          | 0          | 612        | 612        |
| **10** TOTAL CONTRANTS        | 2456       | 2560       | 2840       | 4070       |

| **Result File**               | RST - 1    | RST - 2    | RST - 3    | RST - 4    |
| **2** first Gap in sec         | 4.71       | 0.00       | 4.64       | 4.64       |
| **4** % Gap                     | 0.00%      | 0.00%      | 0.00%      | 0.00%      |
| **5** % Gap sec                 | 4.71%      | 4.64%      | 18.20%     | 4.44%      |
| **8** % Gap sec                 | 0.00%      | 0.00%      | 0.00%      | 0.00%      |
| **12** % Gap sec                | 4.71%      | 4.64%      | 18.20%     | 4.44%      |
| **24** % Gap sec                | 0.00%      | 0.00%      | 0.00%      | 0.00%      |

- Rabigh Steam
- Dbl Ssn 08-10
- Dantzig

100
## "MAKKAH" Power Plant

**Planning Horizon**
- 104

**Generals**
- 18 GU
- 2 Teams
- 2 Contractors

**Variables**
- 28080 Gen. Variables
- 16848 Maint. Variables
- 44,928 Total Variables

### Feasible Variables

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### Result File

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Dantzig Dantzig Dantzig Dantzig

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- "MAKKAH" Power Plant
- infeasible SpnRsv Ti
- infeasible SpnRsv t
- 98
- 98
- 99
- 99
- 100
- 100
APPENDIX 3: The MATLAB code.

The following is an example of the MATLAB code. This example is to construct the MILP of Makkah-PP for the planning horizon of 2008-2010.

clc
%%% A ) Reading Data Input Files:
%
 disp ' ..........................................................
 disp '   A ): Reading Data Input Files:
 tic;
 clear all
 disp ' 
 disp ' Demand        = xlsread('Data_Makkah_Dbl_Ssn.xlsx','Demand');  
 disp '    a. Demand Data stored in ......................... (DEMAND)
 disp ' 
 disp ' M_Seas         = xlsread('Data_Makkah_Dbl_Ssn.xlsx','Maint Season');  
 disp '    b. Maintenance seasons stored in ................ (M_Seas)
 disp ' 
 disp ' G_rate          = xlsread('Data_Makkah_Dbl_Ssn.xlsx','Gnrt');  
 disp '    c. Generation Levels stored in ..................... (G_rate)
 disp ' 
 disp ' F_rate           = xlsread('Data_Makkah_Dbl_Ssn.xlsx','Fuel');  
 disp '    d. Fuel Consumption stored in ...................... (F_rate)
 disp ' 
 disp ' Srv_Hrs_Rec  = xlsread('Data_Makkah_Dbl_Ssn.xlsx','Maint_Dur');  
 disp '    e. Service Hours Records stored in ............... (Srv_Hrs_Rec)
 disp ' 
 disp ' Md_idx          = xlsread('Data_Makkah_Dbl_Ssn.xlsx','Mnt_Dur_Cstr');  
 disp '    f. Maintenance Duration Const. stored in ...... (Md_idx)
 disp ' 
 disp ' Res_Cost      = xlsread('Data_Makkah_Dbl_Ssn.xlsx','Res Cost');  
 disp '    g. Maintenance Resources Costs stored in .... (Res_Cost)
 disp ' 
 disp ' Res_Feas      = xlsread('Data_Makkah_Dbl_Ssn.xlsx','Res Feas');  
 disp '    h. Maintenance Teams Capabilities stored in .. (Res_Feas)
 disp ' 
 disp ' OM_Stdr       = xlsread('Data_Makkah_Dbl_Ssn.xlsx','GUs');  
 disp '    i. GUs Maintenance Standards stored in ........ (OM_Stdr)
 disp ' 
 disp ' F_Li          = xlsread('Data_Makkah_Dbl_Ssn.xlsx','FLi');  
 disp '    c. Consumption Formulas stored in .................. (F_Li)
 disp '
 disp ' ..........................................................
 disp '   A ): Data Files Explored.
 toc
B ) Analysing the Basic input Data:

disp ’ B ):- Analysing the input Data:-'

tic;

% Demand information:
T = size(Demand,2)-2; % Length of Planning Horizon
D = (01.00) *Demand ( 14, 3 : T+2 ); % Demand at each t.

% Maintenance Season Milestones:
Tm1 = 26; % End of Maint. Season 1
Tm2 = 53; % Start of Maint. Season 2
Tm3 = 78; % End of Maint. Season 2

% Fuel consumption at each level:

% Generation Levels:
Ls  =size(G_rate,2); % # of Generation Levels.
GUs=size(G_rate,1); % # of Generation Units.

