TURNAROUND MAINTENANCE PLANNING FOR A NETWORK OF PLANTS USING MATHEMATICAL PROGRAMMING MODEL

BY

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"The more you know,

The more you know you don't know."

-Aristotle

To my first instructor. An architect, a professor and a father. May Allah have mercy on him. This thesis is dedicated to him and to my lovely family

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In the name of ALLAH, the most compassionate and the most merciful

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LIST OF ABBREVIATIONS

TAM	:	Turn Around Maintenance
SM	:	Shutdown Maintenance
NPV	:	Net Present Value
OS	:	Organizational Structure
PTS	:	Plant Turnaround Services
MCDM	:	Multi-Criteria Decision Making
OEM	:	Original Equipment Manufacturer
MILP	:	Mixed Integer Linear Program
CPM	:	Critical Path Method
CMMS	:	Computerized Maintenance Management System
KPI	:	Key Performance Indicator
MMIS	:	Maintenance Management Information System

ABSTRACT

Full Name : Mohamed Mahmoud Mohamed Idris

Thesis Title : Turnaround Maintenance Planning for a Network of Plants Using Mathematical Programming Model

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Turnaround Maintenance (TAM) is a periodic event when a plant is shutdown to perform inspections, repairs, replacement and overhauls to ensure plant reliability, availability and performance. This is practiced in many industries including petrochemical, refineries and chemical processing. TAM is an expensive event and in some plants its cost could reach several million dollars and requires many hours of technical experts.

TAM can be viewed at a single plant level or a network of plants. A lot of research and interest have focused on planning, executing and assessing TAM at a single plant level. However, at the level of coordinating TAM for a complex of multi-plant or a supply chain, opportunities for further research exist. The thesis focuses on coordinating and planning TAM for a complex of many plants.

The objective of this thesis is to develop a mathematical model for coordinating and scheduling the performance of TAM for a group of plants over a given horizon. The developed model minimizes the total cost and incorporates realistic constraints such as the availability of contractor's manpower, appropriate windows for different plants TAM and dependency among plants for raw material supply. In addition, the model includes constraints related to final product demand and capacity for inventory at storage units. The model provides a mechanism for planning TAM for an integrated supply chain.

The developed model is solved using GAMS model builder and CPLEX solver. In addition a heuristic algorithm has been developed to solve the model and its performance is then compared to the exact solution provided by CPLEX solver using Matlab for interfacing the model with the heuristic and GAMS. The heuristic algorithm performs very well in terms of obtaining the exact optimal solution when the number of plants is ranged between 15 and 20 plants. Also performed well when the manpower supply for TAM is abundant.

ملخص الرسالة

الاسم الكامل: محمد محمود محمد إدريس

عنوان الرسالة: تخطيط الصيانة الدورية الشاملة لشبكة من المصانع باستخدام نمذجة البرمجة الرياضية

التخصص: ماجستير العلوم في هندسة النظم.

تاريخ الدرجة العلمية: شعبان 1437 هـ

الصيانة الدورية الشاملة هي حدث موسمي يتم فيها اغلاق المنشأة الصناعية أو المصنع لاجراء التفتيشات، الاصلاحات، الاستبدالات و الترميمات اللازمة لضمان اعتمادية المنشأة الصناعية. هذا الاجراء يتم تطبيقه في العديد من الصناعات المختلفة مثل البتروكيماويات، مصافي تكرير البترول و المعالجات الكيميائية.

الصيانة الدورية الشاملة هو اجراء مكلف مادياً والذي قد يصل لبعض المنشآت إلى ملايين الدولارات وتتطلب العديد من ساعات العمل بواسطة تقنيين مختصين.

يمكن اجراء الصيانة الدورية الشاملة على مستوى المنشأة منفردة أو عدة منشآت. حيث أن العديد من الأبحاث والمقالات العلمية ركزت على تخطيط ، تطبيق و تقييم الصيانة الدورية الشاملة على مستوى المنشأة منفردة و مستقلة. إلا أنه على مستوى التنسيق للصيانة الدورية الشاملة لعدة منشآت مرتبطة في شبكة معقدة ذات سلسلة امدادات، فإن هنالك مساحة كبيرة للبحث العلمي .

تهدف هذه الأطروحة إلى تطوير نموذج رياضي لتنسيق و جدولة تنفيذ الصيانة الدورية الشاملة لمجموعة من المصانع وفقاً للفترة المعطاة. و يتوقع أن يقلل النموذج الرياضي المطور التكلفة الكلية وفقاً لشروط وحدود حقيقية مثل توفر فنيي ومهندسي الصيانة من الشركات المتعاقدة ، الفترة الزمنية المناسبة لاجراء الصيانة لكل منشأة إلى جانب الاعتمادية بين المنشآت المتصلة ببعضها على المواد الخام. اضافة لما سبق، فإن النموذج الرياضي يشتمل على عدد من القيود متعلقة بالطلب على المنتج النهائي و سعة التخزين بالمخازن. هذا النموذج الرياضي يوفر آلية لتخطيط الصيانة الدورية الشاملة لسلسة امدادات متكاملة.

تم انشاء النموذج الرياضي باستخدام برنامج جامس (GAMS) الخاص بانشاء النماذج الرياضية وحله باستخدام أداة الحل سيبلكس (CPLEX). اضافة لما سبق، فقد تم تطوير خوارزمية واستخدامها لحل النموذج الرياضي ثم مقارنة أداء الخوارزمية بالنموذج الرياضي باستخدام برنامج ماتلاب (Matlab). كان أداء الخوارزمية ممتاز من ناحية الحصول على تطابق مع حل النموذج الرياضي وذلك عندما يكون عدد المصانع بين 15 و 20 مصنعاً وتوفر عدد كافي من عمالة الصيانة.

CHAPTER 1

INTRODUCTION

1.1 Overview

Process industries such as power generation, petrochemicals, desalination and steel plants constitute a major sector of world economy. It is very capital-intensive industry. In an era of automation, equipment are getting more complex due to the installation and integration of machines of all kinds such as mechanical, electrical and instruments.

In an integrated supply chain of process industries and competitive markets a great need to keep equipment reliable and safe to operate is a necessity. Thus, planned an effective maintenance came to the forefront. Classically, maintenance is divided into preventive and corrective maintenance as shown in figure 1.1.

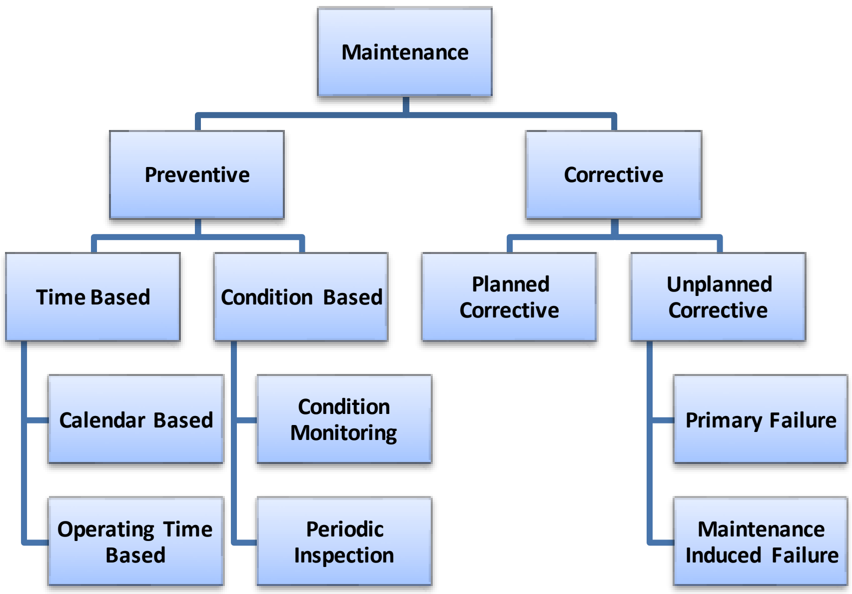

Figure 1.1 Maintenance Classifications

To assure the success of the maintenance, it should be planned and scheduled ahead of execution.

1.1.1 Importance of Maintenance Planning

Planning in general can be defined as; the process by which the elements required to perform a task are determined in advance of the job start time. While scheduling is; the process by which jobs are matched with resources and sequenced to be executed at certain points of time.

Maintenance planning and scheduling are important as they [1]:

- Reduce maintenance cost.
- Improve utilization of the maintenance workforce by reducing delay and interruptions.
- Improve quality of maintenance work.

Process plants need a special type, huge scale time based preventive maintenance called Turnaround Maintenance (TAM). It is also known as Shutdown Maintenance (SM), Overhaul, Shut-in, down-turn or Outage Maintenance. TAM performed on a regular basis to keep/increase asset reliability to continue production integrity, and reduce the risk of unscheduled outages or catastrophic failures [2].

1.1.2 Definitions of Turnaround Maintenance

Turnaround maintenance (TAM) is defined as:

1. A periodic maintenance in which plants are shut down to allow for inspections, repairs, replacements and overhauls that can be carried out only when the assets (plant facilities) are out of service [2].
2. A planned stoppage of production for conducting a comprehensive maintenance of equipment or plant with the purpose of restoring the processes to its original state [3].

1.1.3 Cost of Turnaround Maintenance: An Example

TAM is an expensive and costly practice. It is also labor intensive, and maintenance jobs are conducted within a specific period. Demand for products should be considered during the Shutdown. For example, typical oil refineries go thru shutdown maintenance every 4 years for 42 days with around 300,000 man-hours. It has around 80 % success rate and reaching millions of dollars of total cost [4].

