

# **SIMULATION AND PERFORMANCE ANALYSIS OF MANUFACTURING SYSTEMS USING DETERMINISTIC AND STOCHASTIC PETRI NETS**

**With special reference to Addis Engineering Center Tools and Spare parts Workshop**

**A thesis submitted to the School of Graduate Studies of Addis Ababa University in  
partial fulfillment of the requirements for the Degree of Masters of Science in  
Mechanical Engineering (Industrial Engineering Stream)**

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**ADDIS ABABA UNIVERSITY  
SCHOOL OF GRADUATE STUDIES**

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*Abebayehu Seifu*

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## **Abbreviations**

**AGVs:** Automatic/Automated Guided Vehicles

**AMS:** Automated Manufacturing System

**CAD/CAM:** Computer Aided Design and Manufacturing

**CIM:** Computer Integrated Manufacturing

**CNC:** Computer Numerically Controlled

**CPN:** Colored Petri Net.

**DEDS:** Discrete Event Dynamic Systems

**DMS:** Decision-Making Subsystem

**DTPNs:** Deterministic Timed Petri Nets.

**FMS:** Flexible Manufacturing System

**GreatSPN:** Graphical Editor and Analyzer for Timed and Stochastic Petri Nets

**GSPNs:** Generalized stochastic Petri Nets.

**GUI:** Graphic user interface.

**MLT:** Manufacturing Lead Time

**OEE:** Overall Equipment effectiveness

**PNM:** Petri net model

**PNs:** Petri nets (introduced by Carl Adam Petri in his Ph.D. thesis in 1962).

**SMEs:** Small and Medium Enterprises.

**SPNP:** Stochastic Petri Net Package.

**TLT:** Total Lead Time

**TPNs:** Timed Petri Nets.

**TQC:** Total Quality Control

**WIP:** Work-In-Progress.

## **Abstract**

*Most of manufacturing industries in our country practice the traditional production systems. Effective management of the steady state operation is no longer enough to ensure the survival, let alone the success, of an organization. The performance of the operations has to be improved continually in all its aspects, and it is driven by the quest for increased productivity, flexibility and continuously changing competitive environment.*

*The increasing global character of market for goods and services, is stimulated by the factors like improvements in transport, telecommunication and data communication systems, the rapid technological advancement, and primarily the automation of manufacturing operations to decrease cost of manufacturing, product life and dependable deliveries. These features of the competitive environment certainly point to the need for continuous performance analysis and improvement of manufacturing systems. Therefore, whether it is a manufacturing-based or a service-based company, the key to stay at the apex of global competition is to meet the dynamically changing need of customers.*

*Manufacturing systems simulation and performance analysis using Petri Nets is one of the promising tools employed for assessing performance and then taking the necessary measures for improvements of existing deficiencies. Petri Nets are graphical and mathematical tools for studying discrete event systems and have been under extensive development since Petri defined the language in 1962. Petri Net models are now common place within the sphere of performance modeling of manufacturing systems due to reasons like graphical and precise representation of system activities and models at various levels of detail and ability to capture the existence of concurrency, parallelism, resource constraints and process dependencies accurately.*

*This study therefore, focuses on Modeling and analyzing the performance of the manufacturing process of Addis Engineering Center, one of the manufacturing industries in the country, using Petri Net so as to evaluate various performance parameters such as utilization rate of machines, bottleneck detection, cycle time, and throughput rate of system under consideration and providing solutions and recommendations for the pitfalls and ramification for attaining the optimum productivity.*

# CHAPTER ONE

## 1. INTRODUCTION

### 1.1 Background

Whether it is a manufacturing-based or a service-based company, the key to stay at the apex of global competition is to meet the dynamically changing need of customer [11]. Most of manufacturing industries in our country practice the traditional production systems. Effective management of the steady state operation is no longer enough to ensure the survival, let alone the success, of an organization. The performance of the operations has to be improved continually in all its aspects, and it is driven by the quest for increased productivity, flexibility and continuously changing competitive environment.

The increasing global character of market for goods and services, is stimulated by the factors like improvements in transport, telecommunication, and data communication systems, the rapid technological advancement and primarily the automation of manufacturing operations to decrease product life, cost of manufacturing and dependable deliveries. These features of the competitive environment certainly point to the need for continuous performance analysis, modeling and simulation of manufacturing system. The primary goals of a manufacturing system are to minimize the work in process inventory (WIP) and maximize the system utilization and out put rate. Hence, the traditional production systems of our industries should be relooked to make the best use of the pertinent available technology and resources for better utilization of equipments and machineries [4].

Manufacturing systems simulation and performance analysis using Petri nets is one of the promising tools employed for assessing performance and then taking the necessary measures for improvements of existing deficiencies.

Performance is often a central issue in the design, development, and configuration of systems. It is not always enough to know that systems work properly they must also work effectively. There are numerous studies, e.g. in the areas of computer and telecommunication systems, manufacturing, military, health care, and transportation, that have shown that time, money, and even lives can be saved if the performance of a system is improved. Performance analysis studies are conducted to evaluate existing or planned systems, to compare alternative configurations, or to find an optimal configuration of a system. There are three alternative

techniques for analyzing the performance of a system: measurement, analytical models, and simulation models. There are advantages and drawbacks to each of these techniques

Measuring the performance of a system can provide exact answers regarding the performance of the system. The system in question is observed directly no details are abstracted away, and no simplifying assumptions need to be made regarding the behavior of the system. However, measurement is only an option if the system in question already exists. The measurements that are taken may or may not be accurate depending on the current state of the system. For example, if the utilization of a network is measured during an off-peak period, then no conclusions can be drawn about either the average utilization of the network or the utilization of the network during peak usage periods.

Analytical models, such as Markovian models can provide exact results regarding the performance of a system. The results are exact, in that they are not estimates of the performance of the system. However, the results provided by analytical models may or may not be accurate, depending on the assumptions that have been made in order to create the model. In many cases it is difficult to accurately model industrial-sized systems with analytical models.

Simulation-based performance analysis can be used as an alternative to analytical techniques. Simulation can represent the real world by numbers and other symbols that can be readily manipulated. The availability of computers makes simulation possible for us to deal with extraordinary large quantity of details, which can be incorporated in, to a model and the ability to manipulate the model over many "experiments" (i.e. replicating all the possibility that may be embedded in the external world and events would seem to recur). Simulation can rarely provide exact answers, but it is possible to calculate how precise the estimates are. Furthermore, larger and more complex models can generally be created and analyzed without making restrictive assumptions about the system. There are two main drawbacks to using simulation: it may be time consuming to execute the necessary simulations, and it may be difficult to achieve results that are precise enough. Simulation-based performance analysis of a model involves a statistical investigation of output data, the exploration of large data sets, the appropriate visualization, and the verification and validation of simulation experiments. Performance analysis is both an art and a science. One of the arts of performance analysis is knowing which of these three analysis technique to use in which situation. Measurement can

obviously not be used if the system in question does not exist. Simulation should probably not be used if the system consists of a few servers and queues, in this case queuing networks would be a more appropriate method. Simulation and analytic models are often complementary. Analytic models are excellent for smaller systems that fulfill certain requirements, such as exponentially distributed inter-arrival periods and processing times. Simulation models are more appropriate for large and complex systems with characteristics that render them intractable for analytic models. Performance analysts need to be familiar with a variety of different techniques, models, formalisms and tools. Creating models that contain an appropriate level of detail is also an art. It is important to include enough information to be able to make a reasonable representation of the system; however, it is equally important to be able to determine which details are irrelevant and unnecessary [7].

A Petri Net is one of several mathematical representations of discrete distributed systems. It has been originated from Carl Adam Petri's doctoral dissertation work on communication with automata in 1962 is generally considered as integrated tool and methodology in various aspects of manufacturing systems. As a modeling language, it graphically depicts the structure of a distributed system and a directed bipartite graph with annotations. Petri Nets have proven to be very useful in the modeling, analysis, simulation and control of manufacturing system. The following advantages make Petri Nets an appropriate and effective tool and technology in analysis of manufacturing systems:

- Ease of modeling characteristics of a complex industrial system: concurrency, asynchronous and synchronous features, conflicts, mutual exclusion, precedence relation, and system dead locks.
- Ability to generate supervisory control code directly from the graphical Petri Net representation.
- Ability to check the system for understandable properties such as deadlocks and capacity overflow.
- Status information that allows for real-time control, monitoring and error recovery of the manufacturing system.
- Usefulness for scheduling because the Petri net model contains the system precedence relations as well as constraints on discrete event performance.
- Petri nets are used for modeling, and simulation of automated manufacturing systems.
- Graphical model uses very few but powerful primitives making it easy to understand.

- It can unambiguously describe a system, showing explicitly both states and actions, whereas other descriptive method focuses on either states or actions but not both. This allows users to change between the two perspectives as desired.
- Its wide range applications from a description of working processes, communication protocols and algorithms, to parallel microprocessor design.

Simulation-based performance analysis using Petri nets is the focus of this research work. One of the sciences associated with simulation studies is the application of the appropriate statistical techniques when analyzing simulation output. After a model has been created and validated, there are a multitude of decisions that need to be made before a study can proceed. *Experimental design* is concerned with determining which scenarios are going to be simulated and how each of the scenarios will be simulated in a simulation study. For each scenario in a simulation study one need to decide how many simulations will be run, how long the simulations will be, and how each scenario will be initialized. Both the length of a simulation and the number of replications run can have a significant impact on the performance measure estimates. Making arbitrary, unsystematic or improper decisions is a waste of time, and the simulation study may fail to produce useful results. In some studies, the scenarios may be given, and the purpose of the study may be to compare the performance of the given configurations with a standard or to choose the best of the configurations. If the scenarios are not predetermined, then the purpose of the simulation study may be to locate the parameters that have the most impact on a particular performance measure or to locate important parameters in the system. *Sensitivity analysis* investigates how extreme values of parameters affect performance measures. *Gradient estimation* on the other hand, is used to examine how small changes in numerical parameters affect the performance of the system. *Optimization* is often just a sophisticated form of comparing alternative configurations, in that it is a systematic method for trying different combinations of parameters in hope of finding the combination that gives the best results [11].

## **1.2 Statement of the problem**

Addis Engineering Center (AEC), formerly known as Addis Metal Pressing Enterprise is one of the manufacturing industries of the country, which is located in the capital, near Mexico Square. It was established 50 years back and the prime need for its establishment was to produce and supply bullets needed by the Ministry of National Defense to safeguard the country.

The organization has passed through series of administrative structures and number of changes from time to time. It is expected to go steps forward operationally to strive for manufacturing excellence. Though more than 50 years have passed since its establishment, the company is unable to be competent and maintain its position in the market due to lack of proper management, continuous performance analysis and other various factors. The company's profit declined continuously even below the acceptable level. For this and other related reasons the company is forced to stop producing ammunition. Presently, it has re-structured itself with a new name, Addis Engineering Center, by applying new management concepts and engaged in production of various spare parts, medals, badges, and furniture.

Therefore, the research work will attempt on the analysis of the manufacturing systems in the tools and spare parts work shop of the company and intend to provide solutions for its continuing problems to improve productivity and hence expanding the horizon of contribution for the development of the country.

### **1.3 Objectives**

#### ***General Objectives:***

- Modeling and analyzing the performance of the manufacturing process using Petri Net so as to evaluate various performance parameters such as utilization rate of machines, work-in-process, and throughput rate of system under consideration.
- Providing solutions for the pitfalls and ramification for attaining the optimum productivity.

#### ***Specific Objectives:***

- Identifying the bottlenecks of the production processes.
- Identifying presence of deadlocks, conflicts, priority, maintenance requirement, etc.
- Simulation of the manufacturing processes to analyze the overall performance.
- Comparative analysis of manufacturing system using Deterministic Timed Petri Net (DTPN) and Stochastic Petri Net (SPN).
- Developing user-friendly application software package to simulate the manufacturing entities using Turbo C++ programming language.

## **1.4 Methodology**

The methods employed to achieve the objectives of the research are:

### **➤ Literature Survey**

Different related reading materials like books, journals, previous research works on similar topic, and the Internet sources are referred to have thorough understanding of modeling, simulation, and analysis of the manufacturing processes. The state-of-the-art of the subject matter is assessed in this part.

### **➤ Data Collection**

The types of products and operations, sequence of operations for each product, the number and type of machines required and available for each product and operation, actual production time, machine down time, reasons for rejection of products and other relevant data are collected to conduct the research.

Data collection was conducted by using the following methods:

- Site visiting and taking data during actual operation time,
- Conducting interviews and discussion with engineers, technicians and responsible personnel.
- Using previous records or documents.

### **➤ Analyzing the data by using different performance analysis techniques**

Modeling the various operations and simulating them establishes a relationship between the actual and expected performances in order to make comparison and suggest reconsiderations to be made for improving productivity of the organization under consideration.

### **➤ Conclusion and Recommendations**

The model of manufacturing process is prepared in comprehensive manner to make analysis of the various manufacturing activities.

The result of simulation and performance analysis of the manufacturing process is discussed thoroughly and relevant conclusion and recommendations are duly addressed.

## **1.5 Scope and Limitations**

In the work the tools and spare parts machine shop of AEC is taken in to consideration. Different data are collected using the methods stated above for the analysis of various

performance measures. Based on the findings of the analysis, relevant recommendations are given in order to improve the performance of the workshop and the organization as a result.

More accurate results would have been obtained if correct data were made available; in addition, shortage of relevant materials was the other difficulty faced during the course of this work.

## **1.6 Application of the thesis**

All manufacturing industries in our country are beneficiaries of this research work. As performance analysis is the key for improvement, any organization can adopt the core concept of the thesis and can sufficiently benefit from it by emulating the achievable goals and standards set forth by modeling. Therefore, the application of the thesis will result in positive momentum that makes the organizations or industries improve their manufacturing performance and become competitive in the local as well as the global market.

## **1.7 Structure of the Thesis**

This thesis is composed of six chapters. Chapter one discusses the background, objective methodology, application of results, and scope and limitations of this research work. Chapter two deals with the related literature that presents review of manufacturing systems, Petri nets, simulation, and performance analysis of manufacturing systems. Chapter three contains the background of the factory and case data, which are related to the poor performance of the factory under consideration. Chapter four presents the modeling and model formulation for and various performance measures of manufacturing systems. Chapter five, deals with the software development and its application, which is making simulation runs for the models of selected sample products. Chapter six, the last portion of the thesis, presents conclusion and recommendation drawn based on the findings of the analysis carried out in the preceding chapters of the paper.

## CHAPTER TWO

### 2. REVIEW OF RELATED LITERATURE

#### 2.1 Manufacturing Systems: Overview

Although handicraft production has existed for many millennia, modern-style manufacturing is generally regarded as beginning around 1780 with the British Industrial Revolution, period marking the introduction of mass production, improved transportation, technological progress, and the industrial factory system, spreading thereafter to Continental Europe and North America, and subsequently around the world.

Manufacturing, a branch of industry which accounts for about one-quarter of the world's economic activity, is a wealth producing sector of an economy, whereas a service sector tends to be wealth consuming. This effort includes all intermediate processes required for the production and integration of a product's components. Each production operation is a process of changing the inputs into outputs while adding value to the entity. Interspersed between these value-adding operations are the non value-adding operations, such as transporting, storing and inspecting. It is necessary to minimize, if not eliminate, the non value-adding operations. Manufacturing should be recognized as a series of production activities: planning, design, procurement, production, inventory, marketing, distribution, sales, and management.

A production enterprise is an organization whose core business is focused in the production of products. The production can be defined as the transformation process that converts raw materials or semi-finished products into finished products that have value in the market, using manual labor and machinery, and usually carried out systematically [19].

A production enterprise requires the integration of three main elements: product, process and business. The product vector is related to the product development and design activities, the process vector related to how to produce the products and the business vector is related to distribution, marketing and service infrastructure. The focus of this research work is in the process element.

The production process has as inputs raw materials, information and energy. The guidelines that support the decision of how to produce are the organizational strategies, product demands and external disturbances. The organizational strategies define the guidelines of production,

such as the production type and the long/medium term production plan. During the transformation process, subjected to environment, quality and safety constraints, waste is generated due to the material transformation process, to the failures occurred in the machines and to the quality control rejections.

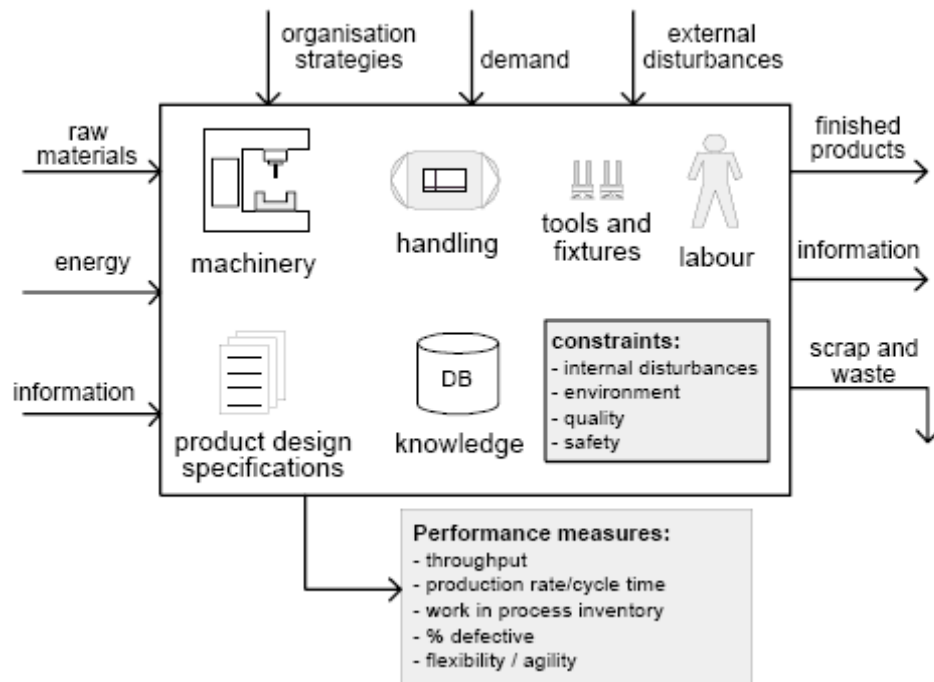


Figure 2-1 Abstract model of manufacturing systems

The variation in product demand and the external disturbances requires the introduction of corrective actions in the planning and control system to maintain the production strategic guidelines. The outputs of the production process are the finished products that will be delivered to the market according to the customer demands [13].

The geographical concentration of the manufacturing industry is changing. The industrial capacity of many of the western nations is being negatively impacted by an imbalance in currency exchange rates, accompanied by wage erosion and a corresponding loss of engineering job opportunities in western nations, due to relocation and outsourcing of enterprises to more exploitive and lower-wage countries of the world which have fewer labor protections and lower environmental standards [10].