% G. Unit Service Hours
St_HR = Srv_Hrs_Rec ( 3:GUs+2 , 1 ); % Chose the Starting Service Hours Record
S_Lngt = OM_Stdr ( : , 7); % Maint. Step Length for Each GU.
Stp_Ctr = mod (St_HR,S_Lngt); % Maint. Step S.Hrs. Counter.
sh = 24*7; % Service hours in each period
W  = (0.30) * S_Lngt; % Maintenance Window Size

Min_Up= OM_Stdr ( : , 8);
Min_Dn= OM_Stdr ( : , 9);

M_stps = 3 ; % Max. # of Maintenance steps to be scheduled.
ms = M_Seas(2,:);
Rt = 2 ; % Defining Maintenance Season
Rc = 2 ; % Number of Maint. Teams
Rs = Rt+(Rc>0); % Contracting Capacity.
M_rate = Res_Cost ( 3:GUs+2 , 1 : (Rs*M_stps) ); % Total # of Maintenance Resources.
Mdus = Srv_Hrs_Rec ( 3:GUs+2 , [11, 15, 19, 23] ); % Maintenance Cost Matrix.
Mdu = Mdus(:,1:M_stps);
M_Feas = Res_Feas( 3:GUs+2 , 1 : (Rs*M_stps) ); % Duration of Next Maintenance

Min_W=ones(size(S_Lngt));
for u=1:GUs
  if cell ( ((S_Lngt(u)) -W(u))/(sh) ) >=1
    Min_W(u) = cell ( ((S_Lngt(u)) -W(u))/(sh) );
  else
    Min_W(u)=1;
  end
end

Min_M1= ceil (((S_Lngt)-W-(Stp_Ctr))/(sh)))+1; % Minimum possible starting time for maintenance step-1.
for u=1:GUs; if Min_M1(u)<=0; Min_M1(u)=1; end; end % Minimum possible starting time for maintenance step-2.
Min_M2= Min_M1 + Mdu(:,1) + Min_W;
Min_M3= Min_M2 + Mdu(:,2) + Min_W;
Min_M4= Min_M3 + Mdu(:,3) + Min_W;
% Minimum possible starting time for maintenance step-4.
Min_M = [ Min_M1, Min_M2, Min_M3, Min_M4];  % Minimum possible starting time for maintenance steps.

[ Min_W, Min_M1, Mdu(:,1), Min_M2, Mdu(:,2), Min_M3, Mdu(:,3), Min_M4];
TGU = zeros(GUs*T,1);  for k=1:T;  TGU((k-1)*GUs + 1 : k*GUs) = repmat(k,GUs,1);  end;

% Initial Model Matrices:
Xi = zeros(GUs,T);  % Generation (On 1/ Off 0).
Li = zeros(GUs,T);  % load variable (1,2,3,4,5,6).
Mi = zeros(GUs,T);  % Maintenance (On 1/ Off 0).
Ri = zeros(GUs,T);  % Resource ID (1,2).
Si = zeros(GUs,T);  % Maintenance Steps.

% 2) Basic Matrices:
GG = repmat(G_rate,T,1); size(GG);
Gzeros=zeros(GUs*T,Ls); size(Gzeros);
Gones=ones(GUs*T,Ls); size(Gones);
Mzeros=zeros(GUs*T,Rs*M_stps); size(Mzeros);
Mones=ones(GUs*T,Rs*M_stps); size(Mones);

disp('.....................................................'
disp('   B ):- Analysing the input Data:-'
disp(' B )...........................

disp(' Periods of the Planning Horizon.......(T) = ', num2str(T) ')
disp(' Number of Generation Units...........(GUs) = ', num2str(GUs) ')
disp(' Number of Generation Levels.........(Ls) = ', num2str(Ls) ')
disp(' Number of Maintenance Steps........(M_stps) = ', num2str(M_stps) ')
disp(' Number of Maintenance Teams.........(Rt) = ', num2str(Rt) ')
disp(' Maintenance Contractor Capacity....(Rc) = ', num2str(Rc) ')
disp(' Total Maintenance Resources...........(Rs) = ', num2str(Rs) ')
disp('............................
toc

%%  (C ) Model Setup Starting %%%%%%%%%%%%%%%%%%%%%%  
disp('....................................................................................');
disp('   C ):- Model Setup Started:-'
disp('........................................................................
tic;
FF = repmat(F_rate,T,1); size(FF);
MM= repmat(M_rate,T,1); size(MM);
clear mp
    mp = Milp('GMS');
    mp.addobj('min',FF,MM);  % Objective.

disp('.....................................................';
disp('   Studying Objective Function Variables :')
disp('............................................................
disp(' Number of Generation Variables = ', num2str(GUs), ' X ', num2str(T), ' X ', num2str(Ls), ' = ', num2str(GUs*T*Ls))
disp(' Number of Maintenance Variables = ', num2str(GUs), ' X ', num2str(T), ' X ', num2str(Rs*M_stps), ' = ', num2str(GUs*T*Rs*M_stps))
disp(' Total number of Variables = ', num2str(GUs*T*Ls), '+ ', num2str(GUs*T*Rs*M_stps), ' = ', num2str((GUs*T*Ls)+(GUs*T*Rs*M_stps)))
toc
Modeling_Total_Time = toc;
%% 1 ) Demand Satisfaction constraints: (Dbl Ssn)

disp '................................................................................................................'

disp ' 1):- Demand Satisfaction constraints:'
tic;
cntr1=0;
cntr2=0;

for t=1:T

for u = 1:GUs

if G_rate(u,Ls)>0

  Gx=zeros(GUs*T,Ls);
  Gx((t-1)*GUs+u,:) = ones(1,Ls);

  Mx=zeros(GUs*T,Rs*M_stps);
  Mx((t-1)*GUs+u,:) = ones(1,Rs*M_stps);
  cntr1 = cntr1 +1;
  mp.addcstr( Gx, Mx, '<=', 1 );

  Gt =zeros(GUs*T,Ls);
  Gt((t-1)*GUs+u,:) = G_rate(u);
  Gt=[zeros((t-1)*GUs,Ls); G_rate((t-1)*GUs,Ls)];
  Gt = sh * ( Tt .* GG );
  Gt = [zeros((t-1)*GUs,Ls); (sh*G_rate); zeros((T-t)*GUs,Ls)];
  mp.addcstr( Gt , 0, '>=', D(t) );
  cntr2 = cntr2 +1;

end
end

disp(['                         Single Decision constraints = ', num2str(cntr1)])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp(['                     Demand Satisfaction constraints = ', num2str(cntr2)])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp('                           Total constraints in this group = ', num2str( cntr1 + cntr2 ) )
disp ''
%% 2) Service Hours Limits: (Db1 Ssn) %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

disp '.............................................................'
disp ' 2):- No generation behind Service Hours Limits :- '
disp ' .............................................................'