It is clear that there is a need for optimizing shutdown maintenance planning and scheduling. An example of that is a case study of a chemical production unit in the UK. The unit with a shutdown every two years involved £320,000 (about $500,000) of work, and 21 days of downtime. The study overall revealed after optimization that a shutdown every four years is better. The net present value (NPV) savings reach more than £2.5 Million (about $4 Million). In another case study, the optimization of 6 units resulted in doubling shutdown interval with net total impact worth more than £4 Million (about $6.4 Million) per year [5].

An important factor in the process industry is its supply chain. It faces new challenges and a lot of improvements as discussed by Shah [6]. Process industry supply chains involve manufacturers, suppliers, retailers and distributors, are therefore facing challenges to cover the demand while executing TAM. In case of a network of process plants, a plant can be a supplier and/or an importer of material from another plant. Some of these plants are connected in series, others in parallel. Thus, shutdown will affect the whole chain and it should be considered when planning TAM and during execution for a network of plants.

1.2 Thesis Objectives

The objectives of this thesis are:

1. Review the literature for planning and coordinating TAM for a single and a network of plants.
2. Develop a mathematical programming model for planning and coordinating TAM planning for a network of plants.
3. Test and validate the developed model on a realistic case study.
4. Develop a heuristic algorithm for TAM planning and coordinating, and test its performance.

1.3 Thesis Organization

The thesis is organized in five chapters; chapter 2 presents the literature review followed by the integrated mathematical model in chapter 3. Chapter 4 presents a heuristic algorithm for solving the model and planning TAM for a network of plants. Finally, conclusions and future research are provided in chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The purpose of this chapter is to review the literature on TAM for a single and a network of plants. Section 2 presents the literature on planning and execution of TAM for a single plant followed by the literature for a network of plants in section 3. Conclusion of this chapter with gaps in research are provided in section 4.

2.2 Turnaround Maintenance for a single plant

TAM is a common practice in a single process plant and that has resulted in a lot of work focused on improving it and how it is implemented. Ghazali and Shamim [7] examined the process of organizing and managing TAM of process-based industry plants. Their main method of data collection was questionnaire-aided sample survey. The analysis highlighted that centralization in turnaround maintenance is generally high and has no significant relationship to the plant technology employed by companies.

Levitt [8] in his book showed the problems of maintenance planning, project maintenance, contracting, accounting, logistics and other problems for shutdowns together with illustrated examples. In his book, Sahoo [9] focused on process plants TAM. He showed the phases of TAM and its steps and devoted a chapter on risk analysis in TAM.

2.2.1 Turnaround Maintenance Phases

Duffuaa and Ben Daya [10] divided TAM phases into four phases:

1. **Initiation:** In this phase detailed planning of all sides of the project is completed. This involves, work scope, pre shutdown work, procurement of material, quality and safety programs, project organization, site logistics, etc.
2. **Preparation:** This phase includes defining the work scope in the form of a list of tasks and activities that need to be done during turnaround maintenance. The success of this type of maintenance depends on the intelligibility of the work scope. In many cases the work scope is usually drawn from historical estimates, inspection reports and past experience. This scope inconstancy causes work force assigning changes during the TAM execution. Several methodologies are reported in the literature for developing clear and brief work scope. Another task in this phase is the preparation of the job packages, selection of contractors, defining safety procedure and estimating the budget.
3. **Execution** is the phase concerned with applying the work and supervising its progress according to time, cost and quality.
4. **Termination** is the phase of closing the project, evaluating performance and documenting lessons learned.

While Sahoo [9] divided TAM into five phases by separating the third phase of the previous classification into two phases, Sahoo classification is as follows:

1. **Initiation phase**.
2. **Planning phase**.
3. **Execution**.
4. **Controlling**: in this phase, the performance measurements are taken and analyzed to determine if the shutdown is staying true to the project plan. If it is discovered that variation exist, corrective action is taken.
5. **Closing**.

2.2.2 Turnaround Maintenance Steps

TAM planning is divided into ten steps by Sahoo [9]:

1. Developing the shutdown work list.
2. Identify task relationships.
3. Manpower strategic planning.
4. Estimate work packages.
5. Calculate an initial schedule.
6. Assign and level resources.
7. Develop a procurement plan.
8. Develop a quality plan.
9. Develop a communication plan.
10. Develop a risk plan.

2.2.3 Turnaround Maintenance Stages

TAM of a plant can be seen as a project divided into three stages:

1. **Before execution:** at this stage, the TAM planning is done. Many papers focused on this stage since it is the most critical stage. Obiajunwa [11] studied the factors responsible for the failures of TAM implementation projects in the process industry. The goal was to create a framework which guide against these factors and establish the key management skills needed to succeed in TAM project. A framework to evaluate TAM performance in process plants considering risk was established by Obiajunwa [4], [12], [13]. The framework is based on a case study of six process plants in the UK. He reported that typical power plant shutdown (turnaround) maintenance is planned for every four years. Oil refinery and petrochemical plant shutdown maintenance is planned for every two years, while chemical, steel, glass and beverage plant shutdown maintenance is planned for every year.

   Ghazali and Halib [14], [15] suggested a new organizational structure (OS) for managing the planning and execution of TAM. Taking their new unit called Plant Turnaround Services department (PTS) which established with the permanent OS in PETRONAS® as an example. PTS department is just dedicated to manage the planning, preparation and execution of TAM activates.

   An overview of successful applied practices and some methods were proposed by Motylenski [16] resulted in reducing TAM cost and downtime. Since contractors have a main role in planning, it is important to consider their selection and contribution. Ghazali et al. [17] used multi-criteria decision making approach (MCDM) to help in the selection of contractors. The contractors should have the needed technical knowledge of the scope of work and guarantee the availability of skilled manpower. These contractors should satisfy: the quality of work, reliability in delivery, availability to meet safety requirements, flexibility to respond to unforeseen circumstances and compatibility of a contractor system with company system. Hameed et al. [18] presented a risk-based methodology to estimate shutdown inspection and maintenance interval. They considered the system availability and safety by identifying the critical equipment. The identification is in terms of the operation unit instead of the original equipment manufacturer's (OEM) recommended periods. The methodology consists of three steps: risk-based equipment selection, shutdown availability modeling of a complex system using the Markov process, and risk-based shutdown inspection and maintenance interval modeling. Hameed and Khan [19] proposed a framework to estimate the risk-based shutdown interval for inspection and maintenance, which cost effective method to minimize the overall financial risk for asset inspection and maintenance considering safety and availability.

Singh et al. [20] suggested high performance contracting to improve the TAM program. It involves all plant departments; team building alignment, mechanical work window, performance evaluation. Muganyi and Mbohwa [21] provided some drivers that guide organizations with TAM plan to be done in an economical way with all the support to the strategies of the organization. Megow et al. [22] proposed a framework for decision support that consists of two phases. In the first phase, they computed an approximate project time-cost trade-off curve along with the stochastic evaluation. In the second phase, they solved the actual scheduling optimization problem of the first phase heuristically. They applied their method on real problem in cooperation with T.A. Cook ® Company and compared the solution with mixed integer linear programmed (MILP) formulation. Elfeituri and Elemnifi [23] presented a case study of optimizing the plan of TAM of Sairi - one of the five petrochemical refineries in Libya- and increasing its availability. They considered risk based inspection (RBI) to increase productivity and reliability, and removing items from turnaround work scope to a routine maintenance plan.

2. **During execution:** this is the second stage where the TAM plan and schedule is applied and performance measurement takes place. Mann et al. [24] showed that the use of mathematical models in costing maintenance requirements and the use of critical path method (CPM) in scheduling main jobs in TAM.

   It is better to execute TAM plan with the aid of a software as recommended by Brown [25], he presented the advantages of using project-management software. Some of these advantages are: plan for new or additional work that may arise during a shutdown, report and document preparation and execution and finally; Identify and record future needs for the shutdown reveals. Palmer [26] in his handbook showed the benefits of using a computerized maintenance management system (CMMS). Some of these are: inventory control, scheduling, PM generation, finding work orders and the common database. Sprague et al. [27] used both simulation and experiment to study the effect of fouling rates on the performance of a tower in a plan to improve the TAM program. Whittington and Gibson [28] discussed the challenges in TAM and introduced a new management tool. The tool developed to help industry professionals in planning and coordinating some integrated multiple construction projects and maintenance activities during TAM. Utne et al. [29] presented an approach to measure the ability of oil and gas production plants to utilize shutdowns opportunistically for maintenance. They developed key performance indicators (KPI) from case studies to measure the quality of work preparation and capability to utilize shutdowns the most.

3. **After execution:** the final stage after finishing the maintenance where updating the records and reporting occurs. Documentation collected during the closing process can be reviewed and utilized. This is to avoid potential problems during future TAMs. Contract closeout occurs here and formal acceptance takes place.

   In this final stage of TAM plan, quality assurance steps of completed jobs are studied for feedback and continuous improvement. Arts et al. [30] discussed some aspects of measuring maintenance performance in the process industry. They described the maintenance management information system (MMIS) required to measure performance. Based on the time horizon, there are three levels of control: Strategic planning, tactical control and operational control.

2.3 Multiple Plants Turnaround Maintenance Planning

A lot of research and interest have focused on planning, executing and assessing TAM at a single plant level. However, TAM can be studied for at a network of plants. This is the case where multiple plants are connected and dependent on each other. The analysis of such situation is important and challenging.