### **2.1.1 Historical Evolution of Manufacturing Paradigms**

The manufacturing environment is in permanent change adapting to the customer demands, advances in information and automation technologies and economical trends. During the last century, several paradigms and organizational concepts were introduced aiming to bring more competitiveness to the production enterprises. According to the Merriam-Webster dictionary a manufacturing paradigm can be defined as *a philosophical and theoretical manufacturing framework of a scientific school or discipline within which theories, principles, laws, generalizations and experiments are formulated.*

Before the 20<sup>th</sup> century, the craft production was the dominant type of production, characterized by skilled workers that used general purpose tools to produce exactly what the customers asked for, being the production level close to the *one-at-a-time*. As a historical example, a sword maker only produced one sword at a time, each one customized for the client, with periodic assessments of weight and balance, appearance, and details prior to delivery.

The industrial revolution introduced machinery in production, helping in the first phase the craft production to be more productive, by using machinery to support some craftsman work. In the beginning of 20<sup>th</sup> century, Henry Ford decided to build a car that everybody could own and drive. However, at that time most cars were customized for the client or built one at a time in limited quantities, following the craft production type. Based in the Taylor's theories, he introduced in 1913 at Highland Park plant in Michigan, the revolutionary concept of mass production, characterized by the production of the same product in large scale using a rigid assembly line to produce a car composed by identical interchangeable parts, Figure 2-2. At the time, everybody could have a Ford T car of any color as far as it was black! With the introduction of the production assembly line, the task cycle for the average Ford assembler (i.e. the amount of time that the operator works before repeating the same operations), was reduced from 514 minutes to 2, 3 minutes. Lately, he had further cut the time from 2, 3 minutes to 1, and 2 minutes with the moving line which brought the car to the stationary worker.

The mass production model requires stability and control in the input variables, markets, and the labor force. In the 1970s and 1980s, these parameters became less stable, with common economic fluctuations, increase of the consumer power, homogeneity of the market eroded and start of the global competition. Additionally, the globalization of markets brought to the

production companies the need to become strong competitively, in order to fulfill the requirements of the market for the reduction of prices, better product quality, and minimum time of delivery and diversity of offer. The mass production, idealized by Henry Ford was a strap down system, incapable to treat variations in the type of product. This rigidity started to be an obstacle and with the worldwide competitiveness the mass manufacturing became viable only for some products.

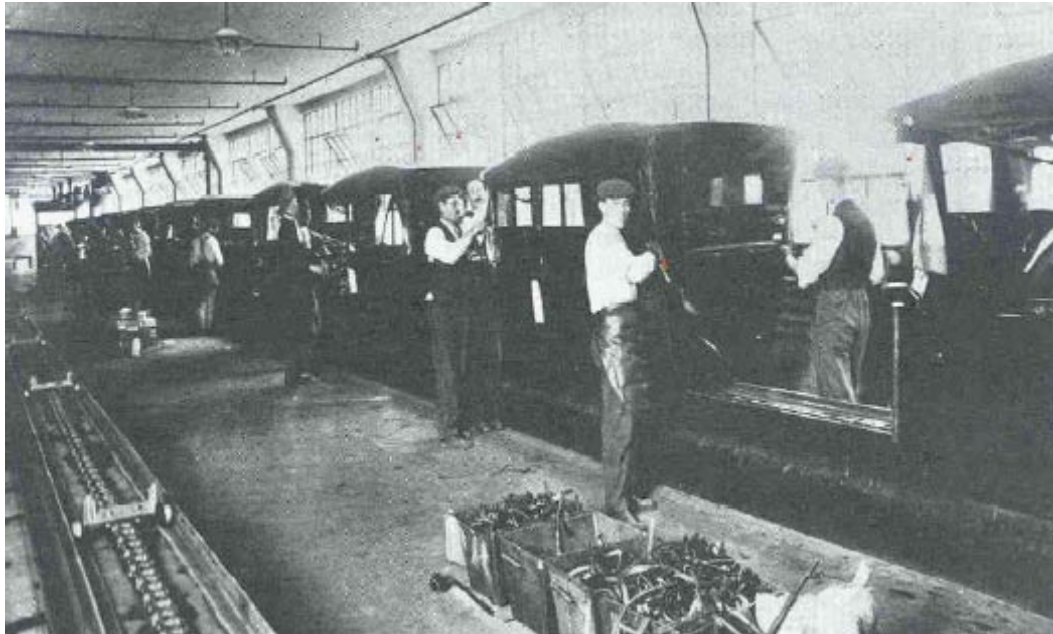


Figure 2-2 Ford's Assembly Line

The Just in Time (JIT) philosophy was introduced by Japanese company Toyota Motor Inc. in its production system, supervised by its engineer chief Taichii Ohno, after studying the production of the Ford model A car. JIT consists in having the right material at right place at right time, eliminating stocks, and using very simple control and scheduling systems, such as the Kanban cards system. The implementation of JIT principles had supported the Japan's ascendancy in the automotive world.

Since the late 1970's the Toyota Production System has been studied, specially by US companies, and their principles have been gathered together as the basis of the lean production concept, which main idea is to eliminate waste in all activities, achieving manufacturing products with less of time to design, less inventory, less defects and reducing the setups.

A concise definition of lean production is "Lean Production is a system of work organization that strives to deliver high quality and low cost products through the efficient use of resources and the elimination of waste". An example of lean production is an automobile production line

with capability to produce several variants of a car to meet the demands of a specific market segment.

In the eighties, the companies addressed technologies and paradigms to achieve flexibility. However, in the nineties they were challenged by the need to increase agility. The agile manufacturing, introduced by the Iacocca Institute at Lehigh University, is the ability to adapt quickly and profitably to continuous and unexpected changes in the manufacturing environment. It presents continuous improvement, rapid response; quality improvement, social responsibility, and total customer focus [14].

#### ❖ *Flexible Manufacturing System*

A flexible manufacturing system is a production system consisting of a group of identical and/or complementary numerically controlled machines connected through an automated transportation system. A dedicated computer, called the cell controller, controls all operations of an FMS. An FMS is capable of processing different types of products in an arbitrary sequence with negligible setup delays between operations. Typically, an FMS can produce over 20 different part types simultaneously in the system. Some large ones can produce over 100 part types if a proper tool management system is provided. An FMS is distinguished from other types of manufacturing systems by following characteristics: high degree of functional integration, arbitrary operational sequence with negligible setup delays, complex tool management, and complicated control software [18].

As illustrated in Figure 2-3, these systems fill the gap between the mass production and the dedicated NC machine production, with the ability to process simultaneously a variety of different part types. The FMS systems present several significant advantages: an increase of productivity (2-3, 5 times), decrease of production costs (50%), reduction of inventory and stocks (85%), increase of quality, decrease of response time, products customized to the customer requirements, etc. The reduction of inventory can be enough to justify the investment in necessary hardware and software to build a flexible manufacturing system.

In spite of the main objective of the FMS being to achieve the flexibility, one of the main disadvantages is its inflexibility to the introduction of new products. FMS are flexible while they are producing a known range of products, becoming difficult the introduction of new product families, due to the complexity of automatically execute the necessary adjustments.

Agility impacts the entire manufacturing organization, including product design, customer relations and logistics, as well as production, and it has been expressed as having four underlying principles: *deliver value to the customer*, *ability to react to changes*, *value of human knowledge and skills*, and *ability to constitute virtual partnerships*. While the first three principles can be found in the lean production paradigm, the fourth principle makes the difference between lean and agile manufacturing: in agile manufacturing the companies form temporary alliances with other companies, even competitors, to react to unexpected situations, with mutual benefits for both companies. Finally, in agile manufacturing it is important to consider that human factors and organizational knowledge are just as important as advanced technology. Additionally, work within agile organization occurs concurrently rather than sequentially.

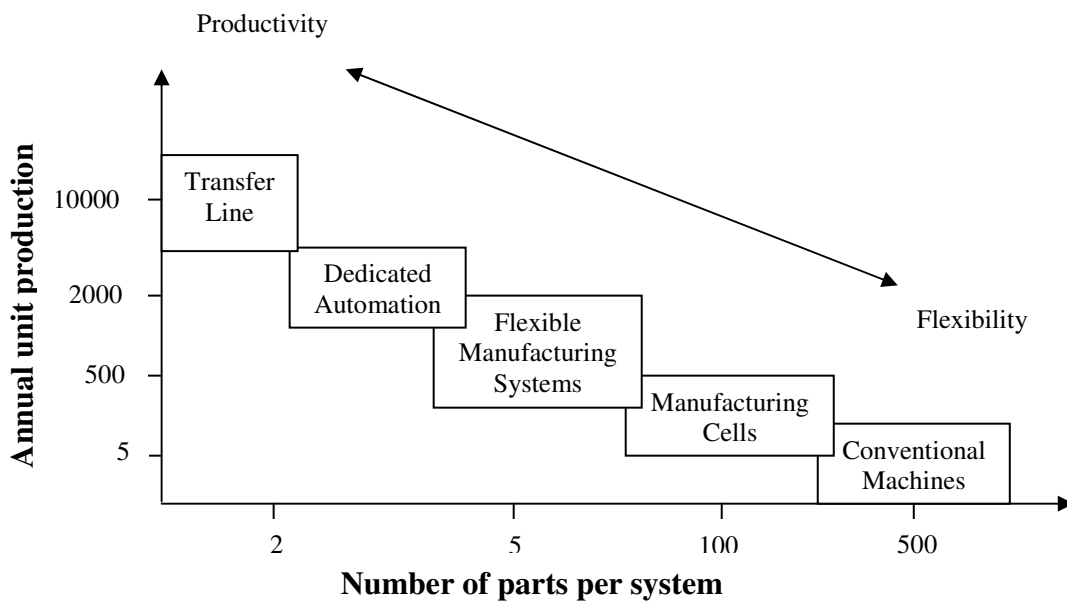


Figure 2-3 Flexible Manufacturing System context

The ideas of lean and agile manufacturing are mainly viable for companies starting from scratch its business or companies prepared to support the significative financial risk of build a new production system. Those risks are acceptable for large companies, like Toyota, but they are often unaffordable for SMEs [14].

Nowadays, the customer demand for specific and customized products leads to the concept of mass customization, which focuses on satisfying the individual customer needs. While in lean production the focus as in the elimination of the waste in the process, in mass customization

the focus is in the elimination of the waste in products by eliminating the features unwanted by customers [3].

Mass customization requires the increase of flexibility and agility, using flexible processes (automation technologies, such as CNC machines, robots and CAD systems) and flexible organizational structures to produce multiple variations of often-customized products at the price of standardized mass products. As an example, Ford’s truck plant in Kentucky offers 2.5 million variant of trucks to its customers. Another illustrative example is related to the Smart car manufacturer, which offers more than a half million different configurations to its customers.

Table 2-1 Comparison between manufacturing paradigms

	<b>Mass Production</b>	<b>Lean Production</b>	<b>Agile Production</b>	<b>Mass Customization</b>
<b>Environment</b>	Stable	Fairly stable	Unstable, uncertain, unpredictable	Turbulent
<b>Product Variety</b>	Few number of products, often only one	Finite number of variants of a single or few products	Customized products	High variety and customization
<b>Product Volume</b>	High volumes	Small-lot production	All levels of production	All levels of production
<b>Equipment</b>	Dedicated equipment, fixed automation	Programmable and flexible automation equipment	Highly flexible and integrated automation equipment	Highly flexible and integrated automation equipment
<b>Workforce Skills</b>	Unskilled workers	Skilled, multi - functional workers	Skilled, multi - functional workers	Skilled, multi - functional workers
<b>Markets</b>	Mass market	Segmented markets	Mass one to one market	Mass one to one market
<b>Emphasis</b>	Standard products at lowest possible cost	Quality, productivity and flexibility	Flexibility and high responsiveness to unexpected change	Low cost production, of high quality and customized products

Table 2-1 presents a brief comparison of the main manufacturing paradigms, resuming the characteristics of each one under different categories, such as the product volume, product variety, and product cost and workforce skills. The significant differences are reflected in the emphasis of each paradigm and are illustrated in Figure 2-4 that shows the evolution of them in terms of product variety and volume.

In spite of the current trend to mass customization, it is possible to find several examples of mass production, such as the Telco 1010 truck production line in India, which produces thousands of trucks with no variation in design. Also, the craft production is nowadays visible in the cases where artisans build products for the customer specifications in specific market niches, and often sell in traditional markets.

The conclusion is that in the 21<sup>st</sup> century, companies are going to operate in a dynamic and challenging environment that requires new approaches to manufacturing. Mass customization is a general trend that is more and more widespread, seeming to be as the production paradigm for the factory of the future. From the manufacturing point of view, much work must be done to develop adequate manufacturing systems meeting the new requirements, since traditional solutions don't seem to be able to face the demands of mass customization [14].

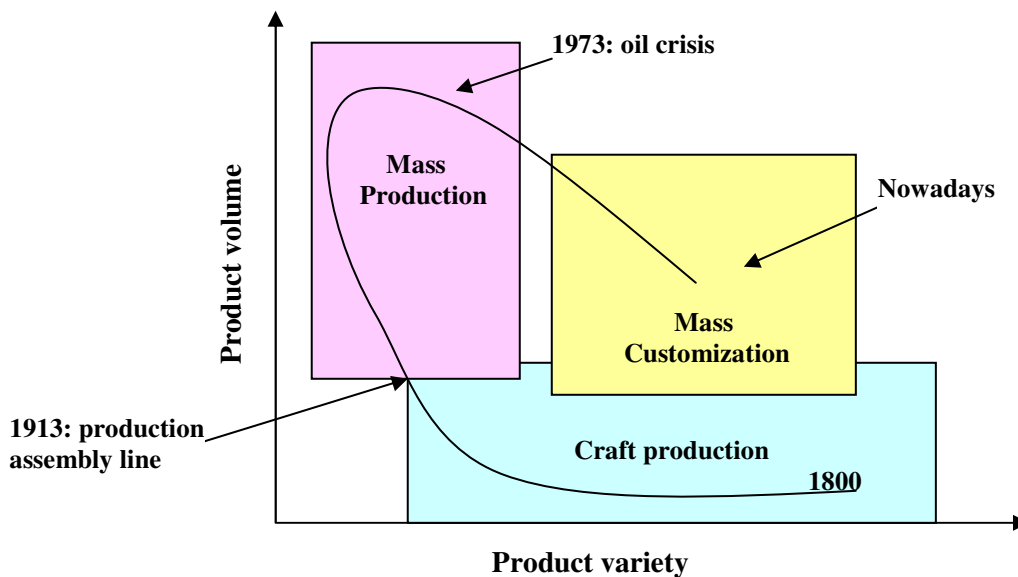


Figure 2-4 Evolution of manufacturing paradigms

### **2.1.2 Manufacturing Industry in Ethiopia**

The history of modern manufacturing industries in Africa began with colonialism. In case of Ethiopia, modern manufacturing was introduced to the country's economy towards the end of 19<sup>th</sup> century, with the emergence of strong central government and political stability. By 1927, about 15 factories were established in different cities of the country, like Addis Ababa, Dire Dawa, Asmara and Massawa which includes 5 wood and clay factories, 2 tanneries, 5 soap and edible oil plants, 1 grain mill, and 2 salt factories. Almost all were established by private entrepreneurs.

During 1928-1941 about 10 manufacturing industries were set up, including the Dire Dawa cement factory and Dire Dawa textile factory that were established by the Italians. The remaining factories were setup by the Armenian and Greek settlers. During the immediate post

war period of 1941-1959 the manufacturing sector increased rapidly. It was promoted for two main reasons:

- The government realized that the victory of Italy over Ethiopia was attributed to military superiorities, like use of superior mechanized armaments and weapons by Italy during 1935-40, and thus the need for modernization and economic development began to be perceived; and
- The close relation of Ethiopian government with the government of United States and United Kingdom, which encouraged social and economic development.

The increase in the number of establishments up to 1950 was not nevertheless a result of a conscious and deliberate development action. The development stages of manufacturing industries can be classified into the following three major political events [12].

➤ **Manufacturing Industry Before 1974**

The level of industrialization during the imperial period was considered as at an incipient stage. A conscious effort towards developing and establishing a modern industrial sector did not start till the 1950's. The main agents for the expansion of the industrial sector during this period were foreign nationals residing in the country. It was believed that the settlement of foreigners along with the expansion of commercial farms would continue to give inertia to the growth and expansion of the industrial sector.

Considerable numbers of manufacturing firms were established as a result of conducive environment created during the later years of this era. By the end of this era, there were some 430 manufacturing establishment with a low level of employment creation comparing to the population size. These industries were designed to satisfy the limited domestic market and were seriously handicapped by poor infrastructure facilities and lack of clearly articulated government economic policies towards the development of the sector. The majority of the industries were in nature employing very few skilled personnel with rudimentary concept of quality and market.

However, whenever private initiatives failed to come forth, the government made direct investment and establish factories. These include cement factories, the petroleum refinery, tyres factory for strategic reason. Some factories like Bahir-Dar Textile and Debre-Berhan Wool factories were established by the government to distribute industries to disadvantaged

area based on available local materials. The Awash tannery was established to process raw hides and skins for export. The tobacco factory was built for revenue purposes. The government also entered into joint ventures with foreign companies to establish factories like the Ethio-Japanese Nylon, Corrugated Iron Sheets and meat concentrates (with Japanese firms), a textile mill with an Indian group, a pulp and paper factory with an American company, sugar mill with a Dutch group, and an abattoirs with a UK group [12].

During this period, large scale and medium sized manufacturing industries were concentrated in the hands of private foreign nationals. There were low management and technical skill transfer as higher management positions and technical department were fully in foreign hands. Ethiopians were limited to small and cottage industries and as wage earners in foreign owned companies.

➤ **Manufacturing Industry during the Derg Era**

After the 1974 revolution, Derg changed the structure of ownership as part of its “socialist” policy, and nationalized virtually almost all medium and large-scale industrial enterprises owned by Ethiopian and foreigner alike. This made the industrial sector to be dominated by public manufacturing enterprise. The era showed its intention to move into production of intermediate and capital goods in its ten years perspective plan. The plan had envisaged to a strong self-reliant national economy with adequate inter-sectoral linkage but it was not materialized.

As a result of the Derg socialist policy, the private sector investment in manufacturing was restricted to small scale-industries and handicrafts and cottage industries with the maximum ceiling of Birr 500,000 in investment. Handicrafts and cottage industries were organized into producers cooperatives based on socialist systems with heavy subsidies. Thus the development and investment in manufacturing sector was monopolized by the state. Besides, imports were restricted and local industries monopolized the domestic market.