%% 2-1) Type-1: S.Hrs. WITH NO Maintenance : %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

tic;
cnt1=0;
for u=1:GU
    if G_rate(u,Ls)>0
        Gh=zeros(GUs*T, Ls);
        Mh=zeros(GUs*T, Rs*M_stps);
        for t= 1:T
            Gh((t-1)*GUs+u,:)=sh;
            if ms(t) ==1
                Mh((t-1)*GUs+u, 1+(Step-1)*Rs) = (-min( ((t-1)*sh)+(Stp_Ctr(u)) , (S_Lngt(u))) / Mdu(u,Step) );
            end
            end
        cntr1=cnt1+1;
        %cnt1
        [%TGU, (repmat([1:GU]',T,1)), Gh(:,1), Mh]
        mp.addcstr( Gh, Mh , '<=', (S_Lngt(u) -Stp_Ctr(u)) );
        %Yes
    end
end
disp('2-1):- Type-1: S.Hrs. with NO Maintenance = ', num2str(cnt1) ])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp ' .................................

%% 2-2) Type-2: S.Hrs. BEFORE any Maintenance .........................(---M). %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
tic;
cnt2=0;
%EE=zeros(1546,3);YY=zeros(T,8);
Step = 1;
    % This part applicable for Step-1 only
for u = 1 : GU
    if G_rate(u,Ls)>0
        %cntsr=0;
        for cstr= Min_M(u,Step) : (Tm3 -Mdu(u,Step)+1)
            if sum ( ms( cstr : (cstr+Mdu(u,Step) -1) ) ) == ( Mdu(u,Step) )
                Gh= zeros( GU*T, Ls );
                Mh= zeros( GUs*T, Rs*M_stps );
                for t= 1: (cstr + Mdu(u,Step) -1 )
                    if t < cstr
                        Gh( (t-1)*GUs +u , :)=sh;
                    end
                    if ms(t) ==1
                        Mh(( t-1)*GUs+u, 1 : Rs ) = (- min( ((t-1)*sh)+(Stp_Ctr(u)) , (S_Lngt(u))) / Mdu(u,Step) );
                    end
        end
end
end
if t >= cstr
    Mh( (t-1)*GUs+u, 1 : Rs ) = ( S_Lngt(u) / Mdu(u,Step) ) ;
end
YY(t,:)=[ cstr, t, (-min(((t-1)*sh)+(Stp_Ctr(u))),(S_Lngt(u))/Mdu(u,Step)), Y.MM( (t-1)*GUs+u, 1:Rs)];
end
cntr2=cntr2+1;
%cntrS=cntrS+1;
%cntr2
[TGU, (repmat([1:GUs]',T,1)), Gh(:,1), Mh]
mp.addcstr(Gh, Mh , '<=', ( 2*S_Lngt(u) -Stp_Ctr(u) ) );
%Yes
%EE(cntr2,:)=[cntr2 u cstr];
end
%HH(u,:) = [u, Mdu(u,1), cntrS, cntr2];
end
end
end

disp([' 2-2): Type-2:  S.Hrs. BEFORE Maintenance = ', num2str(cntr2) ])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp ''

% 2-3) Type-3: S.Hrs. AFTER any Maintenance :......................... (M---). %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
cntr3=0;
Mdu_Stp = repmat(S_Lngt,1,size(Mdu,2))./Mdu;
for i = 1: M_stps
    Md_Rs_St(:, (i-1)*Rs+1:i*Rs) = repmat(Mdu_Stp(:,i),1,Rs);
end
for Step = 1 : M_stps
    for u=1:GUs
        if G_rate(u,Ls)>0
            Min_S = floor ( (S_Lngt(u))/(sh) );
            for cstr= Min_M(u,Step) : (T -Min_S -Mdu(u,Step) +1)
                if sum ( ms( cstr : (cstr+Mdu(u,Step) -1) ) == ( Mdu(u,Step) )
                    Gh=zeros(GUs*T,Ls);
                    Mh=zeros(GUs*T,Rs*M_stps);
                for t = cstr : T
                    if t >= (cstr +Mdu(u,Step) )
                        Gh( (t-1)*GUs+u , : ) = sh ;
                    end
                    if ms(t)==1
                        if t< ( cstr + Mdu(u,Step) )
                            Mh( (t-1)*GUs+u , ( 1+(Step-1) *Rs ) : (Step*Rs) ) = ( S_Lngt(u) / Mdu(u,Step) ) ;
                else
                    Mh( (t-1)*GUs+u , ((Step*Rs) +1) : Rs*M_stps ) = -Md_Rs_St( u, ((Step*Rs) +1) : Rs*M_stps ) ;
                end
            end
        end
        cntr3=cntr3+1;
    %cntr3
    [TGU, (repmat([1:GUs]',T,1)), Gh(:,1), Mh]
    mp.addcstr(Gh, Mh , '<=', ( 2*S_Lngt(u) ));
end
end
end
disp('2-3): Type-3: S.Hrs. AFTER Maintenance = ', num2str(cntr3))
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp(''',
%
2-4) Type-4: S.Hrs. BETWEEN any Two Maintenances:..............(M---M). %%%
tic;