Al-Turki et al. [31] introduced a global TAM multi plant system view as shown in Figure 2.1. The figure shows the relationship of supply chain starting from the raw material supplier to final product customers. The new system view provides the needed aid in developing plans which integrated with both; internal and external stakeholders. For the global system to be integrated for serving the global objective of the supply chain, several issues have been addressed and built within the system. These issues are:

1. Coordination with supply chain partners.
2. Shutdown effectiveness.
3. Learning process and sharing of best practices with similar industries.

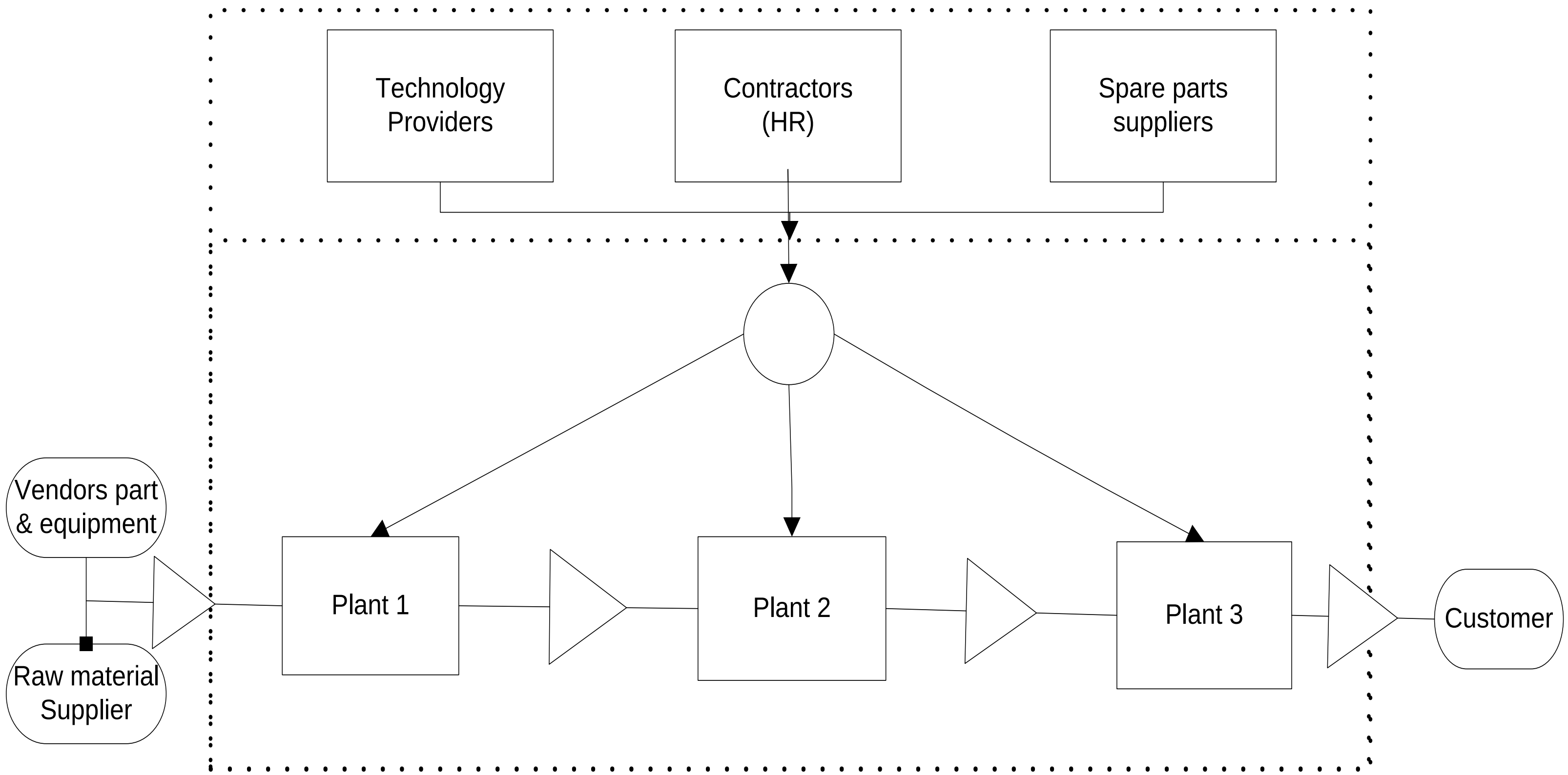

Figure 2.1 Global system view of multi plant TAM [31]

Bohlin and Warja [32] formulated a MILP model to optimize preventive maintenance. The model is for parallel k-out-of-n multi-unit systems. They assumed that the production at a reduced level is possible when some of the units are still operational. They estimated the savings from the model to be 19%.

Castro et al. [33] focused on the maintenance scheduling of a gas engine power plant. They considered only a single maintenance team is available. They scheduled the shutdown of parallel units to minimize idle time and shutdowns in high-tariff periods. This is based on the assumption of seasonal variation in electricity price. A continuous-time formulation was modeled and a general disjunctive programming scheme was used to solve the problem efficiently.

Amaran et al. [34] formulated a long-term TAM planning model for integrated chemical sites using MILP. The model focused on maximizing the NPV considering general and technical assumptions. They applied it on two studies: Fixed cyclic schedule and the rolling horizon framework. They also provided more constraints for special cases (e.g. seasonal constraints and multiple types of turnarounds on a plant).

2.4 Conclusion

The literature presented a lot of work on single plant TAM planning. The literature in single plant TAM planning and execution is well developed. However, few gaps exist: The first gap is in using performance measurements to continually improve TAM planning and execution. In addition, more work is needed to assure the impact of TAM on major plant reliability measures.

The literature on planning TAM for a network of plants is not as developed as for the single plant. More work is still needed to formulate integrated models that reflect the constraints in the supply chain network.

CHAPTER 3

A MATHEMATICAL PROGRAMMING MODEL FOR TAM PLANNING AND COORDINATING

3.1 Introduction

TAM plays an important role in many industries including process industry and power generation to assure the reliability of plants and continuity of production without major failure. Traditionally, TAM planning and execution has been conducted separately for each plant. However, an integrated approach for planning TAM for a network of plants considering them as a connected supply chain may lead to many benefits. Some of these benefits are eliminating or reducing the shortages of material in other plants and customers and reducing the overall cost of TAM.

The purpose of this chapter is to develop a model that formulates planning TAM for a network of plants in an integrated supply considering various constraints. Next, the problem under consideration is stated in details. Followed by the proposed model. Finally, a numerical example to present the functionality of the model.

3.2 Statement of the Problem

An industrial site contains a number of process plants. They may belong to different companies in the same site. These plants are connected to each other in a network either by links or a grid. The plants are divided into levels based on the production flow. These levels belong to three main categories; raw materials level, intermediate products levels and final products level. Each level contains a group or groups of plants. Each group contains a plant or more providing the same product. The flow between levels is consecutive. The state of product may be liquid or solid. A storage unit exists between each pair of groups. Each group is connected to a single or a group of storage units. Each storage unit contains a different product. Raw materials are provided by external suppliers. Each raw material can be provided by a single supplier or several suppliers. There is a dependency between these plants in the site. Each group is supplying the next group with its products by sharing it to the common storage units in the grid. Each storage unit has a maximum capacity which cannot be exceeded. A stoichiometric ratio relates and governs the relation between inputs (products) and outputs (products). There is a maximum flow rate for the production flow between plants and storage units. Figure 1 provides a general schematic representation of such a network.

A general representation as a supply chain network is illustrated in Figure 1. Each level represents a node supplying raw material, an intermediate product or a final product. The arcs represent the flow of material and products. The storage areas are used as buffers or transshipment nodes. The final products are shipped to customers and if shortage occurs, the rest of the demand is outsourced. The outsourced items usually cost higher than produced items.