The intention to build a strong self-reliant national economy with inter-sectoral linkages was neutralized by an objective to satisfy basic needs of the population as a result of which projects in the food, beverages and textiles sectors took over 90 percent of the total investment in between 1976 to 1984. Though industrial production increased during this era, less emphasis was paid to quality and productivity. Together with this, less attention was paid to deepening industrial production and the development of basic industries such as chemicals, metals and

engineering, which would have strengthened the linkage within the industrial sector, reduces dependence on imported inputs and increase the range of industrial processing domestic materials.

➤ **Post 1991 Manufacturing Industries**

Following the collapse of socialism, the only choice that developing countries have in terms of planning their development strategy was following the line of an economic system that goes liberalized the existing economy of the country following its development so as to destine in the more liberalized capitalist system. Accordingly, the transitional government of Ethiopia, which took power from the Derg, announced an economic policy whose basic elements characterized as “cautious capitalism”. The government accepted structural adjustment program although with some reservations to make conducive environment for investment [12].

The government of the EPRDF (Ethiopian People Revolutionary Democratic Front) led federal republic of Ethiopia, which took over the transitional government, indicated its intentions about the future of the Ethiopian economy by outlining its broad five year development program. According to this strategy, the primary focus of development in short and medium terms will be expanding agricultural production through increased availability of modern inputs and extension services. This is supposed to increase the income of the rural people, which will in turn raise the purchasing power of the larger proportion of the population for industrial outputs. Below are facts and the contributions of the manufacturing industry in the country:

▪ **Exports**

While on the face of it, manufactured exports appear to have registered impressive growth in the past few years, a closer look at the structure of exports reveals that leather and leather products, food and textiles in that order constituted the bulk of industrial exports. Manufactured exports are thus limited to agricultural based products. Export earnings generated by the sector have been able to meet only about half the sector's foreign exchange requirements.

▪ **Employment**

Manufacturing industry employs only 0.5% of the labor force, the textile and food industries accounting for over 60% of manufacturing employment. Ethiopia has an abundant supply of unskilled and semi-skilled labor. However, there exist acute shortages of executive personnel such as managers, trained production supervisors, various disciplines in engineering, etc.

- **Linkages**

One of the major weaknesses of manufacturing industry is its inability to create forward and backward linkages with the rest of the economy. Consequently the share of domestic intermediate inputs going to other sectors of the economy has been much less and could only be met from imports. Therefore, the manufacturing sector has failed to raise the technical capacity of the agriculture sector by supplying it with improved implements and other inputs. With regard to the transport sector, the supply of domestically manufactured inputs has been limited to truck assembly, the production of tyres and tubes, and few other manufactured components. The contribution of the manufacturing sector to the construction industry is limited to the supply of cement, bricks, hollow blocks, and reinforcement bars.

Two major conclusions may be drawn regarding linkages. First, the share of locally manufactured inputs supplied to the various sectors would have been significantly higher had the country's foreign exchange reserves been adequate to allow greater amounts of imported inputs. Second, the past import substitution strategy may be said to have failed in Ethiopia. It only resulted in the creation of an industrial enclave with limited linkages with the rest of the economy. The import substitution strategy that concentrated on the processing of final consumption goods stunted the development of the manufacturing sector and the rest of the economy at large. And, as the demand for imports of consumer goods, capital goods and other inputs increased over time, the sector's ability to generate foreign exchange became increasingly constrained.

- **Regional distribution**

Many of the industrial establishments are concentrated in a few regions of the country with Addis Ababa, the Shewa region, and Dire Dawa and the Hararge region accounting for 91.7% of all industrial establishments and 89.5% of industrial employment. Wello, Gojam, Sidamo and Arsi regions account for only 3%, 2% and 1% of public enterprises, respectively.

The distribution of industrial enterprises has been largely determined by the availability of markets and infrastructure, the uneven distribution of electricity, telecommunications and transport facilities and most importantly, the absence of appropriate incentives and policy measures resulted in disparities between regions and have had a negative effect on the overall national development.

▪ **Constraints**

A number of constraints have hampered industrial development in Ethiopia. A brief overview of these constraints will provide us with vision about the challenges and opportunities that lie ahead and will help us in drawing up appropriate development objectives, and for designing an appropriate industrial development strategy. With this in view, the factors that constrained the development of the sector are briefly discussed below:

1. The inadequacy of infrastructure has been one of the major constraints for the industrial development. Roads, energy, water supply, and other facilities have not been developed to support the industrialization process in the country.
2. Although the country's major natural resource base is its rich agricultural potential, it has not been utilized for the development of the industrial sector. The very low productivity in agriculture resulting from the use of obsolete technology could not cope with the demand for industrial raw materials and foreign exchange requirements, in addition to limiting the market for industrial goods. Though Ethiopia is known to possess a wide variety of mineral resources, their utilization is yet to be realized mineral exploration and exploitation still being at its infancy. This thwarted the expansion of industries based on mineral resources that would have otherwise made it possible to reap the benefits of comparative advantage.
3. The industrial sector is characterized by very low inter and intra-sectoral linkages. It has been unable to produce intermediate inputs, spare parts and capital goods for its own use as well as for use by other sectors of the economy. The sector itself has continued to be import dependent for machinery and equipment, spare parts and other inputs with no possibilities for self sustained development.
4. Small and medium scale industries, as well as handicraft and rural industries, were given less priority in the wider spectrum of industrial development. The encouragement and expansion of these industries would have meant an adequate supply of consumer goods, developed domestic entrepreneurship, generated employment opportunities and created inter and intra-sectoral linkages and a balanced regional development.
5. Past industrialization policy was such that it resulted in an unwarranted concentration of industries in and around a few major urban centers. There were no inducements for industrial enterprises to be located in different regions of the country in the interests of promoting balanced regional development.

6. The industrial sector has been characterized by capital-intensive technology. This has led to a number of problems. First, the sector has not been able to generate employment opportunities. Second, having been unable to absorb available labor force, the sector has lost a large potential market for its own products.

7. The absence of appropriate institutions for manpower development and for the selection, transfer, adaptation and diffusion of technology also remained.

## **2.2 Petri Nets as tools in Manufacturing Systems**

Petri nets are graphical and mathematical tools for studying discrete event systems. Petri nets have been under extensive development since Petri defined the language in 1962. Various extensions of Petri nets have been developed to study concurrent, asynchronous, distributed, parallel, deterministic, and stochastic system behavior.

Petri net models are now commonplace within the sphere of performance modeling of manufacturing systems. Their use in manufacturing systems has been strongly influenced by numerous people over the years. Comprehensive surveys of Petri nets in manufacturing systems were presented by Al-Jaar and Desrochers in 1990 and earlier by Martinez, Alla and Silva in 1986. Performance modeling of automated manufacturing systems using stochastic Petri nets is relatively recent and was first demonstrated by Dubois and Stecke in 1983. Further research has been done by Al-Jaar in 1989 and Narahari in 1987 into the use of stochastic Petri nets in manufacturing.

PNs have been used for the modeling, analysis and simulation of automated manufacturing systems for the following reasons: (i) graphical and precise representation of system activities, (ii) ability to represent system models at various levels of detail, (iii) ability to capture the existence of concurrency and parallelism, (iv) existence of analytical and graphical simulation tools for the verification of dynamic system behaviors, and (v) ability to capture resource constraints and process dependencies accurately [16].

### **2.2.1 Introduction to Petri Nets**

Petri nets have been originated from Carl Adam Petri's doctoral dissertation work on communication with automata in 1962. He described using a net the causal relationships between events in a computer system. His work came to the attention of A.W. Holt and others

of the Information System Theory Project of Applied Research, Inc. in the United States. Their work illustrated how Petri nets could be used to model and analyze systems of many concurrent components. Petri's work also came to the attention of The Computation Structure Group of Massachusetts Institute of Technology, led by Professor J.B.Dennis. Several Doctoral theses and technical reports were published during the early 1970s on the topic.

Starting in the late 70's, Petri nets became a very active area, especially in Europe. Annual conferences on Application and Theory of Petri Nets have been held since 1979 and the proceeding published in the series of lecture notes of computer science by Springer-Verlag. Most of the studies focused on information processing systems in the computer science community. Professor T. Murata gave an excellent tutorial paper in 1989, which comprehensively presented properties, analysis, and application of Petri nets and a list of references of significance. Most of the earlier applications and theory of Petri nets aimed to information processing systems. The books and most of the papers were primarily targeted at computer scientists and graduate students [11].

Researchers with engineering background started their probe into the application of Petri nets in engineering system particularly automated manufacturing systems in the early 1980's. They found that Petri nets were powerful tool in describing event-driven systems. These systems may be asynchronous, contain sequential and concurrent operations, and involve conflicts, mutual exclusion and non-determinism. Such systems termed as discrete event systems or discrete event dynamic systems (DEDS).





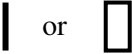
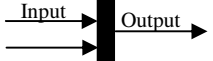
Since the introduction of the classical Petri net by Carl Adam Petri in the '60s, Petri net have been used to model and analyze all kinds of processes with applications ranging from protocols, hardware, embedded systems to flexible manufacturing systems, user interaction, and business processes. However, the main application domains to be mentioned are manufacturing, workflow management and telecommunications. Here from the objective of this thesis, manufacturing application of Petri net is assessed.

### **2.2.2 Fundamentals of Petri Nets**

A Petri net is a bipartite directed graph that contains places represented by circles; transitions represented by boxes or bars, and directed arcs connecting places to transitions and transitions

to places. The movement of tokens represents the dynamic nature of the modeled system in a Petri net. A token, represented as a small dot, is placed in a circle to indicate that the state is active. The current location and distribution of tokens in a Petri net is called its marking. The marking of the Petri net defines the state of the system. A Petri net containing tokens is called a marked Petri net [15].

Table 2-2 Basic elements of Petri Nets

Name	Symbol	Name	Symbol
Place		Token	
Arcs		Marked place	
Transition		Transition with input and output arcs	

❖ *Formal definition of Petri Nets*

A black-and-white Petri net or ordinary PN can be formally defined as a four-tuple<sup>1</sup>:  $PN = (P, T, I, O)$  where:

$P$  is a finite non-empty set of places.  $P = \{p_1, p_2, \dots, p_n\}$

$T$  is a finite non-empty set of transitions.  $T = \{t_1, t_2, \dots, t_s\}$

$I$  is an input function.  $I: (T \times P) \rightarrow \{0,1\}$ ,  $I(t, p) = 1$  if there exists an arc from  $p$  to  $t$ . If so,  $p$  is an input place for  $t$ ;

$O$  is an output function.  $O: (T \times P) \rightarrow \{0,1\}$ ,  $O(t, p) = 1$  if there exists an arc from  $t$  to  $p$ . If so,  $p$  is an output place for  $t$ ;

$M: P \rightarrow N$  is a marking that assigns a non-negative integer to each place. Such a number represents the number of tokens in the place.  $\langle P, T, I, O, M \rangle$  represents a marked Petri net. Fig. 2-5 below shows a simple PN model.

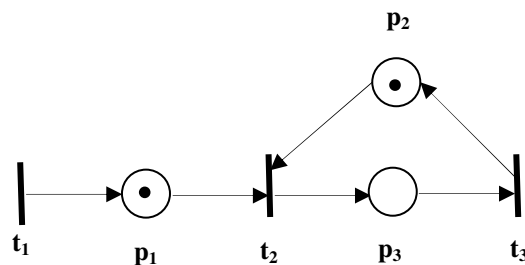


Figure 2-5 A simple PN example

<sup>1</sup>In mathematics, a **tuple** is a finite sequence (also known as an "ordered list") of objects, each of a specified type. A tuple containing n objects is known as an "n-tuple".

Places:  $P = \{p_1, p_2, p_3\}$ ; Transitions:  $T = \{t_1, t_2, t_3\}$ ;

Input places:  $I(t_1) = \{p_1, p_2\}$ ,  $I(t_2) = \{p_1, p_2\}$ ,  $I(t_3) = \{p_3\}$ ;

Output places:  $O(t_1) = \{p_3\}$ ,  $O(t_2) = \{p_3\}$ ,  $O(t_3) = \{p_2\}$ ;

Initial Marking  $M_o = [1 \ 1 \ 0]$

$$I = \begin{matrix} & p_1 & p_2 & p_3 \\ \begin{matrix} t_1 \\ t_2 \\ t_3 \end{matrix} & \begin{bmatrix} 0 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{matrix} \quad O = \begin{matrix} & p_1 & p_2 & p_3 \\ \begin{matrix} t_1 \\ t_2 \\ t_3 \end{matrix} & \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{bmatrix} \quad C = O - I = \begin{matrix} & p_1 & p_2 & p_3 \\ \begin{matrix} t_1 \\ t_2 \\ t_3 \end{matrix} & \begin{bmatrix} 1 & 0 & 0 \\ -1 & -1 & 1 \\ 0 & 1 & -1 \end{bmatrix}$$

The following rules are used to govern the flow of tokens in a Petri net:

- **Enabling Rule:** A transition,  $t$ , is enabled if and only if all the input places of transition  $t$  contains at least one token.
- **Firing Rule:** An enabled transition  $t$  may fire at marking  $M_o$ . Firing an enabled transition  $t$  removes one token from each input place of  $t$  and adds one token to each output place of  $t$ .

A Petri net from stage  $k$  to stage  $k+1$  can be expressed by the following state equation:

$$M_{k+1} = M_k + C_{uk}$$

Where,  $M_k$  is the current marking state vector,  $uk$  is the control vector and  $C = O - I$  is the incident matrix.

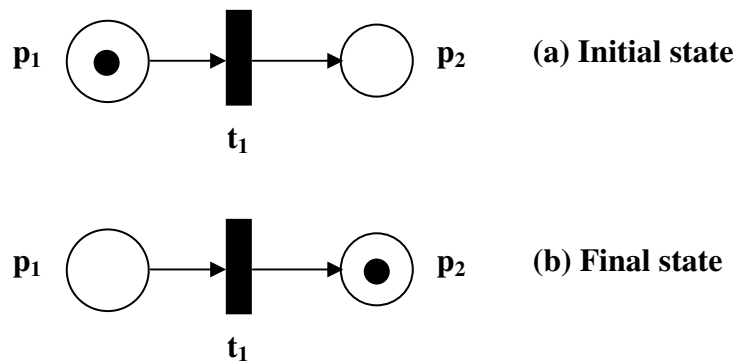


Figure 2-6 Enabling and firing rules of transitions

Using this notation, Petri nets can model discrete event systems and can capture important system characteristics. These include actions that must occur in a sequence, actions that occur concurrently, actions that compete for resources, actions that must be synchronized, actions

that occur in cycles, and actions that cannot occur simultaneously. The evolution of Petri net marking is shown in Fig.2-7 below.

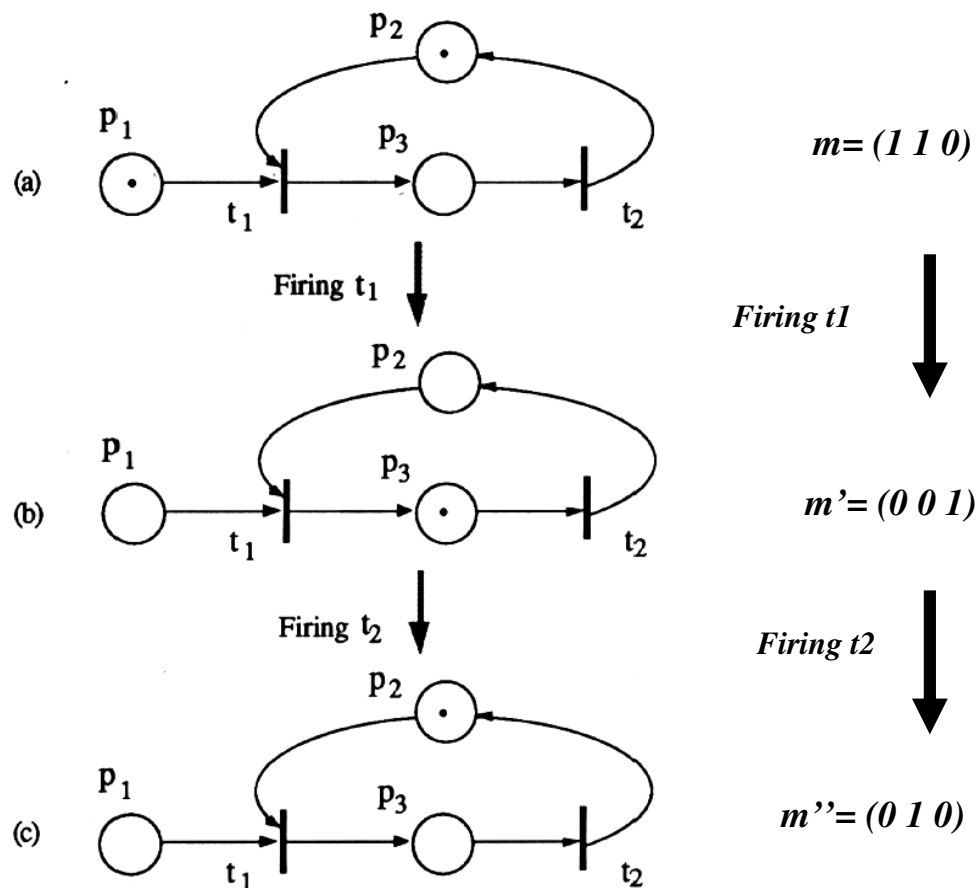


Figure 2-7 Evolution of Petri net markings

### 2.2.3 Properties of Petri Nets

It is important to notice that some of the following properties are related: one property can be deduced from others [11].

- Reachability.** From the model point of view, this property determines whether a given (vector) marking is reachable from the initial marking. From the real system point of view, this property indicates whether a system state is reachable from the initial configuration. It can be used to answer question such as the following: it is possible to reach a state where machine  $M$  is processing two parts while robot  $R$  is busy and machine  $M'$  is free? It is possible to reach a state in which buffer  $B$  is full? The answers to a set of well-defined questions can be used to establish a correct system design. A second related property is coverability. From the Petri net point of view, this determines

whether a reachable marking is greater than or equal to another given marking. From this kind of property, less complete information can be obtained; but this information can be used in a similar way that provided by reachability properties.

- **Boundedness and safeness.** This property determines whether the number of tokens in a given place is always smaller than or equal to a given constant  $k$ . usually in FMS/AMS domains, using the possible meanings of a place as stated previously, all places must be bounded; the model is perhaps, incorrect. If a model is correct and a place is detected to be unbounded, some overflow problems may arise. A related property is safeness (1-boundedness).
- **Reversibility.** When verified, this property determines that the initial state can be reached from each reachable state. In the application domain considered, this property means that each possible erroneous situation has been considered by means of some error recovery strategy. The erroneous situations include the case of system deadlocks and the case of resource failures.