% 4 ) Maintenance Scheduling Logic: (Dbl Ssn) %%%%%%%

disp(''',
%% 3 ) Maintenance Scheduling Logic: (Dbl Ssn) %%%%%%%
disp(''',
%% 3-1): Minimum Starting time for each Maintenance step:____
tic;
cntr1=0;
%[ [(1:GUs)'], Min_W, Min_M1, Mdu(:,1), Min_M2, Mdu(:,2), Min_M3, Mdu(:,3), Min_M4];
  for u=1:GUs;
    if G_rate(u,Ls)>0
    end
  end
end
end

disp('2-4): Type-4: S.Hrs. BETWEEN Maintenances = ', num2str(cntr4))
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp(''',
% Total number in this group = ', num2str(cntr1 +cntr2 +cntr3 +cntr4))
disp(''',

disp('2-3): Type-3: S.Hrs. AFTER Maintenance = ', num2str(cntr3))
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp(''',

cntr4=0;
  for u=1:GUs
    if G_rate(u,Ls)>0
      for Step = 1 : M_stps-1
        Min_Su = floor ( (S_Lngt(u))/(sh));
        for cstr1 = Min_M(u,Step) : Mdu(u,Step) : (Tm3 - Mdu(u,Step+1) - Min_Su +1);
          if ms(cstr1) == 1
            for cstr2 = ( Min_M(u,Step+1) ) : Mdu(u,(Step+1)) : Tm3;
              if cstr1 + Min_Su <= cstr2
                Gh=zeros( GUs*T, Ls);
                Mh=zeros( GUs*T, Rs*M_stps);
                Mh( (cstr1 -1)*GUs+u , (1+ (Step-1)*Rs) : (Step*Rs) ) = S_Lngt(u);
                Mh( (cstr2 -1)*GUs+u , (Step*Rs) +1 : (Step+1)*Rs ) = S_Lngt(u);
                for t = (cstr1 +1) : (cstr2 -1)
                  Gh( (t-1)*GUs+u , : ) = sh ;
                end
                cntr4 = cntr4+1;
                % cntr4, cstr1, cstr2
                % [TGU, (repmat([1:GUs]',T,1)), Gh(:,1), Mh]
                mp.addcstr(Gh, Mh , '<=', (3*S_Lngt(u)));
              end
              if cstr1 + Min_Su >= cstr2
                Gh= zeros( GUs*T, Ls);
                Mh=zeros( GUs*T, Rs*M_stps);
                Mh( (cstr1 -1)*GUs+u , (1+ (Step-1)*Rs) : (Step+1)*Rs ) = S_Lngt(u);
                Mh( (cstr2 -1)*GUs+u , (Step*Rs) +1 : (Step+1)*Rs ) = S_Lngt(u);
                for t = (cstr1 +1) : (cstr2 -1)
                  Gh( (t-1)*GUs+u , : ) = sh ;
                end
                cntr4 = cntr4+1;
                % cntr4, cstr1, cstr2
                % [TGU, (repmat([1:GUs]',T,1)), Gh(:,1), Mh]
                mp.addcstr(Gh, Mh , '<=', (3*S_Lngt(u)));
              end
            end
          end
        end
      end
    end
  end
end
end
Mhw = zeros(GUs*T, Rs*M_stps);

for Step = 1 : M_stps
    for t=1:T
        if t < Min_M(u,Step) || ms(t) == 0 % Min. Start Time & Mint. Season.
            Mhw ((t-1)*GUs+u, (1+(Step-1)*Rs : Step*Rs)) = 1;
        end
    end
    for t=1:T
        if ms(t) == 1
            Mhw ((t-1)*GUs+u, (1+(Step-1)*Rs : Step*Rs)) = 1; % Min. Start Time & Mint. Season.
        end
    end
    cntr1 = cntr1 +1;
    mp.addcstr(0, Mhw, '<=', 0);
end
end
cntr1 = cntr1 +1;
%cntr1
%Mhw
mp.addcstr(0, Mhw, '<=', 0);
end
disp(['3-1):- Minimum starting time for each step = ', num2str(cntr1)])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp('3-1):
end
end
disp(['3-2):- Every Maintenance Step can be executed one time only:
end
cntr2 = 0;
for u=1:GUs
    if G_rate(u,Ls)>0
        for Step = 1 : M_stps
            Mr = zeros(GUs*T,Rs*M_stps);
        end
        for t=1:T
            if ms(t) == 1
                Mr ((t-1)*GUs+u, (1+(Step-1)*Rs : Step*Rs)) = 1;
            end
        end
        cntr2 = cntr2 +1;
        %cntr2
        %Mr
        mp.addcstr(0, Mr, '<=', Mdu(u,Step));
    end
    end
disp(['3-2):- No Maintenance Steps repeating = ', num2str(cntr2)])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp('3-2):
end
end
disp(['3-3):- The Correct Sequence of Maintenance Steps:
end
cntr3 = 0;
for u=1:GUs
    if G_rate(u,Ls)>0
        for Step = 2 : M_stps
            for t= Min_M(u,Step) : Mdu(u,Step) : Tm3
                if ms(t) == 1
                    Mr = zeros(GUs*T,Rs*M_stps);
                    Mr ((t-1)*GUs+u, ((Step-1)*Rs +1) : (Step * Rs)) = -100;
                    for cstr = Min_M(u, (Step-1)) : (t-1)
                        Mr ((cstr-1)*GUs+u, ((Step-2)*Rs +1) : ((Step-1)*Rs)) = (100 / Mdu(u,(Step-1)))
                    end
                end
            end
        end
    end
end
disp(['3-3):
end
end
Mr;
mp.addcstr( 0, Mr , '>=', 0 );
cntr3 =cntr3 +1;
end
end
disp(["\text{Sequencing the Maintenance Steps =} ", num2str( cntr3 ) ])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp ',