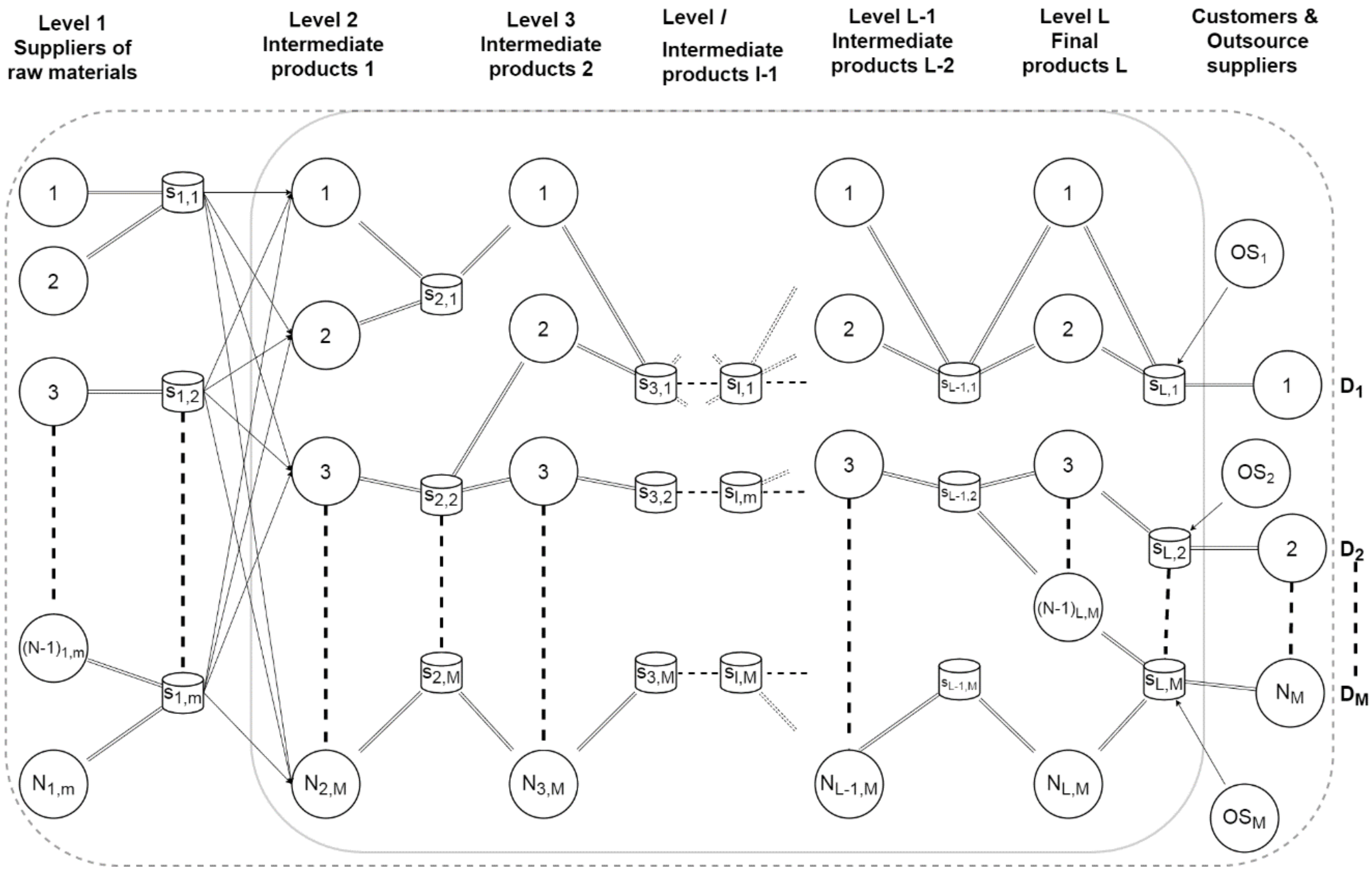

Figure 3.1 Network representation for the plants supply chain

Each plant conducts periodic TAM that should be carried out within a specified time window. The plant shuts down during TAM and production usually ceases. TAM is conducted on continuous basis in other words if it started it is not interrupted. A targeted time is usually provided as preferable period to start TAM. Delaying TAM beyond its targeted time may cause impact on the plant performance and reliability. However, starting TAM earlier than the targeted time may cause loss of production. The execution of TAM requires manpower of different trades and varies along the life cycle of TAM. The availability of manpower is limited from the contractors. In some circumstances a plant may start TAM earlier or later than the targeted period depending on the amount of supply of raw material or intermediate products. The plants at each level are connected by a network grid. Each plant or a group of plants has a known demand for its product. This is also applied during the shutdown period. There is a holding cost on products stored at storage units. A shortage cost is also applied on every final product not meeting customers' demand. This cost represents the shortages substituted by the outsourced suppliers.

Planning and coordinating TAM for the network of plants in the industrial site considering the material flow through the network and other relevant constraints is a complex challenging problem. The main purpose of TAM planning and coordination is to develop a coordinated schedule for all TAM for the network of plants. The benefit from coordinating the schedule will help in effective resource utilization and assure building enough inventories to cover the required demand. This will be achieved by developing an integer linear programming model that represent this problem.

3.3 Model Formulation

A MILP model is formulated for optimizing Turnaround maintenance planning of multiple chemical processing plants. This model extends and generalizes the models proposed by both Al-Turki et al. [31] and Amaran et al. [34].

3.3.1 Notations

Sets:

N	Set of all plants in the network.
J	Set of maintenance trades.
T	Time horizon.
L	Products levels
M,l	Set of products produced at level l
M,L	Set of final products level
U	Set of storage units

Indices:

i	Plant, i=1, 2, …, N,
j	Trade, j=1, 2, …, J,
t	Time period, t=1, 2, …,T,
k	Time period during TAM, k=1, 2, …, $t_{Ui} - \tau_i + 1$,
l	Products level from raw materials (l=1) to final products (l=L), l=1,2,…,L,
m	Product produced at level l, m=1,2,..,M,

u Storage unit, u=1,2,…,U,

Parameters:

t_{Li} Earliest starting period for TAM of plant i,

t_{Ui} Latest ending period for TAM of plant i,

t_{oi} Targeted period to start TAM of plant i,

τ_i Duration of TAM of plant i,

P_{1i} Cost associated with delaying TAM of plant i by one period after targeted time to start TAM of plant i,

P_{2i} Cost associated with starting TAM of plant i earlier by one period before targeted time to start TAM of plant i,

h_i Inventory holding cost per unit per period at storage unit i,

π_i Shortage cost per unit of final product i,

D_{it} External customer demand for final product of storage unit i at time t,

C_i Maximum inventory capacity of storage unit i,

$r_{l,m}$ Stoichiometric ratio or the percentage needed of product l,m to produce product (l+1,m),

ym_{ij} Maximum allowed flow rate between a plant i and a storage unit j,

yn_{ij}	Minimum allowed flow rate to operate between a plant i and a storage unit j,
R_{ijt}	Manpower requirements of trade j for TAM of plant i in period t,
W_{jt}	Number of workers from trade j available in period t,
CM_{jt}	Cost of a single manpower from trade j at time t,

Decision variables:

δ_{it}	1 if TAM of plant i start in period t, and 0 otherwise,
z_{ik}	Binary variable equal 1 in period k while conducting TAM and 0 otherwise,
s_i	TAM starting time period for plant i,
p^+_i	Positive deviation from targeted time of dependent plant i,
n^-_i	Negative deviation from targeted time of dependent plant i,
y_{ijt}	Units of product flow from plant/storage i to storage/plant j at time t,
y_{ojt}	Flow of a final product from an outsourced plant to meet the demand of final product in storage unit j at time t,
I_{it}	Inventory level of storage unit i in period t,

3.3.2 Constraints

Turnaround starting and completion time constraints:

The TAM of plant i should start between (t_{Li}) and (t_{Ui} - τ_i + 1) so that it is completed on or before t_{Ui}, at the latest

$$s_i = \sum_{t=t_{Li}}^{t_{Ui}-\tau_i+1} t\delta_{it} \quad i \in N \tag{3.1}$$

Only one starting period need to be identified

$$\sum_{t=t_{Li}}^{t_{Ui}-\tau_i+1} \delta_{it} = 1 \quad i \in N \tag{3.2}$$

The following constraint is used to start TAM as close as possible to the targeted period of plant i

$$s_i + p_i^+ - n_i^- = t_{oi} \quad i \in N \tag{3.3}$$

Sum of the binary variable z_{ik} during TAM is equal to TAM duration for each plant. This will insure the continuity of TAM when started

$$\sum_{k=t}^{t+\tau_i-1} z_{ik} = \tau_i \ , i \in N, t = t_{li}, t_{li}+1, \dots, t_{ui} - \tau_i + 1 \tag{3.4}$$

The binary variable z_{ik} starts to equal 1 at the beginning of TAM for each plant.

$$z_{ik} \geq \delta_{ik} + B(\delta_{ik} - 1) \quad, i \in N, k = t_{li}, t_{li} + 1, \ldots, t_{ui} - \tau_i + 1 \tag{3.5}$$

Network constraints:

Material balance equation for shared storage between two consecutive levels

$$\sum_{i \in N_{l,m}} y_{ijt} + I_{j,t-1} = \sum_{k \in N_{l+1,m}} y_{jkt} + I_{jt} \quad j \in U, k > i \tag{3.6}$$

Flows between plants include transformation of products with a fixed specific ratio

$$y_{jk} = r_i y_{ij} \quad j \in N_{l,m}, i \in U, k \in U + 1 \tag{3.7}$$

There is no production during shutdown. Otherwise, production should not exceed the maximum rate

$$y_{ijt} \leq ym_{ij} \, (1 - z_{it}), \qquad t = t_{li}, t_{li} + 1, \ldots, t_{ui} - \tau_i + 1 \tag{3.8}$$

There is no production during shutdown. Otherwise, production should not be lower than a minimum operating rate.

$$y_{ijt} \geq yn_{ij} \, (1 - z_{it}), \qquad t = t_{li}, t_{li} + 1, \ldots, t_{ui} - \tau_i + 1 \tag{3.9}$$

Manpower resource constraint:

Sum of all manpower assigned in each period should not exceed the manpower available at that period

$$\sum_{i=1}^{N} z_{it} R_{ijt} \leq W_{jt}, \qquad t = 1,2, \ldots, T \tag{3.10}$$

Demand constraints:

Sum of all production with allowable shortages should meet customer demand of a final product

$$I_{jt-1} + \sum_{i\in N_L} y_{ijt} + y_{ojt} = D_{jt} \ , \qquad j \in U_L \tag{3.11}$$

The inventory level of storage unit i should not exceed the storage capacity at any time

$$I_{jt} \leq C_j, \qquad j \in U \tag{3.12}$$

Objective Function:

The objective is to minimize the penalty of starting later or earlier than the targeted period for TAM of all plants, the sum of inventory holding cost, the shortage cost and the maintenance cost.