Table 2-3 Petri net properties and their meanings

PN properties	Meanings in the modeled Manufacturing System
Reachability	A certain state can be reached from the initial condition
Boundedness	No capacity (of, e.g., buffer, storage area, and work station) overflow
Safeness	Availability of a single resource; or no request to start an ongoing process
Conservativeness	Conservation of non-consumable resources, e.g., machines and AGVs
Liveness	Freedom from deadlock and guarantee the possibility of a modeled event, operation, process or activity to be ongoing.
Reversibility	Re-initialization and cycle behavior
Repetitiveness	Existence of repetitive operations/activities/events for some markings
Consistency	Existence of cyclic behavior for some marking

- **Deadlock-freeness/liveness.** A Petri net system is said to be deadlock-free if at each reachable marking there exists at least one transition that is enabled. In our application domain this means that it is always possible to make some production activity. Deadlock-freeness is not enough for this domain. It is possible to have a part of a system that can always run correctly, but also another part of the system that is in a deadlock. For instance, it is possible to have one type of part being correctly processed,

as well as other parts whose processing has been started but cannot be finished. Thus deadlock-freeness cannot be strong enough for highly automated systems; liveness is a stronger property. A Petri net system is said to be live if for each reachable marking it is always possible to fire any transition. In the application domain considered, this means that it is always possible to execute the system actions modeled by any transition. As a consequence the processing of each part, once started, can always be finished: the transitions “driving” a token (modeling a part) to the system output can be fired. Thus the processing of the part can be finished. This also means that if there are always new raw materials, their processing can be carried out.

### **2.2.4 Representational Power of Petri nets**

The characteristics exhibited by the activities of an AMS such as concurrency, decision-making, synchronization and priorities are modeled very effectively with Petri nets. These characteristics are represented using a set of simple constructs [9]:

**1. Sequential Execution:** If one operation follows the other, then the places and transitions representing them should form a cascade or sequential A relation in Petri nets. In Figure 2-8 (a), transition  $t_2$  can fire only after the firing of  $t_1$ . This imposes the precedence of constraints " $t_2$  after  $t_1$ ".

**2. Conflicting:** If either of two operations can follow an operation, then two transitions form two outputs from a same place. Transitions  $t_1$  and  $t_2$  are in conflict in Figure 2-8 (c). Such a situation will arise, for example, when a machine has to choose among part types or a part has to choose among several machines. The resulting conflict may be resolved in a purely non-deterministic way or in a probabilistic way, by assigning appropriate probabilities to the conflicting transitions.

**3. Concurrency:** If two operations are initiated by an event, they form a parallel structure starting with a transition, i.e., two places are two outputs of the same transition. An example is shown in Figure 2-8 (d). Concurrency is an important attribute of AMS interactions. A necessary condition for transitions to be concurrent is the existence of a forking transition that deposits a token in two or more output places.

**4. Synchronization:** Often, parts in an AMS wait for resources and resources will wait for appropriate parts to arrive. The resulting synchronization of activities can be captured by

transitions of the type shown in Figure 2-8 (b). Here,  $t_1$  will be enabled only when tokens are available in both places  $p_1$  and  $p_2$ .

**5. Merging:** When parts from several streams arrive for service at the same machine the resulting situation can be depicted as in Figure 2-8 (e). Another example is the arrival of several parts of several sources to a centralized warehouse.

**6. Confusion:** A situation where concurrency and conflicts co-exist as in Figure 2-8 (a) below. Both  $t_1$  and  $t_2$  are concurrent and are in conflict.

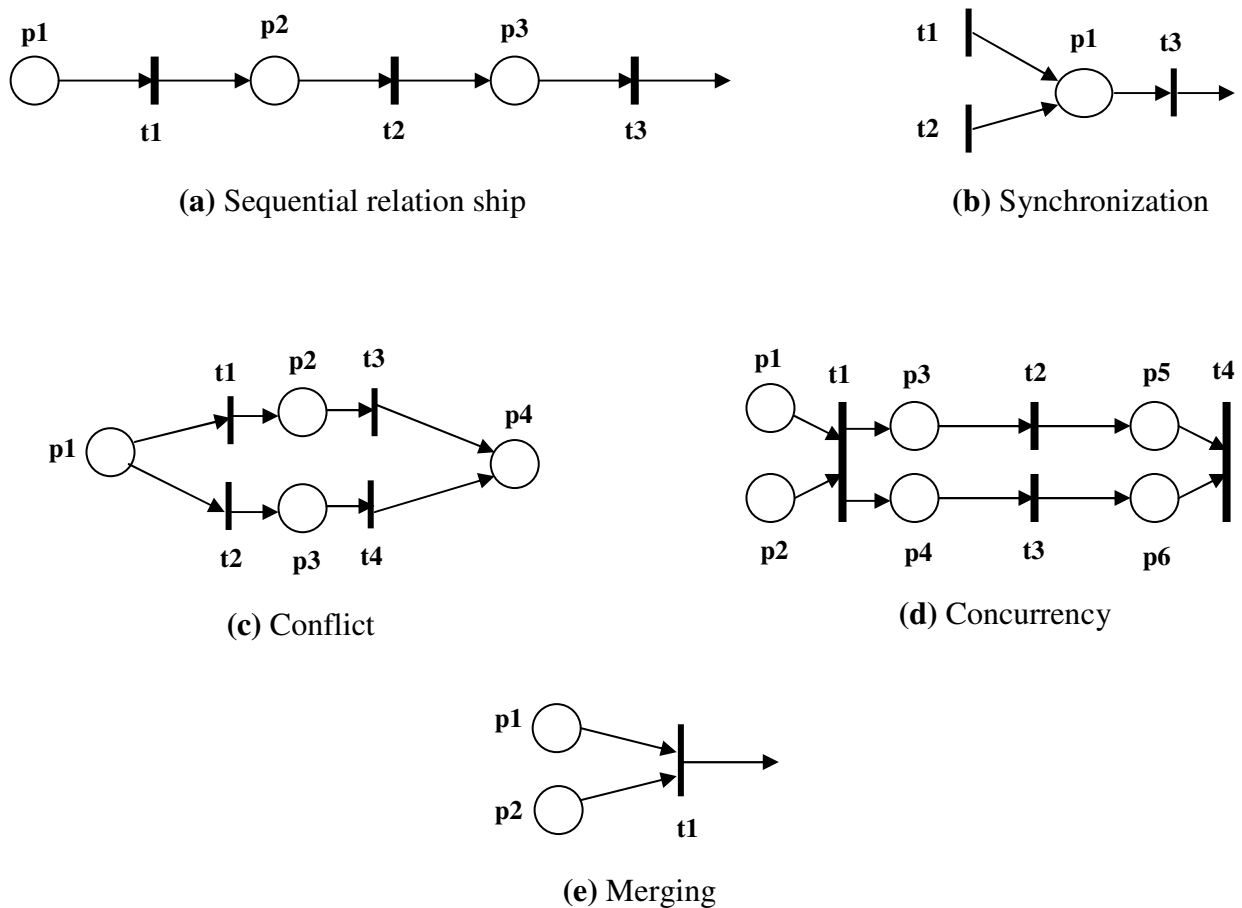


Figure 2-8 PN models with different characteristics

## 2.2.5 Timed Petri Nets

One major extension over the past in PN modeling is inclusion of time into the net. Time is included in a PN model; such a net is referred as Timed Petri Nets (TPNs). Timed Petri nets have been used for the performance evaluation of concurrent systems and, in particular, of communication protocols and multiprocessor computer systems. Time is associated with the transitions and when enabled or fired, the firing delay of the transitions can be either deterministic or stochastic in nature. Due to this nature of transition firing, Timed Petri Nets are grouped into Deterministic Timed Petri Nets (DTPNs) and Generalized Stochastic Petri Nets (GSPNs). Transitions called immediate transitions that take zero time or no time to fire are another extension to the nature of Timed Petri Net transitions. In the following subsections, we describe features related to DTPNs and GSPNs.

### ❖ *Deterministic Timed Petri Nets (DTPNs)*

When time delays for operations or activities in a concurrent conflict or choice-free system are fixed, we can model the system as a deterministic timed Petri net. When a choice is involved in such a system and the system is allowed to make a choice freely, and then its behavior becomes non-deterministic. For the class of choice-free Petri nets, marked graphs or event graphs are suitable and sufficient, which can represent concurrent activities but not choices. The performance index for such a model is cycle time. Transitions, places, and arcs all can be associated with time delays in a marked graph, resulting in a timed marked graph. These elements with time delays can be converted into each other.

Deterministic Timed Petri nets are a class of timed Petri nets where a constant delay is augmented to the transitions of the net. Then a DTPN is defined as,

$N = (P, T, E, W, H, D)$  where,  $P$ : Finite nonempty set of places

$T$ : Finite nonempty set of transitions

$E$ : A set of directed arcs that connects places to transitions and vice versa;

$W$ : Weight of the arcs

$H$ : Finite set of inhibitor arcs

$D$ : Duration of firing

A place is an input (or an output) place of a transition  $t$  if and only if there exists an arc from ( $p$  to  $t$ ) or from ( $t$  to  $p$ ) respectively in the set  $E$ . The sets of all input and output places of a

transition  $t$  are denoted by  $\text{Inp}(t)$  and  $\text{Out}(t)$ , respectively. Similarly, the set of all input and output transitions of a place is denoted by  $\text{Inp}(p)$  and  $\text{Out}(p)$  respectively. A place is denoted by  $\text{Inh}(p)$  if there exists an inhibitor arc from  $p$  to  $t$ . A marking of a Timed Petri net is a pair  $(M, F)$  where,  $M$ : number of tokens in a place

$F$ : remaining firing time where; is the set of transitions, which have initiated and have not yet completed the firing process.

We call  $M$  the marking of places and  $F$  the remaining firing time of transitions. In basic Petri nets, the markings of places are only defined. The marking  $M$  is the number of tokens present in a place at any instant of time. It may appear that the marking  $M$  is sufficient to define the state of the system. Since the tokens are distributed in places as well as in those transitions waiting for the completion of firings, the remaining firing time information of the transitions waiting to complete the firing process is also necessary. Remaining firing time ( $F$ ) represents the time a transition needs more to complete the firing that is in progress [11].

#### ❖ *Stochastic Petri Nets*

Classical Petri nets are useful in investigating qualitative or logical properties of concurrent systems, such as mutual exclusion, existence and absence of deadlocks, boundedness and fairness. However for quantitative evaluation the concept of time needs to be incorporated in to the definition. A convenient way of achieving this is that for every state (marking) has associated with it a time for which no event (i.e. a transaction) can occur until this time has elapsed. An event is the result of activities performed by the system when it is in the situation specified by the marking. Time is therefore naturally associated with transactions, such that they can only fire some time after they have been enabled. The association of time with transactions is the most common form of timed Petri nets although associating time with places is exactly the same. Several researchers investigated the use of timed Petri nets in which places or transitions were associated with deterministic time durations. The analysis of such timed Petri nets is however is tractable only in the case of special classes such as marked graphs. The concept of associating random time durations was first investigated independently by Natkin in 1980 and Moloy in 1981 and this was the origin for the emergence of stochastic Petri Nets and their extensions as a principal performance modeling tool. The use of stochastic Petri nets has become particularly important in the modeling of automated manufacturing systems [2].

A stochastic Petri net (SPN) is essentially a high level model that generates a stochastic process. SPN performance evaluation is simply the modeling of the given system using SPNs and generating the stochastic process that governs the systems behavior. This stochastic process is then further analyzed using known techniques such as Markov Chain models and Semi-Markov chain models. The use of SPNs is considerably useful to the modeler as it is a graphical model and is convenient in the obtaining a credible high-level model of a system. As a modeling tool SPNs offer several advantages:

1. They provide a convenient framework for correctly and faithfully describing an AMS and for generating the underlying stochastic process.
2. Their analysis can be automated and there are available several software tools for this purpose.
3. They can exactly model non-product form features, such as priorities, synchronization, forking, blocking and multiple resource holding.
4. They can be used a both logical and quantitative analysis.
5. Even if their analysis is intractable, they serve as a ready simulation model.

As a method of representation SPNs are very powerful, on a par with Markov chain models. They suffer on the other hand on the computational front as they suffer from state space explosions.

**Definition:** A Stochastic Petri Net is a six-tuple  $(P, T, I, O, M, F)$  where  $(P, T, I, O, M)$  is a Petri net and  $F$  is a function, which associates with each transition in each reachable marking, a random variable. This is a very general definition of a stochastic Petri net.

The basic philosophy underlying the use of various classes of stochastic Petri net in performance evaluation is the equivalence of their marking process, under appropriate distributional assumptions, to a Markov or Semi-Markov process with discrete state space. The typical steps in stochastic Petri net evaluation include:

1. Modeling the given system by a stochastic Petri net.
2. Generating the marking process.
3. Computing the steady state probability distribution of states of the marking process
4. Obtaining the required performance measures from the steady state probabilities.

All steps in the evaluation can be automated and this constitutes an important reason for the popularity of stochastic Petri net performance modeling. Stochastic Petri nets fall into two subsets, these are: *Exponential Timed Petri Nets* and *Generalized Stochastic Petri Nets* [15].

### **2.2.6 Colored Petri nets**

Colored Petri nets (CP-nets or CPN) are extensions of ordinary Petri nets and graphical modeling languages that model both the states of a system and the events that change the system from one state to another. CP-nets combine the strengths of *ordinary Petri nets* (PN) and programming languages. The formalism of Petri nets is well suited for describing concurrent and synchronizing actions in distributed systems. Programming languages can be used to define data types and manipulation of data. Large and complex models can be built using hierarchical CP-nets in which modules, which are called *pages* in CPN terminology, are related to each other in a well-defined way. Without the hierarchical structuring mechanism, it would be difficult to create understandable CP-nets of real-world systems. CP-nets can be used in practice only because there are mature and well-tested tools supporting them. CPN Tools has a new GUI with state-of-the-art interaction techniques such as two-handed input, tool glasses and marking menus, and an improved simulator.

Petri nets provide a framework for modeling and analyzing both the performance and the functionality of distributed and concurrent systems. A distinction is generally made between *high-level Petri nets* and *low-level Petri nets*. CP-nets are an example of high-level Petri nets which combine Petri nets and programming languages and which are aimed at modeling and analyzing realistically-sized systems.. Low-level Petri nets to have a simpler graphical representation, and they are well suited as a theoretical model for concurrency.

In conclusion it is clear to see that Petri nets are a simple but effective method of analyzing manufacturing systems. Their use is commonplace because of the simplicity in understanding the models as well analyzing them. They lend themselves to automation and numerous computer programs exist to create and analyze complex Petri nets with great speed and ease. The use of Petri nets will surely lead to more efficient and more stable manufacturing systems being implemented and therefore increasing the productivity and efficiency of modern manufacturing methods [16].

### **2.2.7 Petri Nets application in Manufacturing Systems**

Petri net model is a network of interconnecting resources and actions representing a real system. By modelling manufacturing systems, performance analysis can be performed to help the operations manager to plan resources, schedule jobs and predict overall throughput rate and system capacity. The resulting parameters can be recorded and compared to form measures of the operations' efficiency and effectiveness. This assists managers to quantify system performance, as opposed to pure judgement, which is subjective and difficult to compare. Petri net also serves as a communication aid to both higher management and people on the shop floor, showing the abstract aspects of work cells coordination and resource cycles graphically. The hierarchical nature of Petri net enables it to manage, display and analyse large and small models in different scales and levels of detail. Although it potentially suffers from state space explosions when dealing with complex manufacturing systems, various extensions of Petri net add richness and flexibility to the modelling language. Reduction theorems and data fusion methods exist to facilitate analysis on such complex models.

For the efficient running of a factory, many issues are required to be solved: ranging from integration among different processes to system capacity planning. Petri net is one of various analytical tools to solve these issues. In modern production plants, where flexible manufacturing systems are used to achieve factory automation, Petri nets can be applied to capture the essence and details of the plant processes. It provides the means to model common manufacturing operations, such as concurrent assembly lines, synchronisation, unreliable machines and resource contention. The behavioural properties of the model provide useful information to the engineer in controller design and managers in job scheduling and capacity planning.

Manufacturing processes often occur in parallel, such as multiple assembly lines and these concurrent operations can be modelled by drawing separate chains of place and transition in the graph. Synchronisation occurs in assembly lines where parts resulting from various processes are brought together to form a final product. Synchronising products from concurrent processes is an important aspect in manufacturing operations. An element of uncertainty exists in operations, such as machine tool failures and these non-deterministic processes can be modelled by using stochastic timed Petri nets, where random time delay can be associated with each place. As the machines breakdown, bottlenecks and deadlocks may occur, which engineers strive to eliminate or prevent.

After time was introduced into Petri nets, one can use timed Petri nets to conduct temporal performance analysis, i.e., to determine production rates of systems, resource utilization, and the like. It is also possible to detect a bottleneck in an FMS or to determine optimal buffer size, optimal pallet distribution, etc.

In the 1985 International Workshop on Timed Petri Nets, many research projects in the field of timed Petri nets for performance analysis were presented, and various applications were reported for analyzing the performance of computer systems, communication protocols, and manufacturing systems.

Table 2-4 Description for places and transitions in Petri net Fig. 2-10

<b>Places/Transitions</b>	<b>Description</b>
p1	Raw material available
p2	Robot Available
p3	Milling machine (WS1) is available
p4	WS1 loaded with raw material by robot
p5	Milling operation performed on raw material
p6	Semi-finished part loaded on WS2 by robot
p7	Drilling operation performed on the part
p8	Drilling machine (WS2) available
p9	Out going conveyor loaded by robot
t1	Starting to load WS1
t2	Initiation of milling operation
t3	Termination of milling operation
t4	Initiation of drilling operation
t5	Termination of drilling operation
t6	Completion of action in p9

Table 2-4 above and figures 2-8 and 2-9 shown below are illustrating the application of Petri nets in manufacturing systems; and table 2-5 below gives the interpretations of transitions, input places and out put places for different situations in manufacturing systems [20].