%%% 3-4):- The Maintenance Durations :

tic;
cntr4=0;
for Step = 1 : M_stps
for u= 1: GUs
    if G_rate(u,Ls)>0
        if Mdu(u, Step)>1
            Md=zeros(GUs*T, Rs*M_stps);
            for t= 1:T
                Md( (t-1)*GUs+u, ((1+(Step-1)*Rs) : (Step*Rs)) ) = Md_idx( Mdu(u,Step), (t+1) );
            end
            [(1:GUs*T)', Md] ;
            mp.addcstr(0,Md,'=',0);
            cntr4=cntr4+1;
        end
    end
end
disp(["\text{Maintenance Durations constraints =} ", num2str( cntr4 ) ])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp ',
disp(["\text{Total constraints in this group =} ", num2str( cntr1 + cntr2 + cntr3 + cntr4) ])
disp ',

%%% 4) Maintenance Resources: (Dbl Ssn)

disp ',
disp(["\text{Maintenance Resources Constraints:} "])'

disp ',

%%% 4-1):- Maintenance Teams Technical Capabilities:

tic;
cntr1 =0;
%MF= ( repmat(M_Feas,T,1) -1); size(MF);
%mp.addcstr( 0 , MF , '<=', 0 );
%cntr1 =cntr1 +1;
%%% OR %%%
for u=1:GUs
    if G_rate(u,Ls)>0
        for Step = 1 : M_stps
            for Rstp= 1: Rs
                if M_Feas( u, (Step-1)*Rs +Rstp)==1
                    MF =zeros( GUs*T, Rs*M_stps);
                    for t= 1:T

MF( (t-1)*GUs+u, ((Step-1)*Rs +Rstp) ) = ( 1 - M_Feas( u, ((Step-1)*Rs +Rstp) ) )
mp.addcstr( 0 , MF , '<=', 0 );
cntr1 =cntr1 +1;
end
end
end

%end
disp([' 4-1):- Teams Technical Capabilities = ', num2str( cntr1 ) ])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp ' 4-1):

%%% 4-2):- Teams handling Capacities :_______________________
tic;
cntr2=0;
for t=1:T
% Team can only maintain 1 unit at a unit time:
for r= 1: (Rs-1)
Mr=zeros (GUs*T, Rs*M_stps);
for Step = 1 : M_stps
Mr( ( (t-1)*GUs+1) : (t*GUs) , ((Step -1)*Rs +r) ) = M_Feas(:, (Step -1)*Rs +r);
end
cntr2 =cntr2 +1;
%cntr2
%[TGU, (repmat([1:GUs]',T,1)), Mr]
mp.addcstr( 0, Mr, '<=', ms(t) );  %3
end

%Contractor can maintain Three of them at a time:
Mc=zeros (GUs*T, Rs*M_stps);
for Step = 1 : M_stps
Mc( ( (t-1)*GUs+1) : (t*GUs) , (Rs*Step) ) = M_Feas(:, (Step*Rs));
end
cntr2 =cntr2 +1;
%cntr2
%Mc
mp.addcstr( 0, Mc, '<=', Rc*ms(t) );  %3
end
disp([' 4-2):- Teams handling Capacities = ', num2str( cntr2 ) ])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp ' 4-2):

%%% 4-3):- Preventing Teams' interference, (GUs can be maintained by one team only)
tic;
cntr3=0;
%EE=zeros(27015,6);
for Step = 1 : M_stps
for u=1:GUs
if G_rate(u,Ls)>0
if Mdu(u,Step)>= 2
   inside = Mdu(u,Step) -1;
   for R =1 : Rs
      if M_Feas(u, ((Step-1)*Rs +R))==1
         %for inside = 1 : ( Mdu(u,Step) -1)
         % Assume Min_M + Mdu < Tm1
         for t = Min_M(u,Step) : Tm3  % (T - inside -1 )
            if ms(t)==1
               %contractor can maintain Three of them at a time:
               Mc( ( (t-1)*GUs+1) : (t*GUs) , (Rs*Step) ) = M_Feas(:, (Step*Rs));
               end
               cntr2 =cntr2 +1;
               Mc
me.addcstr( 0, Mc, '<=', Rc*ms(t) );  %3
end
end
end
end
end
end
end
end
end
end
end
disp([' 4-3):

toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp ' 4-3):