The first cost is a penalty cost for starting maintenance earlier or later than the targeted TAM starting time.

$$\text{Min} \quad \begin{aligned} &\sum_{i\in N}(P_{1i}\, p_i^{+} + \ P_{2i}\ n_i^{-}) + \sum_{t\in T}\left(\sum_{i\in U} h_i\, I_{it} + \sum_{i\in U_L} \pi_i y_{oit}\right) \\ &+ \sum_{i\in N}\ \sum_{t=t_{iL}}^{t_{iU}-\tau_i+1}\ \sum_{j\in J} z_{it}\, CM_{jt} R_{ijk} \end{aligned} \tag{3.13}$$

3.4 Model Verification

In this section, a simple example is used to verify the model. In this example, the network consist of two levels. The first level contains two plants and producing one intermediate product. The second level contains two plants and producing one final product. The network is illustrated in figure 3.2. There are two trades. Each trade has fixed cost and availability. All the four plants in the network have the same fixed requirements of manpower during TAM for each trade. The input data is shown in tables 3.1 to 3.5. While table 3.6 shows the exact solution and the optimal schedule.

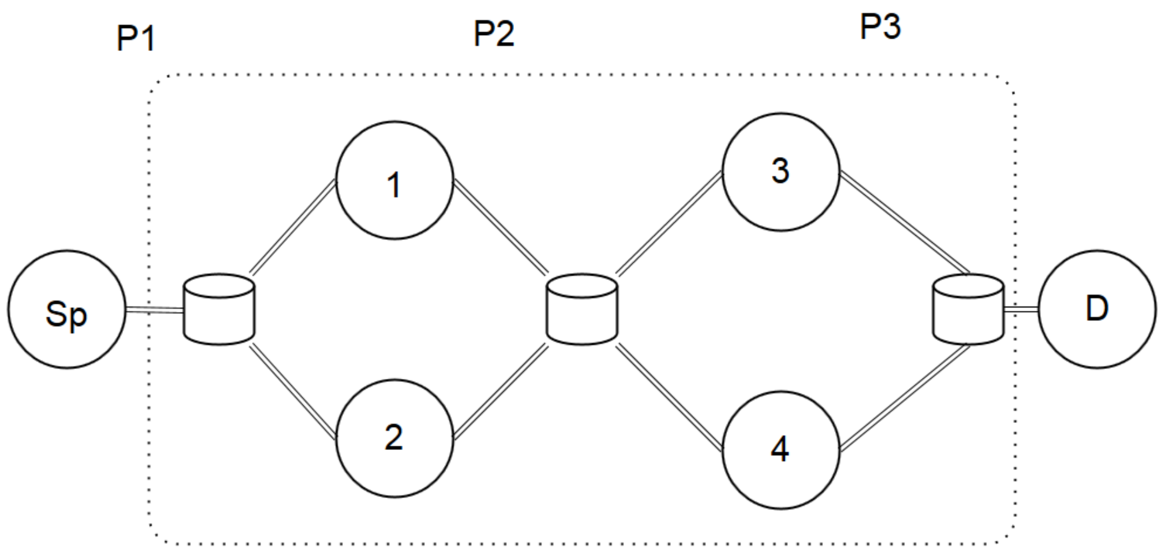

Figure 3.2 Network of Plants for the Verification

Table 3.1 Model Verification: TAM Data

Plant #	TAM window		Targeted Date	TAM Duration	Max Flow Leaving	Min flow Leaving	Penalty Associated with conducting TAM		Stoichiometric Ratio
							Before Target	After Target	
1	1	8	4	4	50	0	5000	10000	1
2	2	9	4	4	100	0	5000	10000	1
3	3	10	5	3	90	0	5000	10000	1
4	4	12	5	4	150	0	5000	10000	1

Table 3.2 Model Verification: Inventory Data

Storage #	Level	Material	Inventory Capacity	Inventory Holding Cost	Shortage Cost (last level only)	Demand	Initial Inventory Level
1	1	1	inf	50	N/A	N/A	1000
2	2	1	10000	30	N/A	N/A	1000
3	3	1	10000	40	80	200	1000

Table 3.3 Model Verification: Manpower Requirement Data

		Manpower required per week during TAM duration			
Period		1	2	3	4
Plant 1	Trade 1	30	30	30	30
	Trade 2	20	20	20	20
Plant 2	Trade 1	30	30	30	30
	Trade 2	20	20	20	20
Plant 3	Trade 1	30	30	30	
	Trade 2	20	20	20	
Plant 4	Trade 1	30	30	30	30
	Trade 2	20	20	20	20

Table 3.4 Model Verification: Manpower Availability Data

Trade Type	Availability Total for all contractors											
	1	2	3	4	5	6	7	8	9	10	11	12
Mechanic	120	120	120	120	120	120	120	120	120	120	120	120
Electrical	80	80	80	80	80	80	80	80	80	80	80	80

Table 3.5 Model Verification: Manpower Costs Data

Trade Type	Cost per person at each period											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Mechanic	5	5	5	5	5	5	5	5	5	5	5	5
Electrical	3	3	3	3	3	3	3	3	3	3	3	3

Table 3.6 Model Verification: Solution

Plant | Period			1	2	3	4	5	6	7	8	9	10	11	12
i	**S**	**Trade**												
1	4	1				30	30	30	30					
		2				20	20	20	20					
2	4	1				30	30	30	30					
		2				20	20	20	20					
3	5	1					30	30	30					
		2					20	20	20					
4	5	1					30	30	30	30				
		2					20	20	20	20				

The solution in table 3.6 shows the starting time (S) for TAM and manpower assignment of each trade for each plant (i). The light gray shows the window while the dark gray represents the targeted period. The starting time is equal to the targeted period for all plants. This verifies the model since the solution of this simple example is designed so that to start TAM at the targeted period for each plant.

3.5 Model Validation

In this thesis after conceptualizing the network representation in figure 3.1, it was presented to two experts from the petrochemical industry they confirmed that it represents real situations in industry. Then the mathematical model is constructed from the network representation.

3.6 Example

The next figure illustrates the network of plants in this example. The industrial site contains a network of eleven plants {1,…,11}. These plants belong to four different companies; A, B, C and D. There is only one supplier for the raw material; P1. This is being supplied to the first group of plants {1,…, 6} which produce the intermediate product; P2. P2 is stored in storage unit {S1} and fed to the next group of plants {7,…, 11} which produce the final product; P3. P3 is then stored in storage unit {S2} before it is exported to the customer. The eleven plants belong to one corporation; however if there is shortage of the final product the company may outsource from other plants that are producing P3. This is summarized in table1and figure 3.2.

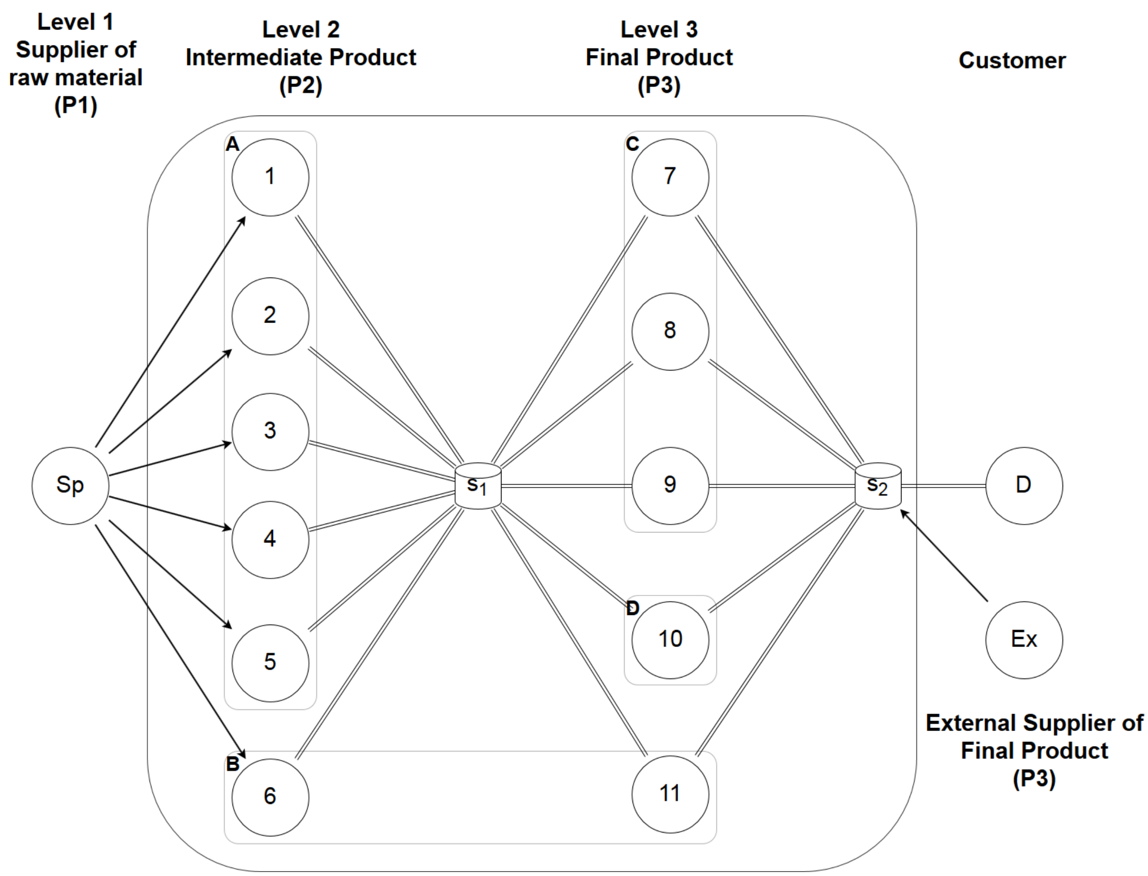

Figure 3.3 Network of Plants for the Example

Table 3.7 Set of Plants in the Example

Company	Product	Plant #
A	P1	1
	P1	2
	P1	3
	P1	4
	P1	5
B	P1	6
	P2	11
C	P2	7
	P2	8
	P2	9
D	P2	10

Some data are available. The demand rate for each plant and customer are known. The maximum possible production rates that flow between the plants and the shared grid are known.