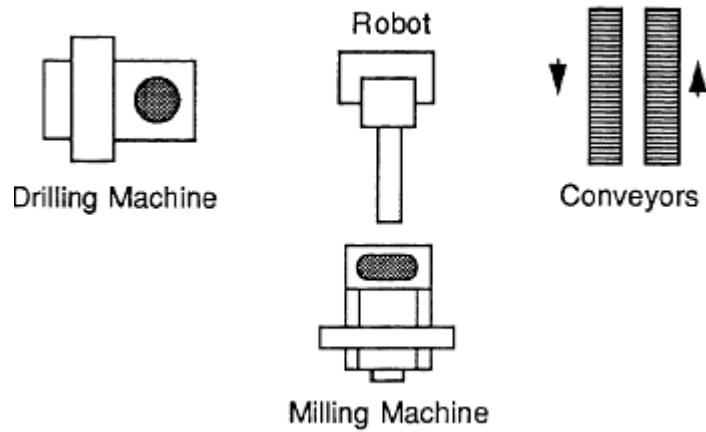


Figure 2-9 System layout for sample machining centre

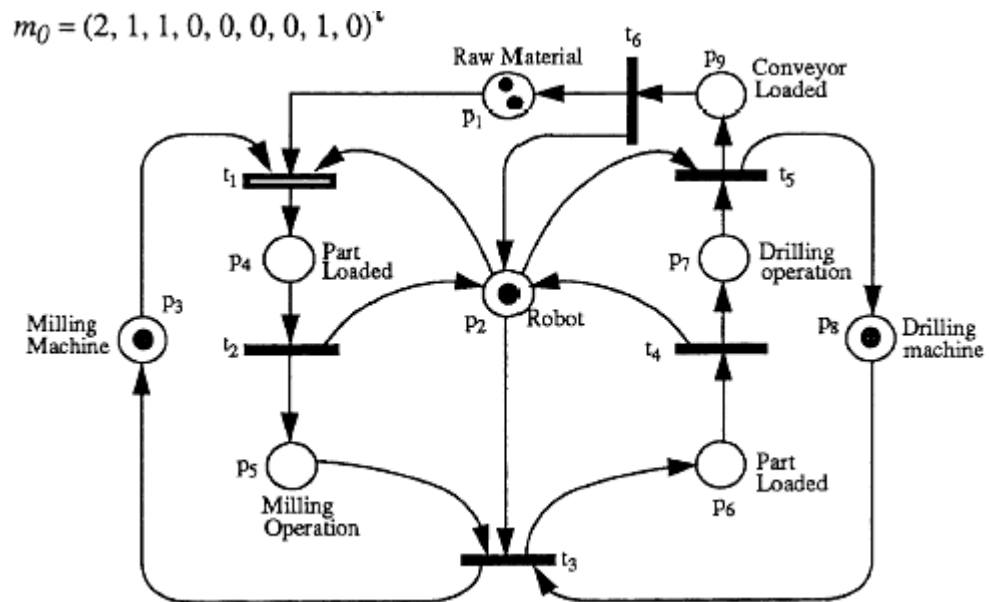


Figure 2-10 PN model of a sample-machining centre in Fig. 2-9

Table 2-5 some typical interpretations of transitions and places

Input Places	Transition	Output Places
Preconditions	Event	Post conditions
Input data	Computation Step	Output data
Input signals	Signal Processor	Output Signals
Resources needed	Task or Job	Resources released
Conditions	Clause in Logic	Conclusions
Buffers	Processor	Buffers

## **2.3 Why Simulation?**

One of the largest application areas for simulation modeling is that of manufacturing systems, with the first uses dating back to at least the early 1960's. Performance analysis plays important roles in achieving goals of better product quality, lower production cost, shorter lead times, and higher flexibility. But, as flexible manufacturing systems become more and more complex, scheduling, control and performance analysis of such integrated systems present a series of problems and challenges. Moreover, the capability of real-time scheduling control and performance analysis of FMS in response to the occurrence of unexpected events (e.g., machine breakdown or tool breakage) is very desirable for highly automated FMS.

Traditionally, these problems are studied using mathematical programming methods. These analytical methods usually can provide a valuable solution within seconds and models can be developed within hours when using a well-developed modeling package and a software tool package for queuing network analysis. But the validations of final solutions rely heavily on the assumptions made for analytical models. These assumptions usually cannot hold because of many practical constraints in scheduling and control on real shop floors. For example, it is very difficult to represent robot control and limited queue length in a queuing network analysis. Therefore, for such a highly coupled nonlinear system as FMS, simulation becomes an important way to design, schedule and control due to the lack of applicable analytical methods [1].

Existing research efforts in the field of on-line simulation for FMS design and control strategies have been attempted in the following directions: (1) parallel processing technologies that enable the consideration of real-time system behaviors, such as distributed or parallel discrete-event simulation; (2) on-line intelligent shop scheduling using simulation combining with expert systems or neural network methods; (3) Petri net based on-line simulation and control. As a result, simulation software packages have been widely used in the design and analysis of manufacturing systems. This is mainly due to three important characteristics of simulation software packages: the capability of providing solutions for what-if questions, the capability of considering details into the model, and the friendly user interactive interface. These simulation packages, especially those specifically developed for the purpose of manufacturing simulation, such as ARENA, PROMODEL, WITNESS, etc., provide very powerful tools for simulation of FMS [6].

✓ ***Manufacturing issues addressed by simulation***

The following are some of the specific issues that simulation is used to address in manufacturing:

*The need for and the quantity of equipment and personnel:*

- Number, type, and layout of machines for a particular objective
- Requirements for transporters, conveyors, and other support equipment (e.g., pallets and fixtures)
- Location and size of inventory buffers
- Evaluation of a change in product volume or mix
- Evaluation of the effect of a new piece of equipment on an existing manufacturing system
- Evaluation of capital investments
- Labor-requirements planning
- Number of shifts

*Performance evaluation:*

- Throughput analysis
- Time-in-system analysis
- Bottleneck analysis
- Utilization analysis

*Evaluation of operational procedures:*

- Production scheduling
- Inventory policies
- Control strategies [e.g., for an automated guided vehicle system (AGVS)]
- Reliability analysis (e.g., effect of preventive maintenance)
- Quality-control policies

✓ ***Statistical issues in simulating manufacturing systems***

Since random samples from input probability distributions “drive” a simulation model of a manufacturing system through time, basic simulation output data (e.g., times in system of parts) or an estimated performance measure computed from them (e.g., average time in system from the entire simulation run) are also random. Therefore, it is important to model system randomness correctly and also to design and analyze simulation experiments in a proper manner.

### ❖ **Modeling System Randomness**

The following are some sources of randomness in simulated manufacturing systems:

- Arrivals of orders, parts, or raw materials
- Processing, assembly, or inspection times
- Machine times to failure
- Machine repair times
- Loading/unloading times
- Setup times

In general, each source of system randomness needs to be modeled by an *appropriate* probability distribution, not what is perceived to be the mean value. Note that sources of randomness encountered in practice are rarely normally distributed.

### ❖ **Design and Analysis of Simulation Experiments**

Because of the random nature of simulation input, a simulation run produces a *statistical estimate* of the (true) performance measure not the measure itself. In order for an estimate to be statistically precise (have a small variance) and free of bias, the analyst must specify for each system design of interest appropriate choices for the following: *Length of each simulation runs*, *number of independent simulation runs*, and *length of the warm up period*. It is recommend that always making at least three to five independent runs for each system design, and using the average of the estimated performance measures from the individual runs as the overall estimate of the performance measure. (Independent runs means using different random numbers for each run; starting each run in the same initial state and resetting the model's statistical counters back to "zero" at the beginning of each run.) This overall estimate should be more statistically precise than the estimated performance measure from one run. Note that independent runs (as compared to one very long run) are required to obtain legitimate and *simple* variance estimates and confidence intervals.

For most simulation studies of manufacturing systems, the long-run (or steady-state) behavior of the system, i.e., its behavior when operating in a "normal" manner is preferred. On the other hand, simulations of these kinds of systems generally begin with the system in an empty and idle state. This results in the output data from the beginning of the simulation run not being representative of the desired "normal" behavior of the system. Therefore, simulations are often run for certain amount of time, the *warm up period*, before the output data are actually used to

estimate the desired performance measure. Use of the warm up period data would bias the estimated performance measure.

✓ *Simulation software for manufacturing applications*

Historically, simulation packages were classified to be of two major types, namely, simulation languages and applications-oriented simulators. Simulation languages were general in nature and model development was done by writing code. Simulation languages provided, in general, a great deal of modeling flexibility, but were often difficult to use. On the other hand, applications-oriented simulators were oriented specifically toward a particular class of applications and a model was developed by using graphics, dialog boxes, and pull-down menus. Simulators were sometimes easier to learn and use, but might not have been flexible enough for some problems. However, in recent years vendors of simulation languages have attempted to make their software easier to use by employing a graphical model-building approach. A typical scenario might be to have a palette of model building icons located on one side of the computer screen. The icons are selected from the palette with a mouse and placed on the work area. The icons are then connected to indicate the flow of entities through the system of interest. Finally, one double-clicks on an icon to bring up a dialog box where detail is added. On the other hand, vendors of simulators have attempted to make their software more flexible by allowing programming in certain model locations using an internal pseudo-language. In at least one simulator, it is now possible to modify existing modeling constructs and to create new ones. Thus, the distinction between simulation languages and simulators has really become blurred [6].

Based on the above discussion, we will now say that there are two types of simulation packages. A *general-purpose simulation package* can be used for any application, but might have special features for certain ones (e.g., for manufacturing or process reengineering). Examples of general-purpose simulation packages are Arena, AweSim, Extend, GPSS/H, Micro Saint, MODSIM III, SIMPLE++, SIMUL8, SLX, and Taylor Enterprise Dynamics Developer. On the other hand, an *applications oriented simulation package* is designed to be used for a certain class of applications such as manufacturing, health care, or call centers. Examples of manufacturing-oriented simulators are Arena Packaging Edition, AutoMod, AutoSched, Extend + MFG, ProModel, QUEST, Taylor Enterprise Dynamics Logistics Suite, and WITNESS [4].

## **2.4 Manufacturing Performance Analysis**

Ever since Henry Ford implemented the first production line in 1913 to produce an engine in 84 stages, their use as a method of manufacture has become the dominant approach for mass production. The emergence of high performance automated manufacturing systems (AMSs) has led to the need for methods of modeling and analysis of these types of system in order to maximize throughput, flexibility and competitiveness.

Performance evaluation falls into two broad categories; performance measurement and performance modeling. Performance measurement is primarily for existing systems and is most commonly used to monitor key systems to enable re-configuration. Performance modeling can be split itself into two sub types; simulation modeling and analytical modeling. Simulation is the original method of modeling and is still commonly used; there are many computer based programs design solely for manufacturing simulations. Analytical modeling is becoming more widely used and is a strong alternative to simulation, there are many accepted models for manufacturing purposes such as stochastic Petri nets, Markov chains and queuing theory. Both systems are commonly used and each has its advantages and disadvantages.

Performance modeling has become a very important part of automated manufacturing system design and is equally important for maintaining the system at its peak of ability. The manufacturing methods in use by companies has change dramatically in recent years with the use of advance robotics and computer control to optimize production, this in turn has led to reduced prices and higher quality of product. The production lines can only get better with more modeling and investment and this is best achieved with the use of performance modeling.

An AMS is a complex network of processing, inspecting and buffering nodes connected by system of transportation mechanisms. For an AMS to be considered viable as capital outlay it must be flexible in the product that it can produce, so it should be able to last for several different product life cycles. It must also have a level of fault tolerance to avoid costly breaks in the production line in the case of sub system failure. It is also desirable that the line is capable of increasing or decreasing output with the rise and fall of demand. All of these specifications show the complexity of decision-making in the field of AMSs and the need for concise and accurate modeling methods. AMSs belong to the domain of discrete event dynamic systems (DEDS) in which the evolution of the system depends on the complex interactions of various discrete events such as the arrival of raw materials, departure of finished goods, failure

of equipment etc. The state of DEDS changes only at these discrete points in time instead of continuously. Over the last decade several models have come about to describe DEDS and these can be grouped into two distinct areas:

- Qualitative models are concerned with the logical aspects of system evolution such as controllability, stability and the existence of deadlocks in system operation, etc. This category also includes Petri Nets, extended state machines and finitely recursive processes.
- Quantitative models are concerned with the quantitative system performance in terms of throughput and lead-time. This category also includes discrete event simulation, min-max algebra, Markov Chains, stochastic Petri nets, queues, and queuing networks.

Quantitative models are a general term including performance modeling which is the area of interest to this research work. Within the life cycle of an AMS various decisions are made concerning implementation, design and operation of the system. The role of performance modeling is to assist in these decisions in an affective way as possible. Typical decisions at the planning stage include number and type of machines, number of material handling devices, number of buffers, size of pallet pool and number of fixtures, best possible layout, tool storage capacity, evaluate candidate AMS configurations, part type selection, machine grouping, batching and balancing decisions, and scheduling policies. During the operational phase of an AMS performance modeling can be used to assist decisions about how to cope with in the event of a breakdown, removal or addition of resources and parts, optimal scheduling in the event of machine failure or sudden changes in the product or its demand and in the avoidance of unstable situations such as deadlocks and ensure competitiveness in the dynamic global market [10].

Performance modeling is also used in the design stage of the system. It is used in decisions such as whether to use central versus local storage, push production versus pull production, shared versus distributed resources, the effect of flexibility, etc. Performance predictions obtained using faithful models can be used to convince customers or investors and also give the designer another perspective on the design enabling better designs.

The performance of an AMS can be measured by a set of generic measures. These are: manufacturing lead-time, work in progress, throughput, machine utilization, capacity,

flexibility, performance, and quality. Using performance measuring these values can be evaluated and used to compare AMS performances. Nowadays, the overall equipment effectiveness (OEE) is widely used to quantify capacity losses in manufacturing equipment. The OEE directly relates to utilization, i.e., the fraction of time a workstation is busy. However, the performance of manufacturing systems is not only determined by utilization, but also by the variability in production processes. By only focussing on utilization one may overlook opportunities for performance improvement by reduction of variability. The measures are quite dependent on each other and each is important in its own right. Some typical questions that are asked and can be answered using performance modeling are:

1. What is the probability that a particular product can be delivered before the deadline?
2. What is the minimum number of working machines required so that the average throughput of finished parts just exceeds the targeted production?
3. How many fixtures/pallets are to be used in order to maximize the average machine utilization?
4. Does the given AMS configuration have enough capacity to deliver the required amounts of products in the set deadlines?
5. Which of the candidate layouts offers the best flexibility to part-mix changes?
6. What is the minimum number of resources in the system (machines, transporters, buffers) that would ensure that the probability of producing at least 100 parts in a shift of 8 hours, in the presence of unscheduled downtime, exceeds 95%?
7. What is the effect of machine blocking on throughput and manufacturing lead-time? Should we add one more buffer?
8. What are the potential bottleneck resources and congestion points in the system?
9. Are there deadlocks in the system? What is the mean time to deadlock?
10. How do throughput and lead-time change when we have one less machine? One more machine? One more transporter? Some more buffers?
11. Is there a spare capacity in the system to undertake some low-priority jobs?

## CHAPTER THREE

### 3. FACTORY BACKGROUND AND CASE DATA

#### 3.1 Introduction

Addis Engineering Center, formerly known as Addis Metal Pressing Enterprise is one of the manufacturing industries of the country, which is located in the capital. It was established in 1945 E.C. and the prime need for its establishment was to produce and supply the continuous demand for ammunition product needed by the country.

The organization has passed through series of administrative structures and number of changes from time to time. It is expected to go steps forward operationally to strive for manufacturing excellence. Though more than 50 years have passed since its establishment, the company is unable to be competent and maintain its position in the market due to lack of continuous performance analysis and other various factors. The company's profit declined continuously even below the acceptable level. For this and other related reasons the company is forced to stop producing ammunition. During bullet production, all other departments were supporters of the main production (i.e. bullet production). Presently, it has re-structured itself with a new name, Addis Engineering Center, by applying new management concepts and engaged in production of various spare parts, medals, badges, and furniture.

The factory has changed its *product-based* production to *make-to-order* production system, where the factory's production became totally dependent on the order of customers. If orders are not received from customers there will no production. In such a production system, it is necessary to have very effective and efficient overall performance to be competitive and cope up with this dynamic global market in order to attract and make reliable customers.

#### 3.2 Vision, Mission, Objectives, and Values of AEC

The *Vision* of the Company:

- ❖ To be competitive modern and quality tools and spare parts supplier, and research center to defense industries.

The *Mission* of the Company:

- ❖ To supply with competitive price and quality products of tools and spare parts for the arms produced, maintained and modified by various defense industries in order to strengthen and ensure the readiness of the national defense force.

- ❖ To work with different industries under the Ministry of National Defense in order to satisfy the needs of the Ministry cope up the dynamic change of technology and the influence of the global market.
- ❖ To be a source of income for defense Minister by producing products to the local market.

The **Objectives** of the Company:

- ❖ To produce competitive price and quality products based up on the requisition of Minster of Defense and Defense Industries.
- ❖ To produce competitive price and qualitative products for the local market so as to satisfy the demand of customer.
- ❖ To Design and produce tools, dies, jigs, fixtures, and so on
- ❖ To produce different types of spare parts.
- ❖ To perform different engraving and pressing works (like medals, badges, etc)
- ❖ To conduct research on machine tool design and engineering materials.
- ❖ To produce wood works and metal works furniture.
- ❖ To buy raw materials for the above-mentioned products.

The **Values** of the company:

- ❖ To have well known Company's name and to keep Company's reputation.
- ❖ Customer is partner
- ❖ Customer satisfaction
- ❖ Company with no ground for corruption
- ❖ Avoiding environmental pollution.

### **3.3 Case data**

In the factory there is organized data collection method for the maintenance department only. As a result, the history of each machine, i.e. frequency and reason for failure, the time taken to repair and other relevant information is readily available for reference. Although few other departments have trend of data collection, it is not well organized and consistent. In majority of departments including the tools and spare parts workshop the culture of data collection and preservation is at its lowest stage. As a result, there was great difficulty to obtain relevant data. The data required for this study such as the number and type of orders (products) with in a given period of time, the out put rate of a given production line, the production schedule, machine down time, etc were gathered by personal observation, discussion with foremen,

machinists and workers who have contact with the subject matter, and referring previous documents. Below are the case data that are believed to have relevance to the work being carried out and the performance of the factory.

**1) Plan versus actual production**

Table 3-1 below shows the plan and actual production of the factory with respect to each workshop for the years 1994-1998 E.C. As it can be observed from the table, the tools and spare parts workshop was able to meet the planned production in 1995 only; and failed to achieve its plan in the remaining years. This is an indication of its poor performance.

Table 3-1 Planned and actual achievements of AEC in the years 1994-1998 E.C

Year	W/shop(Product type)	Plan (Br.)	Actual (Br.)	% Success
1994	Wood and metal	3,000,000	3,165,871	106
	Medals and badges	1,500,000	1,371,500	91
	Tools and spare parts	500,000	222,339	44
	<b>Total</b>	<b>5,000,000</b>	<b>4,759,710</b>	<b>95</b>
1995	Wood and metal	3,450,000	5,495,400	159
	Medals and badges	1,725,000	1,402,462	81
	Tools and spare parts	575,000	709,790	123
	<b>Total</b>	<b>5,750,000</b>	<b>7,607,652</b>	<b>132</b>
1996	Wood and metal	17,995,000	12,211,098	68
	Medals and badges	2,245,800	4,236,720	189
	Tools and spare parts	2,000,000	491,484	25
	<b>Total</b>	<b>22,240,800</b>	<b>16,939,302</b>	<b>76</b>
1997	Wood and metal	11,851,000	11,797,790	100
	Medals and badges	5,271,000	8,643,129	164
	Tools and spare parts	3,000,000	1,247,982	42
	<b>Total</b>	<b>20,122,000</b>	<b>21,688,901</b>	<b>108</b>
1998	Wood and metal	10,000,000	9,547,710	95
	Medals and badges	5,210,000	6,526,706	125
	Tools and spare parts	5,000,000	748,908	15
	<b>Total</b>	<b>20,210,000</b>	<b>16,823,324</b>	<b>83</b>

**2) Rejections of products**

Table 3-2 below shows the reasons and frequency of rejections and the total cost incurred in the factory for the year 2001. Table 3-3 shows the cumulative percentage of the frequency of reasons for rejection of products. Figure 3-1 shown below is the respective Pareto curve for frequency of the reasons for the scraped products, where the cumulative percentage measures are plotted on the vertical axis against the reasons for scrap, plotted along the horizontal axis.