%%% 4-4):- Preventing Teams' interference, (GUs can be maintained by one team only)
tic;
cntr3=0;
%EE=zeros(27015,6);
for Step = 1 : M_stps
for u=1:GUs
if G_rate(u,Ls)>0
if Mdu(u,Step)>= 2
   inside = Mdu(u,Step) -1;
   for R =1 : Rs
      if M_Feas(u, ((Step-1)*Rs +R))==1
         %for inside = 1 : ( Mdu(u,Step) -1)
         % Assume Min_M + Mdu < Tm1
         for t = Min_M(u,Step) : Tm3  % (T - inside -1 )
            if ms(t)==1
               %contractor can maintain Three of them at a time:
               Mc( ( (t-1)*GUs+1) : (t*GUs) , (Rs*Step) ) = M_Feas(:, (Step*Rs));
               end
               cntr2 =cntr2 +1;
               Mc
me.addcstr( 0, Mc, '<=', Rc*ms(t) );  %3
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
end
Rsc = zeros (GUs*T,Rs*M_stps);
if t== Min_M(u,Step) || t== Tm2
  for c1 = t : t + inside
    if c1 == t + inside
      Rsc( (c1 -1) * GUs+u, (Rs*(Step-1) +R) ) = -100;
    else
      Rsc( (c1 -1) * GUs+u, (Rs*(Step-1) +R) ) = (100/inside);
    end
  end
disp(4-3):

%inside, t, cntr3
%[TGU, (repmat([1:GUs]',T,1)), Rsc]
mp.addcstr ( 0, Rsc, '<=' , 0);
end
cntr3 =cntr3 +1;
end
disp(['','Preventing Teams interference = ',num2str( cntr3 ) ])
toc
%inside, t, cntr3
%[TGU, (repmat([1:GUs]',T,1)), Rsc]
Modeling_Total_Time = Modeling_Total_Time + toc;
disp(['','Total constraints in this group = ',num2str( cntr1 + cntr2 + cntr3 ) ])

disp('5):

%% 5) Maintenance window:-(Dbl Ssn) %%%%%%%%%%%%%%%%%%%
% This Part is only applicable for Maintenance Step-1 )
% 5):
% Maintenance Windows Constraints:

tic;
cntr1 =0;
%EE = zeros(1285,3);
for u=1:GUs
  if G_rate(u,Ls)>0
    Step = 1;
    for cstr = Min_M(u,Step) : Mdu(u,Step) : Tm3
      if ms(cstr) == 1
        Gh = zeros(GUs*T,Ls);
        Mh1 = zeros(GUs*Step, Rs*M_stps);
        Mh1( (cstr-1)*GUs+u , 1:Rs ) = (S_Lngt(u) - W(u));
        for t=1 : (cstr -1)
          %Mh1( (t-1)*GUs+u, 1:Rs) = (S_Lngt(u) - W(u));
          Gh( (t-1)*GUs+u, :) = -sh ;
        end
        disp(['5):

% This Part is only applicable for Maintenance Step-1 )
% Maintenance Windows Constraints:-']
% 5):
% First Maintenance Window Control_______ ( ---w-- M ) _________

cntr1 = cntr1 + 1;
%EE (cntr1, :) = [cntr1, u, cstr];
%cnntr1; u;
%[Gh, Mhw];
mp.addcstr(Gh, Mh1, '<=', Stp_Ctr(u));
end
end
end
end
end
disp(['5-1):- First Maintenance Step Window = ', num2str(cntr1)])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp('')
%
5-2):- Window between Maint. Steps___________ ( M ---w-- M)________
tic;
cntr2=0;
for u=1:GUs
    if G_rate(u,Ls)>0
        for Step = 1 : M_stps-1
            for cstr1 = Min_M(u,Step) : Mdu(u,Step+1)
                if ms(cstr1) == 1
                    for cstr2 = (Min_M(u,Step+1)) : Mdu(u,(Step+1)) : Tm3
                        if ms(cstr2) == 1
                            if cstr1 < cstr2
                                Gh=zeros( GUs*T, Ls);
                                Mh=zeros( GUs*T, Rs*M_stps);
                                Mh( (cstr1-1)*GUs+u , (1+ (Step-1)*Rs) : (Step*Rs) ) = (S_Lngt(u) - W(u));
                                Mh( (cstr2-1)*GUs+u , ((Step*Rs) +1) : (Step+1)*Rs ) = (S_Lngt(u) - W(u));
                                for t = (cstr1 +1) : (cstr2 -1)
                                    Gh( (t-1)*GUs+u , :) = sh;
                                end
                                cntr2 = cntr2+1;
                                % cstr4, cstr1, cstr2
                                % [TGU, (repmat([1:GUs]',T,1)), Gh(:,1), Mh]
                                mp.addcstr(Gh, Mh, '==', (S_Lngt(u) - W(u)));
                            end
                        end
                    end
                end
            end
        end
    end
end
disp(['5-2):- Window between Maint. Steps = ', num2str(cntr2)])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp('')

disp(['6):- Total Reserve Constraints: ']
disp('')
tic;
cntr2=0;
Ds=D/sh;
TR=0.05;
%%% Excluding GU receiving maintenance:___________________
% # of constraints = (0).
for t=1:T
    %Mt=zeros(GUs*T,Rs*M_stps);
    %Mt ( (((t-1)*GUs+1): (t*GUs)),:) = repmat( (G_rate(:,Ls)), 1, Rs*M_stps);
    %Mt;
    mp.addcstr( 0, Mt, '<=', ( sum(G_rate(:,Ls)) - (1+TR)*Ds(t) )
    cntr2=cntr2+1;
end
%%% Excluding GU exceeded the window W2:___________________
% # of constraints = (0).
disp([' Tota'.......Total Reserve constraints =       ' , num2str( cntr2 ) 
			