The model was built in GAMS 24.5.6 and was solved using the mixed-integer solver CPLEX.

The size of the MILP model in this example is giving by the GAMS Model Statistics. There are 2,624 constraints with 1,214 variables in total.

The problem was solved on a PC with Windows 7 Professional 64-bit, Intel processor core i5 – 2410M CPU @ 2.3GHz and 6 GB of RAM.

All available data are shown in tables 3.2 to 3.6, the results are shown in table..

Table 3.8 Example: TAM Data

Company	Plant and Product	Plant #	TAM window		Targeted Period	TAM Duration	Max Flow Leaving	Min flow Leaving
A	P1	1	3	13	4	4	50	10
	P1	2	1	10	8	4	100	20
	P1	3	5	14	7	3	90	18
	P1	4	1	16	11	4	150	30
	P1	5	5	10	11	3	50	10
B	P1	6	4	12	10	4	50	10
	P2	7	2	12	2	3	50	10
C	P2	8	3	14	6	4	100	20
	P2	9	5	12	7	4	50	10
	P2	10	4	10	6	3	50	10
D	P2	11	4	10	6	3	50	10

Table 3.9 Example: Penalty Costs and Stoichiometric Ratios Data

Plant #	Penalty Associated with conducting TAM		Stoichiometric Ratio
	Before Target	After Target	
1	50 000	100 000	0.6
2	50 000	100 000	0.6
3	50 000	100 000	0.6
4	50 000	100 000	0.6
5	50 000	100 000	0.6
6	50 000	100 000	0.6
7	50 000	100 000	2
8	50 000	100 000	2
9	50 000	100 000	2
10	50 000	100 000	2
11	50 000	100 000	2

Table 3.10 Example: Inventory Data

Storage #	Level	Material	Inventory Capacity	Inventory Holding Cost	Shortage Cost (last level only)	Demand	Initial Inventory Level
1	1	1	inf	50	N/A	N/A	100,000
2	2	1	10,000	30	N/A	N/A	3,000
3	3	1	10,000	40	80	2,500	1,000

Table 3.11 Example: Manpower Availability Data

Trade Type	Availability Total for all contractors									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Mechanic	200	200	200	200	200	200	235	200	200	200
Electrical	200	200	200	200	200	200	235	200	200	200
Plumbing	200	200	200	200	200	200	235	200	200	200
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Mechanic	200	200	200	200	200	200	200	200	200	200
Electrical	200	200	200	200	200	200	200	200	200	200
Plumbing	200	200	200	200	200	200	200	200	200	200

Table 3.12 Example: Manpower Costs Data

Trade Type	Cost per person at each period									
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Mechanic	5	5	5	5	8	8	8	8	7	7
Electrical	4	4	4	4	7	7	7	7	8	8
Plumbing	3	3	3	3	6	6	6	6	7	7
	11	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Mechanic	7	7	4	4	4	4	3	3	3	3
Electrical	8	8	4	4	4	4	3	3	3	3
Plumbing	7	7	3	3	3	3	2	2	2	2

Table 3.13 Example: Manpower Requirement Data

Plant #	Period / Trade type	Manpower required per week during TAM duration			
		1	2	3	4
Plant 1	Trade 1	20	30	20	25
	Trade 2	30	20	20	30
	Trade 3	35	30	40	45
Plant 2	Trade 1	30	35	30	24
	Trade 2	26	30	33	35
	Trade 3	40	35	38	42
Plant 3	Trade 1	24	26	33	
	Trade 2	25	30	28	
	Trade 3	35	33	36	
Plant 4	Trade 1	25	28	29	20
	Trade 2	33	40	45	40
	Trade 3	30	36	38	30
Plant 5	Trade 1	30	20	20	
	Trade 2	33	30	30	
	Trade 3	38	35	44	
Plant 6	Trade 1	24	30	24	29
	Trade 2	25	20	25	45
	Trade 3	35	30	35	42
Plant 7	Trade 1	29	26	30	
	Trade 2	45	30	26	
	Trade 3	38	33	40	
Plant 8	Trade 1	25	20	30	20
	Trade 2	30	20	20	30
	Trade 3	45	40	30	35
Plant 9	Trade 1	25	30	30	24
	Trade 2	30	40	26	25
	Trade 3	45	30	40	35
Plant 10	Trade 1	20	30	33	
	Trade 2	20	33	28	
	Trade 3	40	38	36	
Plant 11	Trade 1	24	30	24	
	Trade 2	25	20	25	
	Trade 3	35	30	35	

Table 3.14 summarizes the results of the optimal solution. The table shows the TAM starting time obtained comparing to the giving data, while tables A.1 and A.2 in Appendix A shows the detailed optimum schedule for the network with manpower assignment.

Table 3.14 Example: Solution

Plant #	Starting Time	Targeted Period	TAM window	
1	4	4	3	15
2	8	8	1	12
3	7	7	5	16
4	11	11	1	15
5	11	11	5	14
6	10	10	4	14
7	2	2	2	13
8	6	6	3	15
9	7	7	5	16
10	6	6	4	11
11	6	6	4	11

CHAPTER 4

A HEURISTIC ALGORITHM FOR TAM PLANNING

In this chapter, an alternative approach for solving the TAM planning problem for a network of plants is introduced. This approach is based on a heuristic algorithm.

The chapter starts with an introduction about the motivation for using this method in section 4.1 and the heuristic algorithm is presented in section 4.2. In section 4.3 the algorithm is tested by the same example in section 3.3. Finally, a comparison between the exact method and the heuristic algorithm is presented in section 4.4.

4.1 Introduction

The previous chapter provides a model that is solved by an exact algorithm. This example in section 3.5 contains only eleven plants (N=11) which distributed on two levels and producing one product at each level. Although the example is simple, the size of the model was enormous. There were 2,624 constraints with 1,214 variables in total. With larger networks of plants, the model will get more complex. Therefore the exact algorithm may take a long time, an alternative approach is heuristics algorithms.

The word heuristic is educed from the Greek word heuriskein which mean to find or discover. Another terminology for Heuristics is Approximative Algorithms. The reason for calling Heuristics Approximative Algorithms is because they mostly do not guarantee the optimum solution. However, the solution should be good (near optimal) and obtained in reasonable time.

The heuristic algorithm for coordinating TAM exploit the flexibility provided in scheduling the TAM for each plant. The flexibility is based on the ratio of the TAM duration to the length of the window. The plants are ranked according to this ratio. The one with the highest ratio is given the lowest rank. The one with lowest rank is scheduled first at the target set for the TAM if the required manpower is available. The process is repeated for the remaining plants. If all plants are scheduled then this is the optimal solution. Otherwise starting time is shifted by one period before the target and check feasibility. If the solution is still infeasible, keep shifting before the target each time until reaching the lowest possible starting time. If the solution is still infeasible, then schedule its TAM by one period after the target and check feasibility. If the solution is infeasible, keep shifting by one period after the target until reaching the maximum possible time to start TAM. If still no feasible solution obtained, then give the plant the highest priority and shift the rank of the previous plants by one more. Repeat the previous steps until reaching a feasible solution or reaching the stopping criteria. For more details check section 4.2.

4.2 The Heuristic Algorithm

In this section the heuristic algorithm is introduced for solving TAM scheduling problem. In this algorithm, a greedy heuristic approach based on the ratio mentioned in the introduction to assign the priority for the plants. The following flow chart describes the algorithm:

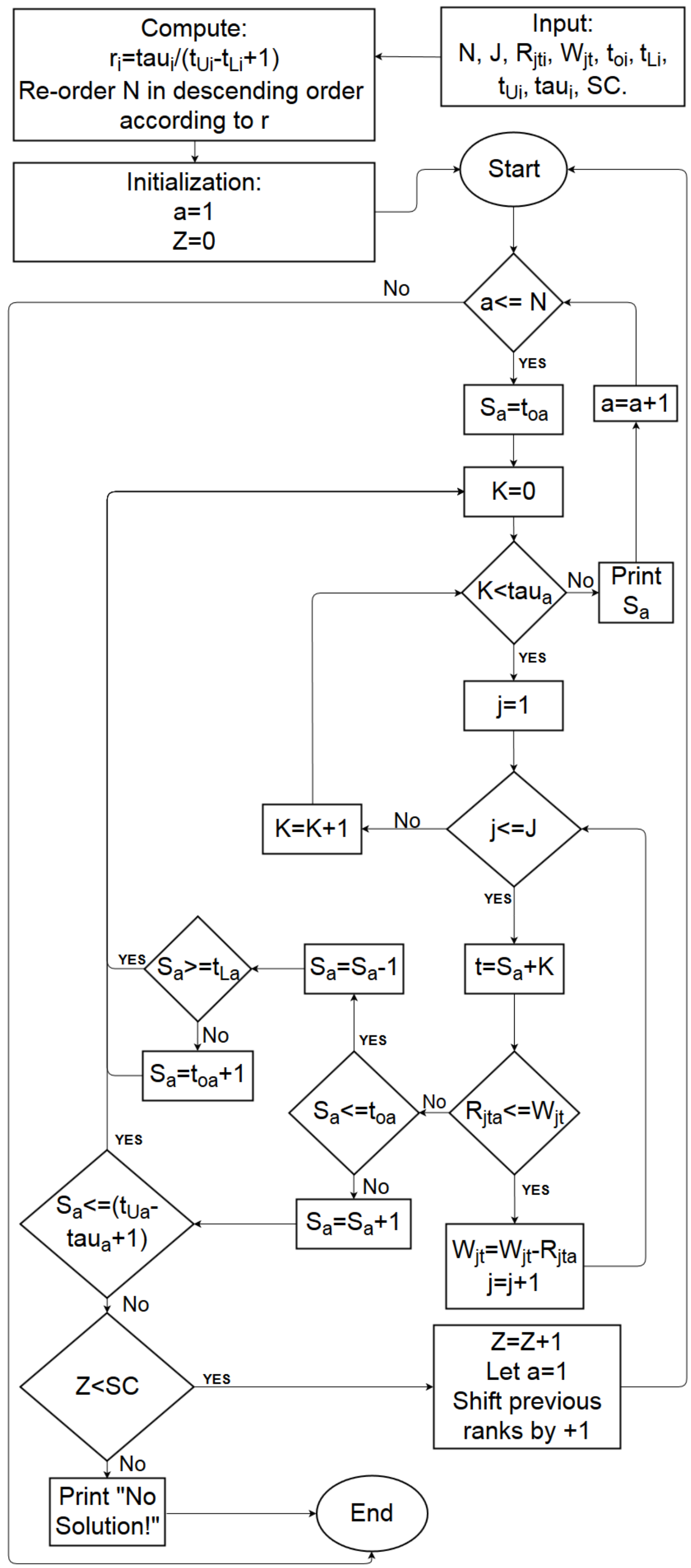

Figure 4.1 Heuristic Algorithm

The following is the algorithm in steps:

1. Input the needed parameters: N, J, R_{jti}, W_{jt}, t_{oi}, t_{Li}, t_{Ui}, tau_i, SC.

2. Calculate the time ratio (r) for all plants using the following equation: $r_i = \tau_i / (t_{Ui}-t_{Li}+1)$

3. Order the plants in descending order of the ratio in (2).

4. Let 'a' be the priority order of plants where the highest time ratio is a=1 and the lowest time ratio is a= N and the counter for the stopping criteria (SC) is Z=0.

4. Use the following pseudocode to find TAM schedule.

Start

For a=1 to N

$S_a = t_{oa}$

For K= 0 to τ_a

For j=1 to J

$t= S_a+ K$

If $R_{jta} <= W_{jt}$

$W_{jt}= W_{jt} - R_{jta}$

Else If $t_{La} < S_a <= t_{oa}$

$S_a = S_a -1$

Go to K=0

Else If $t_{oa} < S_a <= (t_{Ua} - \tau_a + 1)$

$S_a = S_a + 1$

Go to K=0

Else If $S_a < t_{La}$

$S_a = t_{oa} + 1$

Go to K=0

Else If $Z < SC$

$Z = Z + 1$

let a =1 and shift the previous ranks by +1

Go to Start

Else Print “No Solution!”

Go to End

Next j

Next k

Print S_a

Next a

End

4.3 Example

In this section, the same example mentioned in section 3.5 is solved using the heuristic algorithm. The data needed for the algorithm were given in tables 3.8, 3.11 and 3.13.

The algorithm was programed using Matlab R2015b. The problem was solved on a PC with Windows 7 Professional 64-bit, Intel processor core i5 – 2410M CPU @ 2.3GHz and 6 GB of RAM. The results are summarized in table 4.1, while tables A.3 and A.4 in Appendix A show the detailed schedule for the network with manpower assignment.

Table 4.1 presents the new descending order and the starting time for each plant after applying the algorithm. The plants were ordered starting from plant 7 and ending with plant 5 based on the greedy ratio. The solution shows that the starting time for all the plants is equal to the target. This is due to the excess manpower availability.

Changing the manpower availability of the 7^{th} period to 200 instead of 235 for all trades will lead to a shift of the starting time of plant 3 (ranked 6^{th}) from the 7^{th} period to the 5^{th} period. The rest of the schedule will remain the same and equal to the target. The new solution is feasible with minimum deviation from the target considering manpower availability.

Table 4.1 Example: Solution of the Heuristic method

Plant #	Targeted Period	Rank	Solution Heuristic
1	4	5	4
2	8	9	8
3	7	6	7
4	11	10	11
5	11	11	11
6	10	2	10
7	2	1	2
8	6	8	6
9	7	3	7
10	6	7	6
11	6	4	6

4.4 Comparison between the exact model and the heuristic algorithm

In this section, a comparison between the exact solution and the solution obtained by the heuristic algorithm is discussed. Table 4.4 shows a comparison between the results obtained by the two approaches. The table presents the starting time for both algorithms. This is also illustrated in Figure 4.2. The results of the two approaches match except at plant three where the exact solution gives different result for the starting time. It is suggesting starting two weeks before the targeted period while the heuristic gives the targeted period as starting time for plant three. This change is due to the relaxation of many constraints in the heuristic which are considered in the exact method.

Table 4.2 Comparison of the Two Approaches

Plant #	Targeted Period	Rank Heuristic	Solution Heuristic	Solution MILP
1	4	5	4	4
2	8	9	8	8
3	7	6	7	5
4	11	10	11	11
5	11	11	11	11
6	10	2	10	10
7	2	1	2	2
8	6	8	6	6
9	7	3	7	7
10	6	7	6	6
11	6	4	6	6

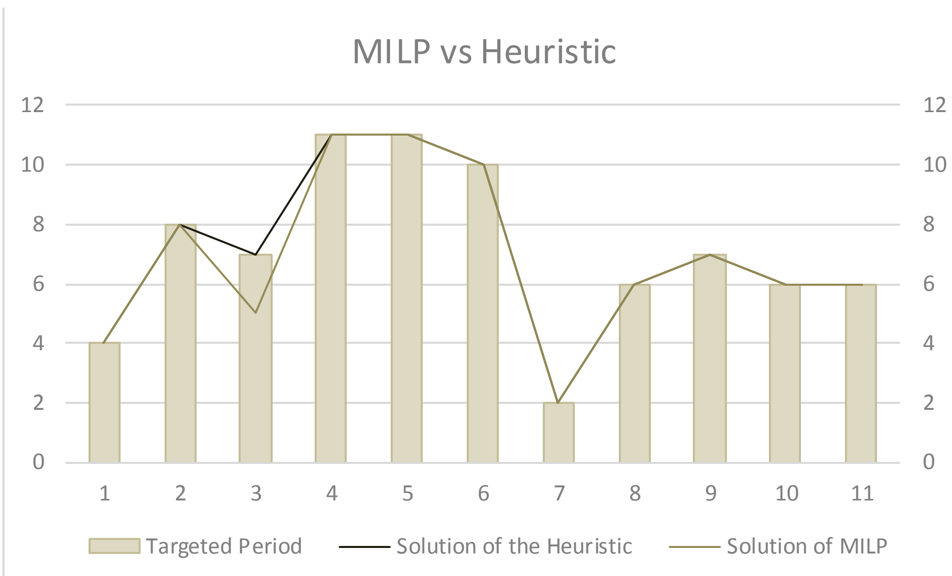

Figure 4.2 MILP vs Heuristic

For the same example, if the penalty of starting TAM before the target by one period is $P_1 = 50$ instead of 50,000 and the penalty of shifting after the target by one period is still $P_2=2P_1$, the solution of the MILP model will be as in table 4.3. The results are illustrated in figure 4.3, the effect of the penalties of starting before and after the targeted period are significant. With lower cost on deviation from targeted periods, the model change the schedule to reduce the total cost considering maintenance cost, shortages cost and holding cost while satisfying the constraints.