Table 3-2 Frequency distribution and total cost of scrap

Reasons for scrap	Frequency	Annual Total cost (Birr.)
Machine	23	1,211,776.69
Tool	1	857.42
Work piece Material	2	1,224.94
Material handling	1	1,256.06
Operator	15	13,759.54
Adjustment	2	1,889.08
Heat treatment	1	1,061.74
Adjuster	1	989.05

Table 3-3 Frequency of reasons for scrap in the year 2001

Reasons for scrap	Frequency	% of frequency	% of total
Machine	23	50	50
Operator	15	32.6	82.6
Adjustment	2	4.3	86.9
Work piece material	2	4.3	91.2
Tool	1	2.2	93.4
Heat treatment	1	2.2	95.6
Adjuster	1	2.2	97.8
Transport	1	2.2	100

**Pareto analysis for reasons of rejection**

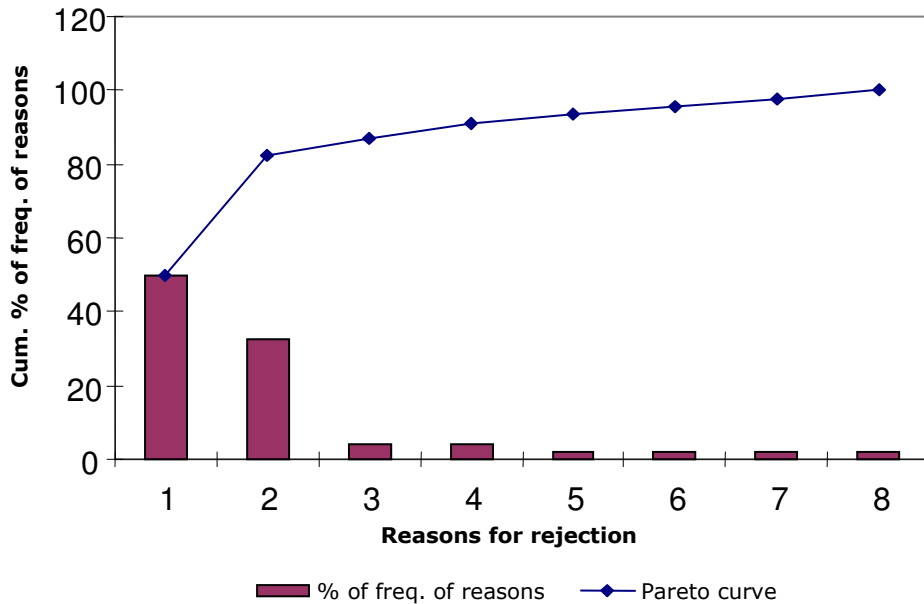


Figure 3-1 Pareto curve for frequency of reasons for rejection/scrap

Where:

- 1: Machine                      3: Adjustment                      5: tool                                  7: Adjuster
- 2: Operator                      4: Work piece material                      6: Heat treatment                      8: Material handling

### 3) Machine down time

Data collection was made for three consecutive months, from August to October 2006. Some of the reasons for machine downtime are identified to be: *power break, lack of work, technological problems (unclear drawings, tolerances, etc) machine break down, lack of tools and gages, delayed QC checking, workers absence due to various reasons, and others like meeting, sick leave, absenteeism, etc.* Table 3.4 below shows the available machine hours and the respective down time for three months.

Table 3-4 Machines down time for three months

Month	Available machine hour (hr.)	Down time (hr.)	% Down time
August	6720	1665	24.8
September	6080	1756	28.9
October	6400	1701	26.6

(Available Machine hour = working days/month\*working hours/day\*number of machines)

The available and down time data shown in table 3-4 above represents only **40** machines (on avg.) out of **86**, which are being used since the bullet production ceased (1994). The remaining **46** machines are out of use, even if they are functional (no failure/breakdown), due to lack of work and inconsistent decision of the management of the company. Therefore, roughly, the factory is using **46.5%** of its capacity. The following table summarizes the total down time in the factory due to various reasons.

Table 3-5 Reasons for machines down time for three months (for all machines)

Reasons for idle time	Months/Hr.			% of total idle time hrs.
	August	September	October	
Lack of work	8,201	7,048	7,620	82.9
Power break	62	151	71	1.1
Machine failure	-	-	-	-
Lack of tools and gages	3	5	2	0.04
Technological problem	-	-	7	0.03
Others (meetings,...)	1,495	1,544	1,361	15.9
<b>Total down time</b>	<b>9,761</b>	<b>8,748</b>	<b>9,061</b>	
<b>Total available time</b>	<b>14,816</b>	<b>13,072</b>	<b>13,760</b>	

Considering all the 86 machine tools in the shop the total available working time of three months equals 41,648 hrs and total down time during this period of time equals 27, 570 hrs, which is 66.2% of the available time. Assuming average hourly rate of machines to be Birr 25 per machine, roughly the factory would have generated revenue of 27,570 hrs\*25 Birr/hr = 689,250 Birr in three months time.

#### **4) Customer feedback/complaint**

Assessment was made to know the degree of customer satisfaction in the company. Based on the information and various data gathered from different departments, it has been found that the factory is unable to satisfy both its internal and external customers. Table 3-5 below summarizes customer complaint.

Table 3-6 Factors for customer complaint

<b>Factors</b>	<b>Frequency</b>	<b>% of total number of complaint</b>
Unable to meet due date	45	90
Customer handling/treatment	1	2
Quality	1	2
Failure to meet intended purpose	1	2
Cost	2	4

Among the various factors for external customer dissatisfaction, the *failure to meet due date* takes the lion share. The main cause for this problem is found to be the variation between the estimated and the actual production time. The production (machining) time estimation is made based on personal experience, which has big variance with the actual time of production.

#### **5) Variation between estimated and actual machining/production time**

This is the major factor for the occurrence of the above problem. It also has direct relation with the factory's loss or profit. For analysis purpose the following data have been collected and shown in the table hereunder. From the table we can observe that the variation between estimated time ranges from 3:30 to 10:00 hrs. It is clear how this variation will affect the performance of the factory. Therefore, in order to improve the performance of the factory this problem has to be solved first.

Table 3-7 Estimated and actual production time of sample products.

<b>Product type</b>	<b>Machine used</b>	<b>Estimated time (hr.)</b>	<b>Actual time(hr.)</b>	<b>Variation (hr)</b>
Shaft	Lathe	8:00	18:00	10:00
	Milling	6:00	14:00	8:00
	Grinding	4:00	8:00	4:00
Roller	Grinding	7:00	2:15	4:45
	Milling	3:00	7:00	4:00
Screw	Lathe	2:00	7:00	5:00
	Milling	5:00	1:30	(3:30)
Spinning disc finger	Lathe	9:00	5:00	(4:00)
Punch	Lathe	5:30	11:45	6:15
	Grinding	3:00	10:00	7:00

The data discussed in this section of the paper are those, which related to the performance of the factory. The role of each case in the performance of the factory has also been discussed clearly. Therefore, in this thesis work these cases are taken in to account so that improved performance can be obtained.

## **CHAPTER FOUR**

### **4. MODELING AND PERFORMANCE MEASURES OF MANUFACTURING SYSTEMS**

#### **4.1 Introduction**

Modeling and performance analysis of manufacturing systems helps decision makers at higher levels to conduct an economic feasibility analysis for expansion/diversification or modification of the system. Also, this could help in installing a new manufacturing system with a substantial reduction in the number of machines, floor space, inventory level, throughput and lead time and also high quality products, with a greater flexibility to respond to the market needs.

Manufacturing systems design is a complex phenomenon, which is concerned with the selection from a wide variety of available system configurations and control strategy alternatives in the light of several criteria (flexibility, quality, productivity, costs etc.), many of which are difficult to quantify. Justification and implementation of advanced manufacturing technology involve decisions that are crucial for the practitioner regarding the survival of business in the present day uncertain manufacturing world. Since advanced systems require huge capital investments and offer large number of intangible benefits such as flexibility, quality, competitiveness, customer satisfaction etc., which are ill structured in nature and sometimes very difficult to quantify. Basically, the justification and implementation of advanced manufacturing systems is a very difficult question to answer because:

- Profitability and survival of a manufacturing firm depends upon accommodating fluctuating product demands, day-to-day technological advancements, and competition from and among different firms. Flexibility plays a vital role for operation in such a scenario. To meet the objective, various manufacturing flexibilities need to be measured to evaluate and select a desired flexible manufacturing system.
- Organizations should act to improve performance in critical areas. To help in such decision-making, an integrated manufacturing performance analysis is essential. This would help in, planning of business strategy at the strategic level, decision-making regarding implementation of AMT projects, and competitive disposal of individual products at the global market.
- To evaluate different manufacturing alternatives under unpredictable market environments, changes in product design, demand, and mix, a system for different manufacturing scenarios under conflicting multi-objectives is required [20].

## **4.2 Performance Measures of Manufacturing Systems**

Performance measures of manufacturing systems are: Manufacturing Lead Time, Work-in-process (WIP), Machine Utilization, Throughput, Capacity, Flexibility, and Quality.

### **1. Manufacturing Lead Time**

Manufacturing is a transformation process that converts raw materials into quality products and that the process of manufacturing consists of a sequence of machining and assembly operations. In between these operations, non-value-adding operations are performed. Ideally, we would want to eliminate these wasteful operations or at least minimize the time that a part spends in a manufacturing system. There are two variants of lead-time: Manufacturing Lead Time (MLT) and Total Lead Time (TLT)

- **MLT & TLT**

The manufacturing lead time (MLT) of a product is the total time required to process the product through the manufacturing plant. The total lead time (TLT) of a product is the total time elapsed from the instant at which raw materials are ordered until the instant the finished product is delivered. Ideally, MLT should be equal to the actual machining and assembly time. This is possible with zero inventories, zero material handling, zero setup time, zero defects, zero breakdowns and a batch size of one. The TLT is a complex quantity since it involves procurement, vendor, manufacturing; engineering, tooling and customer lead times. Here we focus on manufacturing lead time (MLT).

#### ***Components of MLT***

While focusing on MLT, we assume that raw materials are currently in stock (i.e., procurement lead time is zero and that we have made these items before, we have on hand the design, the process plan and the necessary tooling). Four components that constitute MLT: Setup time, Processing time, Move time, and Queue time.

**Processing time:** Processing time is the actual time spent on processing the manufacturing operation like machining, etc. In conventional batch processing, actual processing time and setup time together represent less than 5 % of MLT. Queuing and transport times account for the rest of the MLT.

**Setup Time:** Setup time or changeover time is the time required by a machine or a system manufacturing one product type to switch to another product type. The setup time generally includes time required for fixturing, tool changing and preparing the work piece. To minimize

the setup time and costs, a batch of products is manufactured after a single setup. However, large batch size results in high inventory levels.

**Move Time:** The moving of work pieces could be within the machine shop, within a factory, across factories or between various subcontracted processes performed by the vendors.

Small batch sizes imply more number of moves between machine processes for the same production target. The need then would be for a smart material handling system that can make a large number of deliveries of small loads in a short time. The best material handling is no material handling and optimal move time is zero move time. Three ways to reduce transport times: creating versatile computer-controlled machine centers with automatic tool changers capable of performing a variety of processing operations, adapting product layouts or cellular layouts based on group technology principles, and using more efficient transfer mechanism such as belt conveyors, fork lifts, chutes and smart AGVs that can make faster delivery of unit loads.

**Queuing Time:** Queuing times or waiting time before the resources such as machine centers, AGVs, etc., are the longest elements that make up the MLT. Queues occur before machine centers and AGVs because there are almost always jobs waiting to be processed by these resources. The queue length is proportional to the amount of work in process (WIP). The three contributory factors for long queues include inadequate capacity, erratic flow and poor part release policies.

## **2. Work in Process (WIP)**

Work in process (WIP) is the amount of semi-finished product currently resident on the factory floor. A semi-finished product is either being processed or is waiting for the next processing operation. Inventories are also seen as the insurance buffer against various uncertainties induced by delayed supplies, machine breakdowns, absenteeism and uncertain customer orders. Inventory is the evidence of poor design, poor forecasting, poor coordination and poor operation of the manufacturing system. WIP should be low.

## **3. Machine Utilization**

High machine utilization is assumed to be good because it amortizes the cost of the machinery faster. Idle time is supposed to be bad since high-priced equipment does not produce anything. Trade off, which one would benefit business more? Idle machine asset or idle inventory asset. Effective resource utilization is to run the machine to manufacture exactly the right quantity of exactly the right things at exactly the right time.

- **Overall Equipment Efficiency (OEE)**

It has been identified that a large proportion of the total costs of production can be attributed to production losses and other indirect and “hidden” costs. The overall equipment effectiveness (OEE) measure attempts to reveal these hidden costs and is function of availability (A), performance rate (P) and quality rate (Q). The exact definition of OEE differs between applications and authors. Nakajima was the original author of OEE and De Groote is one of several later authors, see table 4.1 below.

The availability measures the total time that the system is not operating because of breakdown, set-up and adjustment, and other stoppages. It indicates the ratio of actual operating time to the planned time available. Planned production time (or loading time) is separated from theoretical production time and measures unplanned downtime in the equipment, i.e. by this definition unavailability would not include time for preventive maintenance. This definition gives rise to planning of preventive activities, such as preventive maintenance, but it might lead to too much maintenance of the equipment and too long set-up times. If planned downtime is included in the production time, the availability would be significantly lower, but the true availability would be shown. That would create motives for decreasing the planned downtime, e.g. through more efficient tools for set-up and more efficient planned maintenance.

The performance rate measures the ratio of actual operating speed of the equipment (i.e. the ideal speed minus speed losses, minor stoppages and idling) and the ideal speed (based on the equipment capacity as initially designed). Thus (P) can be found by measuring a fixed amount of output, which indicates the actual deviation in time from ideal cycle time; or by calculating the deviation in production from planned. Both methods measure the actual amount of production, but in somewhat different ways.

Table 4-1 The OEE definitions

	<b>Nakajima (1988)</b>	<b>De Groote (1995)</b>
<b>Availability (A)</b>	$\frac{\text{Loading time} - \text{downtime}}{\text{Loading time}}$	$\frac{\text{Planned production time} - \text{unplanned downtime}}{\text{Planned production time}}$
<b>Performance (P)</b>	$\frac{\text{Ideal cycle time} \times \text{output}}{\text{Operating time}}$	$\frac{\text{Actual amount of production}}{\text{Planned amount of production}}$
<b>Quality (Q)</b>	$\frac{\text{Input} - \text{volume of quality defects}}{\text{Input}}$	$\frac{\text{Actual amount of production} - \text{non-accepted amount}}{\text{Actual amount}}$
<b>OEE</b>	<b>(A) × (P) × (Q)</b>	<b>(A) × (P) × (Q)</b>

The quality rate only takes into consideration the quality losses (number of items rejected due to quality defects) that happen close to the equipment, not the quality losses that appear downstream. This is a very introspective approach. A wider definition of (Q) would be interesting, but would complicate the calculations and interpretations. It should be according to which process is to blame, and this is not always easy to identify.

Owing to different definitions of OEE and other varying circumstances between companies, it is difficult to identify optimum OEE figures and to compare OEE between firms or shops. Some authors have tried to do it though; e.g. Nakajima asserted that under ideal conditions firms should have  $A > 0.90$ ,  $P > 0.95$  and  $Q > 0.99$ . These figures would result in an  $OEE > 0.84$  for world-class firms and Nakajima considers this figure to be a good benchmark for a typical manufacturing capability. Kotze, on the other hand, argues that an OEE less than 0.50 is more realistic. This figure corresponds to the summary of different OEE measurements presented by Ericsson, where OEE varies between 0.30 and 0.80. These disparate figures indicate the difficulties of comparing OEE between processes.

#### **4. Throughput**

For a manufacturing system, the throughput is generally expressed as an hourly or daily production rate (i.e., the number of parts produced per hour or day). The reciprocal of the throughput or production rate is the production time per unit of the product. For transfer lines the throughput approximates the reciprocal of the cycle time (transfer time + longest operation time).

#### **5. Capacity**

The term capacity, or plant capacity, is used to define the maximum possible output of the transformation process the plant is able to produce over some specified duration. For a continuous plant, the duration is 24 hours a day, 7 days a week, whereas for an automobile plant the capacity is defined over a shift period.

#### **6. Flexibility**

A flexible system is one that is able to respond to change, and flexibility is the ability of the system to respond effectively to change. Flexibility is fundamental to achieve competitiveness. In general, high degree of flexibility requires higher levels of automation and more investments. However, such a system will be an adapting organism capable of surviving in

uncertain and changing markets. Changing circumstances include both internal and external changes. Internal changes or disturbances include breakdown of equipment, variability in processing time, work absenteeism and quality problems. External changes are typically changes in design, demand and product mix. The ability to cope with internal changes requires a degree of redundancy in the system, whereas the ability to cope with external changes requires that the system should be versatile and capable of producing a wide variety of part types with minimum changeover times and costs to switch from one product to another.

## **7. Quality**

Maintenance of high quality requires conscious efforts in various stages in design and manufacture. The effects of total quality control (TQC) are “fewer rework labor hours” and “less material waste” in addition to higher quality of finished goods. Thus good quality is not expensive but actually increases productivity, because so many costs such as rework, scrap, inspection, customer returns and warranty costs are all avoided with quality improvement. Continual improvement is a must since what was good last year will not make the grade this year [8].