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp('

%%% 7) Spinning Reserve Constraints: %%%%%%%%%%%%%%%%%%%%%%%
  7.1) Studying the Spinning Reserve Feasibility:
MaxGUs = 1; %Originaly only 1 One GU, the largest capacity GU.
GR = G_rate(:,Ls);
Max_Spn = sum(GR);
for n=1:MaxGUs
    [Y,I] = max(GR);
    Max_Spn= sum(GR)- Y;
    GR(I)=0;
end
MaxGUs, GR, Max_Spn
for t= 1:T
    if ( D(t) / sh ) <= Max_Spn
        Spn_Feas ( t ) = 1;
    else
        Spn_Feas ( t ) = 0;
        disp([' Spinning Reserve is infeasible at period Number :     ' , num2str( t ) ])
    end
end
if sum(Spn_Feas) < T
disp ' Modeling the Spinning Reserve Constraints for the feasible periods:- '
disp '
else
disp ' The Spinning Reserve Constraints are feasible During all periods:- '
disp ' 
end
'' 7.2) Modeling the Spinning Reserve Constraints:

```matlab
for t=1:T
    if Spn_Feas(t) == 1
        GR = G_rate(:,Ls);
        for u=1:GUs, if GR(u)==0, GR(u)=NaN; end, end
        Rsrv=zeros(GUs*T,Ls);
        Ds = ( D(t) / sh );
        for u=1:sum(G_rate(:,Ls)>0)-1  % Considering Partitionning Experiment.
            [Y,I] = max(GR, [], 'omitnan');
            Rsrv((t-1)*GUs+1):((t-1)*GUs+1) = -repmat( G_rate(:,Ls), 1, Ls);
            Rsv((t-1)*GUs+1,:) = Ds;
            cntr1=cntr1+1;
            % cntr1
            % [TGU, (repmat([1:GUs]',T,1)), Rsrv ]
            mp.addcstr( Rsrv, 0, '<=', 0 );
            GR(I)=NaN;
        end
        end
    end
end
disp('Spinning Reserve constraints = ', num2str( cntr1 ));

toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp('','

%%% 8) Minimum Up/Down-time Constraints: %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp('');
disp('8):- Minimum Up/Down-time Constraints: '-'
disp('');

%%%8.1)% Minimum "Up" time: ______________________________
tic;

cntr1=0;

% first period constraint:
if Min_Up(u)>= 2
    for u=1:GUs,
        Gud=zeros(GUs*T,Ls);
        Gud(u,:) =1;
        Gud(GUs+u,:)=-2;
        Gud;
        mp.addcstr(Gud,0,'<=',0);
        cntr1=cntr1+1;
    end
end

%_________following:_________
for u=1:GUs,
    if Min_Up(u)>= 2
        for Gud_id = 1:Min_Up(u)-1
            for t=1:T-(Gud_id)-1
                Gud = zeros(GUs*T,Ls);
```
for cntn = 1 : Gud_id+2

if cntn == 1
    Gud( (t-1)*GUs+u,:) = -60/2;
elseif cntn == Gud_id+2
    Gud( (t+cntn-2)*GUs+u,:) = -60/2;
else
    Gud( (t+cntn-2)*GUs+u,:) = (60/Gud_id);
end
end

Gud;
mp.addcstr(Gud,0,'<='.,59);
cntr1=cntr1+1;
end

end
end

disp(['8-1):- Minimum Up-time constraints = ', num2str( cntr1 ) ])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp'

%%% (7.2)% Minimum "Down" time: ____________________________

tic;
cntr2=0;
% first period constraint:
% No Need:
% Assumed that the GU was already in Shut-Down status...

%_________following:_________

for u=1:GUs;
    if Min_Dn(u)> = 2
        for Gud_id = 1:Min_Dn(u)-1

            for t=1:T-(Gud_id)-1
                Gud = zeros(GUs*T,Ls);
            end

            for cntn = 1 : Gud_id+2

                if cntn == 1
                    Gud( (t-1)*GUs+u,:) = -60/2;
                elseif cntn == Gud_id+2
                    Gud( (t+cntn-2)*GUs+u,:) = -60/2;
                else
                    Gud( (t+cntn-2)*GUs+u,:) = (60/Gud_id);
                end
            end
        end
    end
end
Gud;  
mp.addcstr(Gud,0,'>=',-59);  
end
end

cntr2=cntr2+1;
end
end

disp(['                   7-2):- Minimum Down-time constraints = ',num2str( cntr2 ) ])
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp('                  Total constraints in this group = ',num2str( cntr1 + cntr2 ) ])
disp('                     ');

%% 11) Model Setup closed %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%save MP_Jeddah_3Stps_D100_W30_NoSpin_NOV11 mp
save Nov_29_Makkah_(Full_) mp

disp('                     ');
disp('  11):- Model Setup Completed                     ');
toc
Modeling_Total_Time = Modeling_Total_Time + toc;
disp(['Total Model Constructing Time = ',num2str( floor(Modeling_Total_Time) ),' Seconds', ])
disp('                     ');
disp('                     ');

disp('                     ');

disp('                     ');

disp('                     ');
%% 12-1) CPLEX Solver
 disp%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp '................................................................................................................'
disp '................12-1):- CPLEX Solver started:'
disp' 
 tic;
cp = Cplex;
cp.Model = mp.Model
cp.Param.timelimit.Cur=72000
%save CP_Makkah_3Stps_D100_W30_Oct21_NoSpin cp
cp.solve
x = cp.Solution.x;
TC = cp.Solution.objval;
Total_Cost = TC*sh;
disp' 
disp '       12-1):- CPLEX Solver finished .................',
disp' 
disp('[Number of Solutions Found = ', num2str(size(cp.Solution.pool.solution,1)),']')
format long g;
disp('Final Plan Total Cost =', num2str(Total_Cost))
format short g;
disp' 
toc
disp' ' 