Table 4.3 Effect of Penalty Value on the Exact Solution

Plant #	Targeted Period	Solution MILP (Low P)
1	4	5
2	8	7
3	7	5
4	11	10
5	11	11
6	10	10
7	2	4
8	6	5
9	7	7
10	6	4
11	6	4

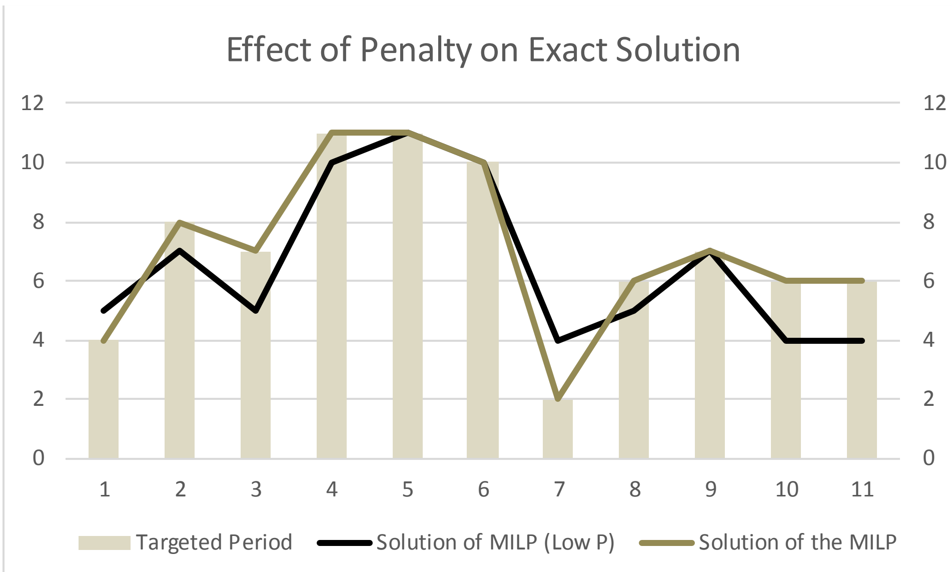

Figure 4.3 Effect of Penalty Value on the Exact Solution

Further comparisons were done to test the effect of some parameters. A random data of some of the main parameters were generated by Matlab and tested in both approaches.

Data were selected randomly at each run. Tables A.5 and A.6 in Appendix A show the range of data for each parameter, the number of iterations at each run is 1,000 iterations.

With relaxing the manpower availability, the percentage of exact match between the exact and heuristic for all feasible solutions is 100%.

When manpower availability is as shown in the following table for each number of plants, the percentage reduced to 96%.

Table 4.4 Availabilty of Manpower for Each Numberof Plants

Number of Plants	Availability of Manpower
10	290
15	350
20	390

Moreover, when reducing the availability of manpower to 200 only for any number of plants, the percentage decreases to 85.43% in average. However, another test was conducted to study the effect of the number of plants on the percentage of exact matches with fixed low manpower availability. Figure 4.2 shows the relation between the number of plants (N) and the percentage of the exact matching. It is found out that the increase in number of plants has an impact on reducing the percentage of the matched solutions. However, unmatched results often defer only in few number of plants. Sometimes, in one plant.

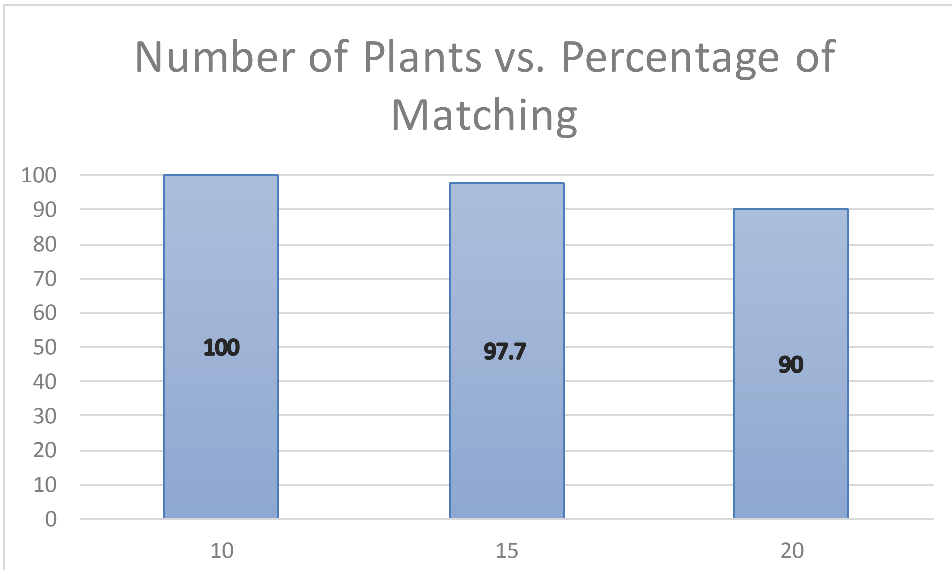

Figure 4.4 Effect of Number of Plants on Matching Percentage

CHAPTER 5

CONCLUSION AND FUTURE RESEARCH

5.1 Introduction

This chapter provides a summary of the thesis and directions for further research. The summary is provided in section 2 followed by directions for further research in section 3.

5.2 Summary

The TAM schedule for a network of plants is formulated and modeled in this thesis. The plants are assumed to be connected by links or a grid to represent the shared inventory and divided into levels based on the product flow. There is a demand on the final products produced at the last level. Each plant has duration for its maintenance which must be conducted within a defined time window. There is a preferable time to conduct maintenance within this window. The objective is to schedule the execution of TAM for a group of plants over a given horizon considering the supply chain in between. The problem is formulated as an integer linear model. The developed model is verified and validated. An example is solved to illustrate how the model works.

In chapter 4, a heuristic algorithm is introduced to solve the TAM problem. The algorithm provides an effective and fast alternative for the exact method. Comparisons between the two approaches are made to test the quality and the effect of some parameters on the efficiency of the heuristic algorithm.

5.3 Possible Extensions

The TAM model presented in chapter 3 can be tested and extended in several directions. These directions include:

1. Testing the model with real data: The model can be tested using real data from the industry as a real case study. The results are then compared with the current practice in scheduling TAM.
2. Relaxing the assumption that intermediate products are only within the network and include the possibility of having external supply and demand for these products. The demand constraint is added to the other levels.
3. Relaxing the assumption that each plant produces a single product, to multiple products per plant. Some plants produce different products at the same time. Other plants switch between products on the same production line. The new assumption will make the model more realistic and applicable to the real industries. Many techniques can be used such as virtual nodes.
4. Include and test the effect of unskilled manpower on the maintenance execution. This will add some uncertainty to the model and stochastic programming techniques may be used.
5. Studying the effect of unplanned failures during TAM horizon of the network. Example of this situation is when executing a planned TAM for a plant producing a specific product and an unexpected break down occur to a different plant producing the same product before its planned TAM. This

may lead to the need of more manpower and having shortages of the product due to the discontinued production.

APPENDIX A

Table A.1 Solution for exact method: manpower assignment schedule for plants 1 to 5.

Plant i	S	Trade	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	4	1				20	30	20	25							
		2				30	20	20	30							
		3				35	30	40	45							
2	8	1								30	35	30	24			
		2								26	30	33	35			
		3								40	35	38	42			
3	7	1							24	26	33					
		2							25	30	28					
		3							35	33	36					
4	11	1											25	28	29	20
		2											33	40	45	40
		3											30	36	38	30
5	11	1											30	20	20	
		2											33	30	30	
		3											38	35	44	

Table A.2 Solution for exact method: manpower assignment schedule for plants 6 to 11.

Plant | Period			1	2	3	4	5	6	7	8	9	10	11	12	13	14
i	S	Trade														
6	10	1										24	30	24	29	
		2										25	20	25	45	
		3										35	30	35	42	
7	2	1		29	26	30										
		2		45	30	26										
		3		38	33	40										
8	6	1						25	20	30	20					
		2						30	20	20	30					
		3						45	40	30	35					
9	7	1							25	30	30	24				
		2							30	40	26	25				
		3							45	30	40	35				
10	6	1						20	30	33						
		2						20	33	28						
		3						40	38	36						
11	6	1						24	30	24						
		2						25	20	25						
		3						35	30	35						

Table A.3 Solution for the heuristic method: manpower assignment schedule for plants 1 to 5.

Plant | Period			1	2	3	4	5	6	7	8	9	10	11	12	13	14
i	r	Trade														
1	5	1				20	30	20	25							
		2				30	20	20	30							
		3				35	30	40	45							
2	9	1								30	35	30	24			
		2								26	30	33	35			
		3								40	35	38	42			
3	6	1					24	26	33							
		2					25	30	28							
		3					35	33	36							
4	10	1											25	28	29	20
		2											33	40	45	40
		3											30	36	38	30
5	11	1											30	20	20	
		2											33	30	30	
		3											38	35	44	

Table A.4 Solution for the heuristic method: manpower assignment schedule for plants 6 to 11.

Plant | Period			1	2	3	4	5	6	7	8	9	10	11	12	13	14
i	r	Trade														
6	2	1										24	30	24	29	
		2										25	20	25	45	
		3										35	30	35	42	
7	1	1		29	26	30										
		2		45	30	26										
		3		38	33	40										
8	8	1						25	20	30	20					
		2						30	20	20	30					
		3						45	40	30	35					
9	3	1							25	30	30	24				
		2							30	40	26	25				
		3							45	30	40	35				
10	7	1						20	30	33						
		2						20	33	28						
		3						40	38	36						
11	4	1						24	30	24						
		2						25	20	25						
		3						35	30	35						

Table A.5 Random Data Source 1

Number of Plants	Duration	Min starting	TAM Window
10	3	1	8
15	4	2	9
20	5	3	10
		4	11
		5	12
		6	13
		7	14
		8	15
		9	16
		10	

Table A.6 Random Data Source 2

Cost of Manpower at each trade			Required Manpower
1	**2**	**3**	30
5	4	3	20
5	4	3	20
5	4	3	20
5	4	3	20
8	7	6	20
8	7	6	20
8	7	6	26
8	7	6	26
7	8	7	28
7	8	7	30
7	8	7	30
7	8	7	30
4	4	3	30
4	4	3	30
4	4	3	30
4	4	3	30
3	3	2	30
3	3	2	30
3	3	2	30
3	3	2	30
			30
			33
			33
			33
			35
			35
			35
			36
			38
			40
			40
			45

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