## **4.3 Production system modules**

In this part of the paper, a concrete step-by-step methodology is presented using PNs for modeling, performance analysis and simulation of production systems, composed of a network of workstations and buffers, where machines fail and are repaired randomly. Petri Nets (PNs) and their extensions being both a mathematical and graphical tool are widely used for modeling discrete event dynamic systems including production systems and networks. PNs have been proven to be a powerful tool for studying system concurrency, sequential, parallel, asynchronous, distributed deterministic or stochastic behavior, resource allocation, mutual exclusion and conflicts. For a production system or network, whether single or multiple parts type or cyclically scheduled, with finite or infinite capacity buffers, the following are accomplished [9]:

***Production system decomposition – analysis:*** The generic production system is decomposed into four sets of modules, corresponding to the production line or transfer chain, assembly, disassembly and parallel machines modules. Their respective modular PN models are derived. The production system component modules and their respective PN equivalents refer to the simplest and most general scenario, i.e. generic modules and generic PN modules that

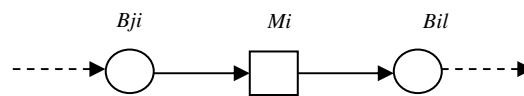
correspond to the one input buffer-one machine-one output buffer transfer chain module, two input buffers-one machine-one output buffer assembly module, one input buffer-one machine-two output buffers disassembly module, and two parallel machines module and generalized modules and generalized PN modules that correspond to the  $n_{TCi}$  machines–  $(n_{TCi} + 1)$  buffers transfer chain module.

**Production system composition – synthesis:** The overall production system PN model is obtained via synthesis of the component PN models considering component connectivity and complexity as follows:

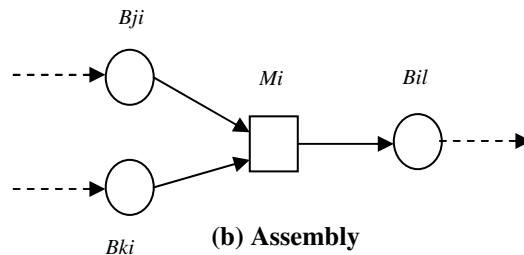
(i) *Component connectivity:* This is determined by places fusion at the respective module connecting points. (For example considering two sequential transfer chains, the output buffer of the first and the input buffer of the second are fused to one place, connecting the two modules.)

(ii) *Component complexity and overall system complexity:* This is determined by calculating for any random topology production system, the total number of the PN module nodes (places, transitions) and the overall PN system nodes.

**Production system simulation and performance evaluation:** The production system is simulated and evaluated through the corresponding PN model. As such, buffer levels, machine utilization (up-time down-time, idle-time), production rates, cycle times and overall production time are calculated and if necessary modified based on specifications and constraints.



(a) Transfer line



(b) Assembly

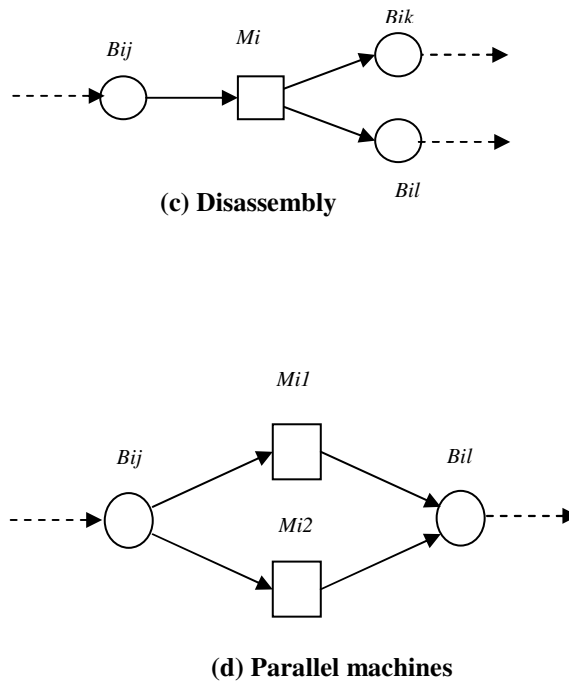


Figure 4-1 Fundamental production system modules

The major contributions of the methodology may be summarized as follows:

1. The PN based system modeling, analysis, synthesis and performance evaluation is independent of the system architecture and structure,
2. The model construction method may be extended and slightly modified in order to be applied to any configuration DEDS,
3. Analysis and synthesis of any complicated system is accomplished in terms of analysis and synthesis of the generalized PN modules, which means that the overall complexity is significantly reduced,
4. Large number of machines/ workstations could be handled, while buffer capacities may be considered either finite or infinite,
5. Whole system's analysis and properties are obtained with respect to the corresponding characteristics of the fundamental modules,
6. The generic models are simple, based in realistic assumptions and are easily applied and understandable.

A production system is usually viewed as a network of machines/workstations and buffers. Items receive an operation at each machine and wait for the next operation in a buffer with finite capacity. Random machine breakdowns disturb the production process and phenomena

such as starvation and/or blocking, may occur. Due to a failed machine with operational neighbors, the level of the downstream buffer decreases, while the level of the upstream buffer increases. If the repair time is large enough, the broken machine will either block the next station or starve the previous one. This adverse effect will propagate throughout the system. Production control policies may be classified as token-based or time-based. Token-based systems involve token movement in the manufacturing system to trigger events. Time-based systems operate on a time basis.

The production systems concerned here in the work are non-dedicated machine production systems. In these, each machine is assigned to various operations of different product types. In such systems all parts follow the different routes. According to the proposed approach, it is possible to recognize a small number of subsystems, called from now on fundamental modules. Their corresponding Timed PN models are implemented, analyzed and used as structural components for the representation of the majority of production systems. Modules are repeated and appropriately connected in order to produce the total model of the system under review. By using a modular approach, it is possible to simplify the description, qualitative (properties and invariants) and quantitative (mean production cycle, WIP etc) analysis of a complicated system by splitting its complexity into small and simple entities (that can also be considered and analyzed independently each other and to overcome problems relative to the systems behavior (e.g., some conflicts types)). After that, integration of the subsystems must be done in a consistent with the reality way in order to produce the corresponding results for the total system.

The use of modular subsystems in production systems modeling is a need, as this allows the independent modification of the model, results in increased flexibility (required changes to produce a new product are minimized) that meets one of the major requirements of such systems and allows the use of more efficient advanced performance evaluation and analysis techniques, as distributed simulation.

The production floor modeling approach introduced is extended so that every production network is decomposed into four generic modules: the production line, assembly, disassembly and parallel machines module, the simplest (generic) version of which is shown in Fig.4-1 (circles and rectangles represent buffers and machines, respectively). In system's operational phase the use of transferring facilities and similar equipment is not analytically presented. The

line module includes a machine  $M_i$ , which takes unfinished items from an upstream buffer  $B_{ji}$  and after processing sends them to a downstream buffer  $B_{il}$ . In the assembly operation a machine  $M_i$  obtains parts from two upstream buffers  $B_{ji}$  to  $B_{ki}$ , brings them to form a single unit and sends it to a downstream buffer  $B_{il}$ . In disassembly a machine  $M_i$  takes unfinished parts from an upstream buffer  $B_{ji}$ , separates them to two parts and sends them to downstream buffers  $B_{ik}$  to  $B_{il}$ . The two parallel machines module shows machines with potentially different settings and functions working on the same product. The two machines work independently each other and process parts of the same type. They correspond to the case of two servers for the same customer type. These four modules, if connected to each other may represent manufacturing networks of various layouts. Generalizations of the generic modules correspond to:  $n_{TCi}$  machines-  $(n_{TCi} + 1)$  buffers transfer chain module.

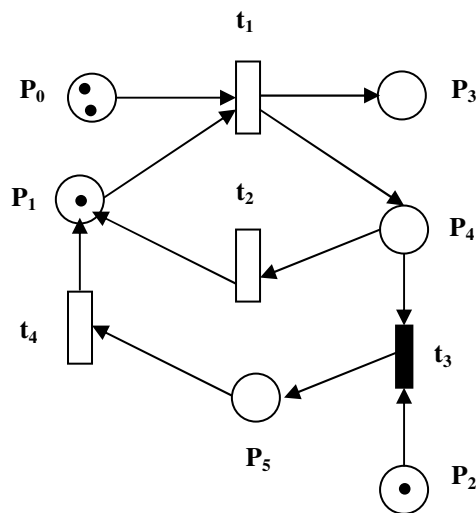
A buffer tends to be empty when the upstream machine is either under repair or producing at a slower rate than the downstream machine. Similarly a buffer tends to fill when the downstream machine is either under repair or producing at a slower rate than the upstream machine. The information needed to synchronize the operation of the production network is transferred to each control module by the level change of each buffer. Every event occurring in the production network is affecting level of buffers close to the area of the event. The time that a part spends in a manufacturing system between the start of first operation in a machine and completion of its last operation (time in which process of raw materials starts, until final products are ready) is known as the manufacturing cycle time. Reduction of manufacturing cycle time has many benefits, including lower inventory, reduced costs, faster response to needs and increased flexibility [9].

#### **4.4 Petri net modules**

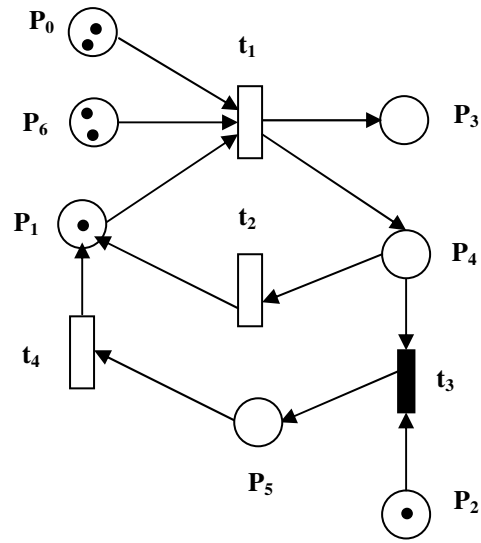
As already has been discussed in the preceding sections, places represent conditions; transitions represent events and arcs direct logical connection between places and transitions. PN structural and behavioral properties (reachability, safeness, conflicts, liveness, reversibility, persistency, and deadlock freeness) capture precedence relations and structural interactions between system components. Behavioral properties depend on, and are coupled with, the PN initial marking  $m_0$ . Structural properties are determined using the PN topological structure following matrix-based analysis methods.

The incidence matrix  $A$  for a PN consisting of  $n_p$  places and  $n_t$  transitions is defined as  $A = [a_{ij}]$ , where  $a_{ij} = a_{ij}^+ - a_{ij}^-$ ;  $a_{ij}^+ = w(i, j)$  is the arc weight from transition  $i$  to its output place  $j$  and  $a_{ij}^- = w(j, i)$  is the arc weight to transition  $i$  from its input place  $j$ .  $a_{ij}^+$ ,  $a_{ij}^-$  and  $a_{ij}$  represent the tokens added, removed and totally changed in a place  $j$  by the firing of transition  $i$ , respectively. The incidence matrix cannot represent self-loops (since the total difference of tokens in a self loop is equal to 0).

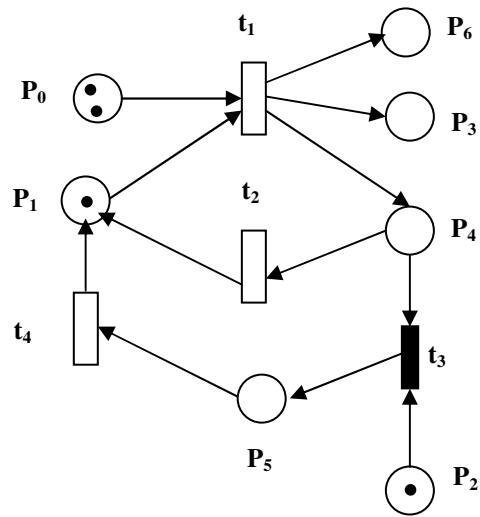
Dealing with time in a PN is accomplished by assigning time delays to places or transitions. Time can be associated with both nodes, but TPN models analysis is simpler when time is attached to one kind of nodes. The case described is that of PNs where time is attached to *transitions*, called ***t*-timed** Petri Nets. A *t*-timed PN arises from the corresponding Ordinary PN by associating each transition  $t_i$  a firing delay that may be constant or follow a given distribution. A TPN is defined by the tuple  $TPN = \{P, T, I, O, m_0, D, \}$  such that the first five elements are as described above for ordinary PNs while  $D$  represents time delay and is a function from the set of non-negative real numbers  $\{0, R^+\}$ .  $D(t_i)$  is a vector whose number of elements is the same with the number of net's transitions, where  $d_i$  =delay associated with transition  $i$ . A timed transition's firing consists of two events namely, “**start firing**” and “**end firing**”. In between these two events the firing is in progress. Tokens are removed from input places at “start firing” and are deposited to output places at “end of firing”. The transitions delays may be deterministic or described by a distribution. In TPNs some transitions may have zero occurrence times and are called “immediate”.



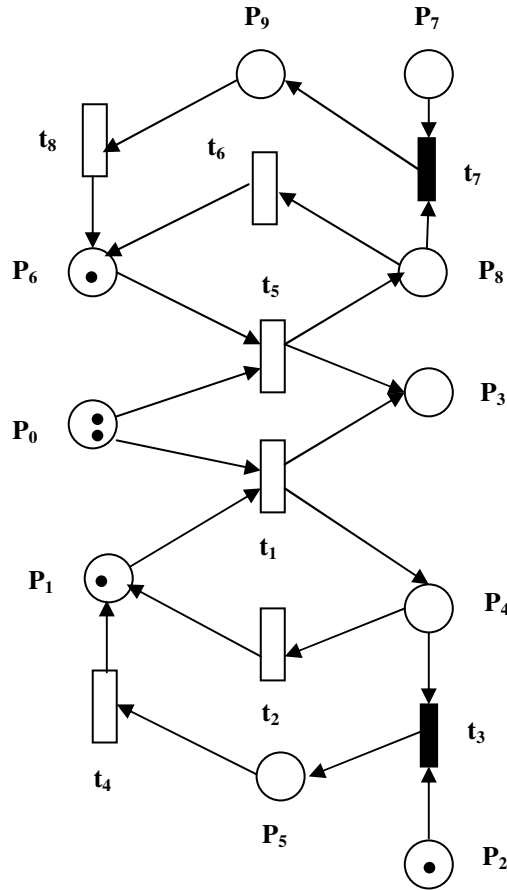
(a) production line (chain) generic PN model



(b) Assembly generic PN model



(c) Disassembly generic PN model



(d) Two parallel machines generic PN model

Figure 4-2 A corresponding PN modules of fundamental production systems

The PN models describe all the main events taking place in fundamental systems and are suitable for production systems simulation, analysis and performance evaluation. Modules describe common events but partially differ in operational and structural features. *Timed transitions* are presented as **white** rectangles, while *immediate transitions* as **black**. All transition input and output arc weights are equal to one. Table 4-1 explains places and transitions meanings. Places  $p_0 - p_5$  and transitions  $t_1 - t_4$  have the same meaning in all four generic PNs. Transitions correspond to system activities resulting in state changes, while places correspond to resource (machine, parts) availability or state (machine up, down, and idle).

Table 4-2 PN module nodes ( $P$  and  $T$ ) explanation (Fig. 4-2)

Node	Model	Meaning
$p_0$	All four modules	Parts available in initial buffer
$p_1$	All four modules	Machine available to process part
$p_2$	All four modules	Machine breakdown
$p_3$	All four modules	Parts in final buffer
$p_4$	All four modules	Machine finished process of a part
$p_5$	All four modules	Machine out of order
$p_6$	Assembly	Second type parts available in corresponding initial buffer (raw materials)
	Disassembly	Second type parts in the corresponding final buffer (processed parts)
	Parallel machines	Second Machine ( $M_2$ ) available to process part
$p_7$	Parallel machines	Machine $M_2$ breakdown
$p_8$	Parallel machines	Machine finished process of a part
$p_9$	Parallel machines	Machine $M_2$ out of order
$t_1$	Common	Machine processing (producing) part
$t_2$	Common	Empty machine's signal return
$t_3$	Common	Machine breaks down
$t_4$	Common	Machine has been repaired and is available to produce again
$t_5$	Parallel machines	Machine $M_2$ is processing (producing) part
$t_6$	Parallel machines	Empty machine's signal return for $M_2$
$t_7$	Parallel machines	Machine $M_2$ breaks down
$t_8$	Parallel machines	Machine $M_2$ has been repaired and is available to produce again

The generic PN modules have been derived based on the realistic assumptions that: (i) buffers are finite, (ii) machines operate at a given speed that changes periodically according to events taking place in the system, (iii) setup and transportation times of parts through the system are negligible compared to production times, (iv) machine breakdowns happen infinitely often, but only after the completion of a production cycle.

The generic transfer chain module is considered first. In this, places  $p_0$  and  $p_3$  represent the raw materials and final products buffers respectively, while  $t_1$  describes process performance when machine is available. To avoid multiple parts reaching a machine concurrently, a signal of machine being empty and ready to produce is represented through a token produced from the firing of  $t_1$  and led to  $p_4$ . Empty machine's signal returns to  $p_1$ , where it is initially found, meaning that next parts process may begin, following one of two possible routes. One is after firing of  $t_1$ , meaning that the next part process can begin without other events mediation. The second is after a machine breakdown represented by  $p_2$ ,  $t_3$  fires causing machine to go out of

order ( $p_5$ ), which is repaired after firing of  $t_4$ . In all generic and generalized PN modules, conflict between  $t_2$  and  $t_3$  that have common input place  $p_4$ , exists – machine finished a part process (in modules that have multiple machines, there exist proportional conflicts in all sets of them). To solve this conflict efficiently,  $t_2$  has been considered as a timed transition (with minimum delay) while  $t_3$  as an immediate one.  $t_3$  has also a second input place ( $p_2$ ) (tokens are available there only in the case of a machine breakdown according to a distribution or stochastically), which means that it cannot become enabled and consequently fire if there exist no tokens in this place. So, when machine operates, timed transition  $t_2$  fires, since immediate  $t_3$  has no token in one input place, else  $t_3$  fires. It must be noted that in the models presented both transitions have the same priority (equal to one), since in another case the execution of the net would be different. Generic assembly module's main difference is that two initial buffers ( $p_0$ ,  $p_6$ ) provide different part types to the machine for the process to begin, while generic disassembly module has two final product buffers ( $p_3$ ,  $p_6$ ). In generic parallel machine module two transfer chain PN modules are composed so that they obtain parts from the same input buffer ( $p_0$ ) and lead their products to the same final buffer ( $p_6$ ). These facts are generalized for the cases of generalized PN modules. Definition of buffers maximum capacities in PN modules ensures the representation of phenomena as starved and blocked machines. Tokens shown in all four generic PN modules are for demonstration purposes only.

Observing the four generic PN modules as shown in Fig. 4-2 with any finite initial marking  $m_0$ , one may conclude that: (i) As long as there is part availability in the input buffer(s), all four generic PNs after the completion of one production cycle return to the state of starting a new cycle; (ii) the parts number in the initial buffer(s) defines the exact number of production cycles; (iii) all modules are k- bounded; (iv) modules are non-conservative (at least  $t_3$  consumes two tokens and produces one, in assembly and disassembly transition  $t_1$  is also non-conservative, in parallel machines module  $t_7$  is non-conservative); (v) modules are non-persistent (firing of  $t_3$  may disable  $t_2$ ); (vi) modules are not repetitive and not consistent.