%% 12-2) Extracting CPLEX Results
 disp.............................................
disp'...................................................................' 
disp'................12-2):- Extracting CPLEX Results:--'
disp' 
tic; 
LM= reshape(x, [GUs*T,(Ls+(Rs*M_stps))]);
% Generation Plan: _______________
LL = int8( (LM( :, 1:Ls)).*repmat((1:Ls),GUs*T,1));
for t=1:T; Li(:,t)= sum(LL((1+(t-1)*GUs : GUs*t)),2); end
Xi =Li>0 ;
disp '1) Generation Status __ Done', 
Li ;
disp '2) Levels of Generationi __ Done',
% Maintenance Plan: _______________
RR = int8( (LM( :, (Ls+1) : (Ls + Rs*M_stps)) ).*repmat((1:Rs),GUs*T,M_stps) );
for t=1:T; Ri(:,t)= sum(RR((1+(t-1)*GUs : GUs*t)),2); end
Ri ;
disp '3) Maintenance Resources __ Done',
Mi=Ri>0;
disp '4) Maintenance Status __ Done',
% Maintenance Steps: _______________
Si = zeros(GUs,T);
for s=1:M_stps; ss( 1, ( (s-1)*Rs +1 : s*Rs ) ) = s*ones(1,Rs); end
SS = int8( (LM( :, (Ls+1) : (Ls + Rs*M_stps)) ).*repmat( ss ,GUs*T,1) );
% for rs= 1:M_stps;
repmat(rs,GUs*T,rs);end;
for t=1:T; Si(:,t)= sum( SS( (1+(t-1)*GUs : GUs*t ), :) ,2); end
Si ;
toc 
disp '................12-2):- CPLEX Results extracted ..........',
disp' ' 

118
 disp '................................................................................................................',
% disp '................13-1): GUROBI Solver started: 
tic;
clear model params
model = mp.milp2gb;
%model.start = full(x0'); % Incumbent must be a non-sparse (dense) vector
%model.start = [x.FF, x.MM]; % Incumbent must be a non-sparse (dense) vector
%model.start = [HS_FF, HS_MM] ; % Incumbent must be a non-sparse (dense) vector
params.outputflag = 1;
params.timelimit = 7200;
params.MIPGap = 0.01;
result = gurobi(model,params);
x = mp.namesolution(result.x);
TCgb = result.objval;
tgb = result.runtime;
toc
% disp '................13-1): GUROBI Solver finished ..........',
% disp '.....................................................................................',
% disp ' ',
%% 13-2) Extracting GUROBI Results
% disp '.............................................................................................'
% disp '................13-2): Extracting GUROBI Results: ',
% disp ' ',
tic;
% Generation Plan: 
LL = int8 (x.FF .* repmat((1:Ls),GUs*T,1));
for t=1:T
    Li(:,t)= sum( LL((1+(t-1)*GUs : GUs*t),:),2 );
end

Xi =Li>0 ;
disp ' 1) Generation Status __ Done',
Li ;
disp ' 2) Levels of Generationi __ Done',

% Maintenance Plan: 
RR = int8 (x.MM .* repmat((1:Rs),GUs*T,M_stps));
for t=1:T; Ri(:,t)= sum(RR((1+(t-1)*GUs : GUs*t),:),2);
end

Ri ;
disp ' 3) Maintenance Resources __ Done',
Mi=Ri>0;
disp ' 4) Maintenance Status  __ Done',

% Maintenance Steps: 
for s=1:M_stps; ss( 1, ( (s-1)*Rs +1 : s*Rs) ) = s*ones(1,Rs); end
SS = int8 (x.MM .* repmat( ss ,GUs*T,1) );
for t=1:T; Si(:,t)= sum( SS( (1+(t-1)*GUs : GUs*t ), :) ,2);
end
Si ;
disp ' 5) Maintenance Steps  __ Done',

% Maintenance cost: 
for u=1:GUs
    for t= 1:T
        if Ri(u,t)>=1
            M_cost(u,t)=M_rate(u,Ri(u,t))*Mdu(u);
        end
    end
end
M_cost;
sum (M_cost)
toc
disp '.................13-2):- GUROBI Results Extracted .........',
disp '............................................................................',
disp ',

%%% 14) Write Schedule to Excel File   %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
disp '................................................................................................................',
disp '.............14):- Exporting Results to the Excel File:-',
disp ',
tic,

warning('off','MATLAB:xlswrite:AddSheet');
A=[1;GUs];
xlswrite('Rslts_Makkah.xlsx',[ X; L; M; R; S; A,mdus,St_HR,S_Lngt,Stp_Ctr,Min_M,A,W,zeros(GUs, T-14); D ], 'DBL_Transf', 'E3');

toc
disp '.................14) Excel File updated ...............................',
disp '..................................................................................',
disp ',