The synthesis procedure of two simplest transfer chains is shown in Fig. 4-3 below. Observing this figure, it is obvious that places  $p_3$  and  $p_6$  are fused in one place  $p_{3-6}$ . The total number of places is reduced by one, while transitions are equal to the total of each module transitions. The combined PN input places are reduced by one ( $p_{3-6}$  is an internal place, not input buffer).

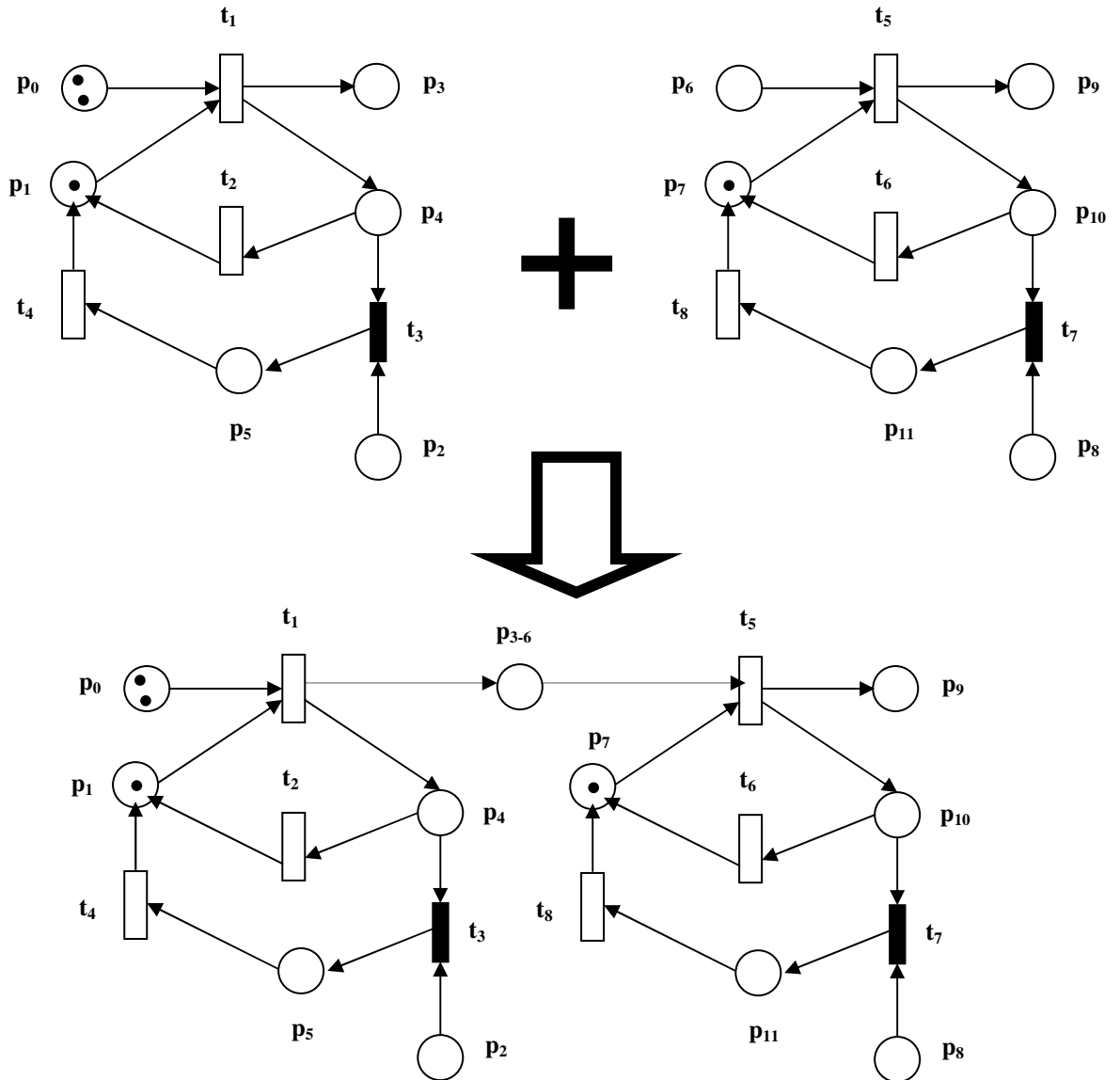


Figure 4-3 Synthesis of two generic transfer chain modules

#### 4.5 Modeling of the machining processes

The tools and spare parts workshop of AEC has 86 different types of machine tools that are used for the production purpose. This number does not include the machines that are still in the shop but broken down (those which need maintenance). There are machining stations separated by the type and capacity of the machine tools. The lathe, milling, drilling, grinding, shaping and slotting, gear shaping, jig boring, and some other machining centers are there.

For performance analysis of the various processes of the shop it is necessary to model the entire shop by using the Petri net modeling, which has already been discussed in the preceding sections of this chapter. The various production process carried out in the workshop can be modeled by applying the concept explained in sections 4-3 and 4-4. Fig. 4-4 below gives the basic model of the various production operations such as machining, heat treatment...etc.

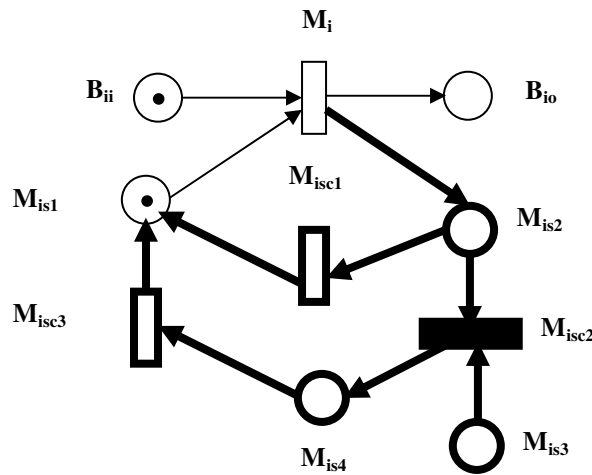


Figure 4-4 The basic model for different operations

Table 4-3 Place and Transitions description of the basic model (Fig. 4-4)

Places/transitions	Description
$B_{ii}$	Input buffer of $i^{\text{th}}$ machine
$B_{io}$	output buffer of $i^{\text{th}}$ machine
$M_{is1}$	$i^{\text{th}}$ machine status 1 (available/ready for operation)
$M_{is2}$	$i^{\text{th}}$ machine status 2 (machine has completed its operation)
$M_{is3}$	$i^{\text{th}}$ machine status 3 (machine failed)
$M_{is4}$	$i^{\text{th}}$ machine status 4 (machine has under repair)
$M_i$	$i^{\text{th}}$ machine
$M_{isc1}$	$i^{\text{th}}$ machine status change 1 (from un availability to availability)
$M_{isc2}$	$i^{\text{th}}$ machine status change 2 (from failure to repair)
$M_{isc3}$	$i^{\text{th}}$ machine status change 3 (from repair to availability)

Presence of tokens in places  $B_{ii}$  and  $M_{is1}$  is the pre-condition for machine  $M_i$  that initiates the operation (to be enabled and then fired). The start of operation of  $M_i$  removes one token each from the input places,  $B_{ii}$  and  $M_{is1}$ , and adds it to the out put place  $B_{io}$  and  $M_{is2}$ , which represents the end of operation is being performed on the part/work piece. The token in  $B_{io}$  represents the *termination* of operation on previous processor (machine)  $M_i$  and *availability of finished or semi-processed part* for the next process.

In the fig. 4-4 above the part of the model in bold is dedicated for the status of the machine, i.e. updating the machine for the next operation/process and taking care of the random failure of machine. Therefore, for the sake of simplicity the model can be further simplified as shown in fig.4-5 below.

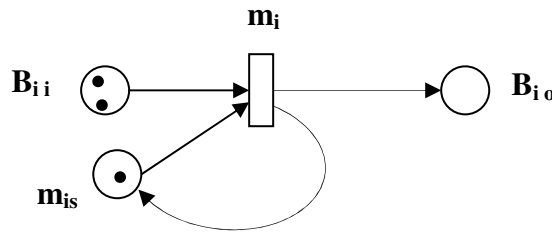


Figure 4-5 Simplified PNM of single machine

Table 4-4 Modelling conventions with Petri nets

Concepts in manufacturing	Petri net modeling
Moving or production lot size	Weight of directed arcs modeling moving or production kanban
No. of resources, e.g. machine, workstations, and robots	The number of tokens in places modeling quantity of the corresponding resources
Capacity of work station	The number of tokens in places modeling its availability
Work-in-process	The number of tokens in places modeling the buffers and operations of all machines
Production volume	The number of tokens in places modeling the counter for or the number of firings of transitions modeling end of a product
The time of an operation, e.g. setup, processing, and loading	The delays associated with the place or transition modeling the operation
Conveyance or transportation time	The delays associated with the directed arc, place or transition modeling the conveyance or transportation
System state	Petri net marking (plus the timing information for timed Petri net)

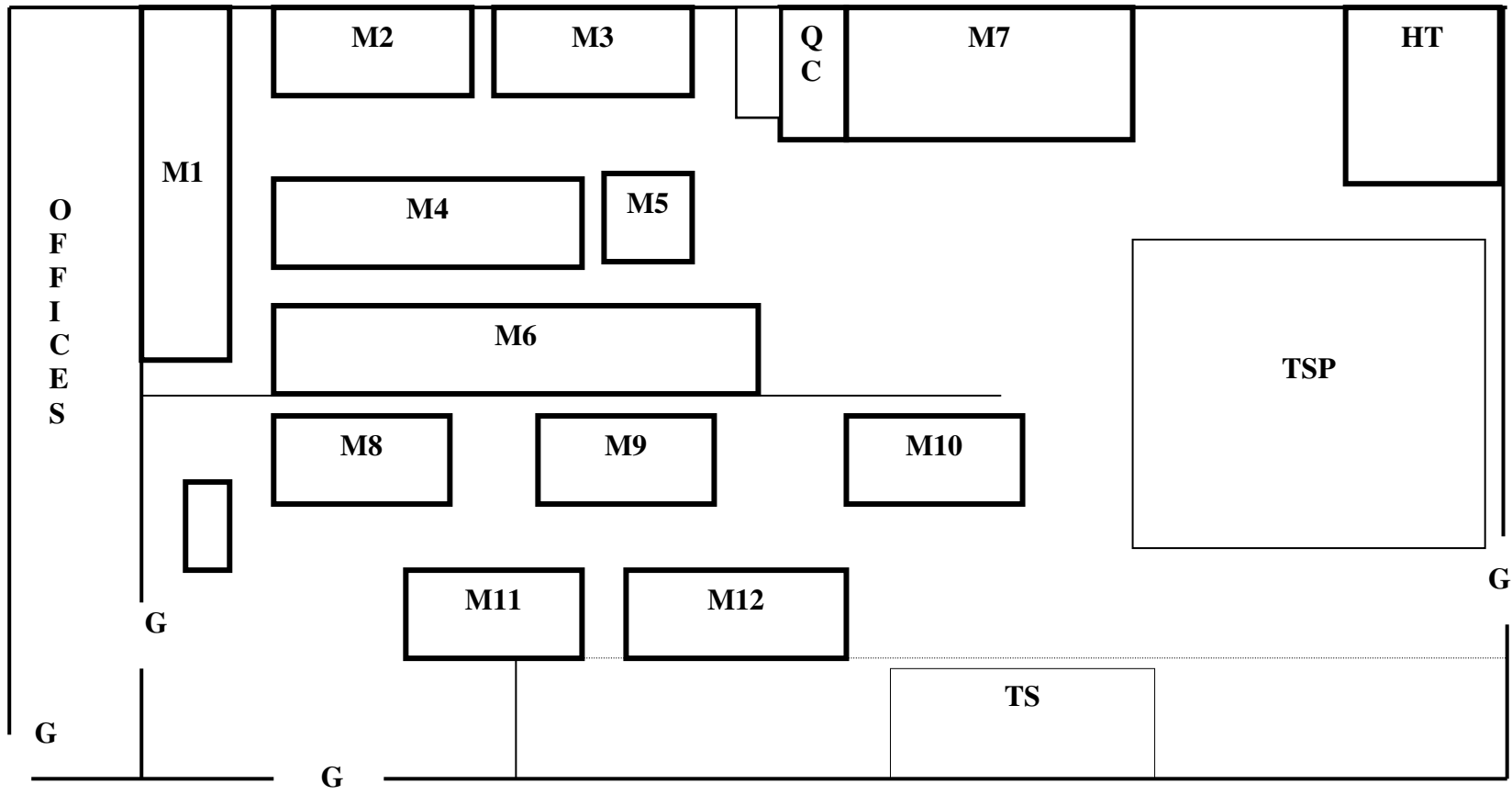


Figure 4-6 the layout of tools and spare parts workshop of AEC

<b><u>Module</u></b>	<b><u>Description</u></b>
<b>M1</b>	contains 3 turret and 2 collate lathe machines
<b>M2</b>	contains 9 monark lathe machines
<b>M3</b>	contains 2 milling machines
<b>M4</b>	contains 4 lathe machines
<b>M5</b>	contains 4 milling machines
<b>M6</b>	contains 6 lathe machines
<b>M7</b>	contains 17 grinding machines of different types
<b>M8</b>	contains 8 milling machines
<b>M9</b>	contains 6 lathe machines
<b>M10</b>	contains 2 jig boring machines
<b>M11</b>	contains 2 lathe machines
<b>M12</b>	contains 1 shaper and 2 gear shaping machines
<b>M13</b>	contains 1 boring machine
<b>QC</b>	Quality control section
<b>HT</b>	Heat treatment room
<b>TS</b>	Tool sharpening section contains 8 different machine tools.
<b>TSP</b>	Temporary storage and painting space
<b>G</b>	Stands for Gate

In the modeling, (chapter 4) it is assumed that the route of the product can pass through different modules with out any restriction, which increases the flexibility of the model. Therefore, the above layout of the factory can be taken for the simulation with no need of any adjustment or modification.

## CHAPTER FIVE

### 5. SOFTWARE DEVELOPMENT

#### 5.1 Introduction to Discrete Event simulation procedure

A discrete event model comprises system building blocks and a schedule or rules that govern the flow of work in an FMS. Discrete event simulation is a process through which a discrete event model mimics the behavior of a discrete-event system such as FMS event by event. Qualitative and quantitative data from this process are obtained to predict the behavior of the system and its level of performance. Simulation has two basic motives, rapid prototyping to determine the correctness of system behavior, and performance prediction. Some performance measures of interest are throughput, resource utilization, buffer capacity, yield, and effects of failures. Simulation studies are conducted using computers. The software model can capture all the dynamics and interactions of a real system. Since real manufacturing systems are expensive to build, simulation is an important means to predict performance accurately, investigate effects of parameter changes, identify bottlenecks, and choose the best design among alternatives [11].

In discrete event simulation, the model contains entities or objects, attributes, events, activities, and the interrelationships among them. The collection of entities and their statuses define the system state. A system state may change only at discrete points in time. These changes are driven by the event occurrences, generally asynchronous. In manufacturing systems, an entity can be a machine, a robot, material (work in progress), and a controller, with its schedule. The attributes of a machine include its operation rate, the nature of its operation, and its reliability. Event examples are the arrival of raw material, loading, unloading, the change of a tool, and the start of an operation. The following steps are involved in discrete event system simulation as shown in Fig. 5-1 below.

***Goal Definition and Requirements Specification:*** Determine the requirements specification and simulation goal of the manufacturing system under study or design. The goals are to determine the best system among several alternatives and to investigate the system behavior and performance. An appropriate level of detail is selected to match the modeling goal. For example, it could be to optimize the performance of an individual flexible manufacturing system (FMS) cell, or to optimize the performance of a shop floor containing many cells. Informal requirements have to be converted into formal requirements specifications which are

understandable to both managers and designers or analysts. Simulation environments and related languages may be used to formulate requirements although they may differ from the language used to construct the simulation model.

***Model Development:*** Formulate a model, which could be a Petri net, or other models, e.g. a queuing model, state machine, and object-oriented model. Construction of a model can be a difficult task, requiring a modeler's understanding of the problem and modeling experience. The model has to capture the essence of the real system without excessive detail. Hierarchical models that could represent different levels of detail are required for large-scale flexible manufacturing systems. Simulation results can be presented to planners and managers for their decision-making and serve the basis for design and real-time implementation of FMS. Assumptions and simplifications have to be justified.

***Computer Model Construction:*** Construct a computer representation of the model, e.g., program a mathematical formulation using a simulation language or general-purpose programming language, or build up a graphical model in a computer using a graphic editor and simulator in which simulation algorithms are embedded and not apparent to a user. The latter approach is used in all Petri net-based methods.

***Data Collection:*** Analyze all parameters involved in the model and specifications set, and collect data based on accounting data, experience, or from lower-level simulation runs. The quality of data has direct impact on the results obtained from the simulation. Thus care has to be taken during this process.

***Simulation Run:*** Run the computer model or simulator to verify its correctness. The model verification process ensures that the computer simulation models the system properly. If the logic structure, inputs, and outputs are correctly represented in the computer model, verification is completed. Simple cases and common sense are used during this process. Various animation techniques can facilitate this process. Validation ensures that the model is an accurate representation of a real system. Thus the model can be used as a substitute for the actual system for the prediction of performance with a high level of confidence. The use of Petri nets and other graphical tools are very helpful in this step.

**Evaluation of Simulation Results:** Obtain and evaluate simulation results. In this step statistical data analysis techniques may be needed to analyze the system simulation results and to validate them. Generally, the performances of two or more alternative system designs are compared. The system is simulated over a range of key operational parameters and thus the optimal settings can be determined.

**Documentation:** Document the input data, methods, simulation tools, computational time, and results. The results should be presented in graphs for patterns and trends over the parameters of interest. Histograms and bar charts are often used to present the simulation data pictorially. The use of formal description techniques in the construction of simulation models allows for the verification of these models, with respect to their behavioral properties, using strict mathematical techniques. For example, Petri nets allow for the construction of simulation models, as well as their formal verification through analysis methods. Two advantages of this approach are:

- The correctness, if present or absence of behavioral properties of the simulation model can be established at the early stages of the simulation system development. This results in increasing confidence in the validity of the simulation and computer models; and
- As a result of incorrect or missing behavioral properties identified during the test runs, the cost involved in redevelopment of the simulation and computer models can be reduced with this approach.

The simulation results need be compared with real-world data, if available, for existing systems, or with results produced by theoretical models. For complex systems, obtaining analytical solutions for models involving all facets of the system functionality is often computationally prohibitive. Queuing theory and models are, used, in most cases, for obtaining the reference results. The use of queuing theory, as any other technique that yields results representing steady state operation of the modeled systems, poses an additional problem. The effects of the initial bias have to be eliminated. These effects are due to the transient period, which follows the start (of the simulation run, and influenced by the nature of the system simulated as well as the simulation environment.

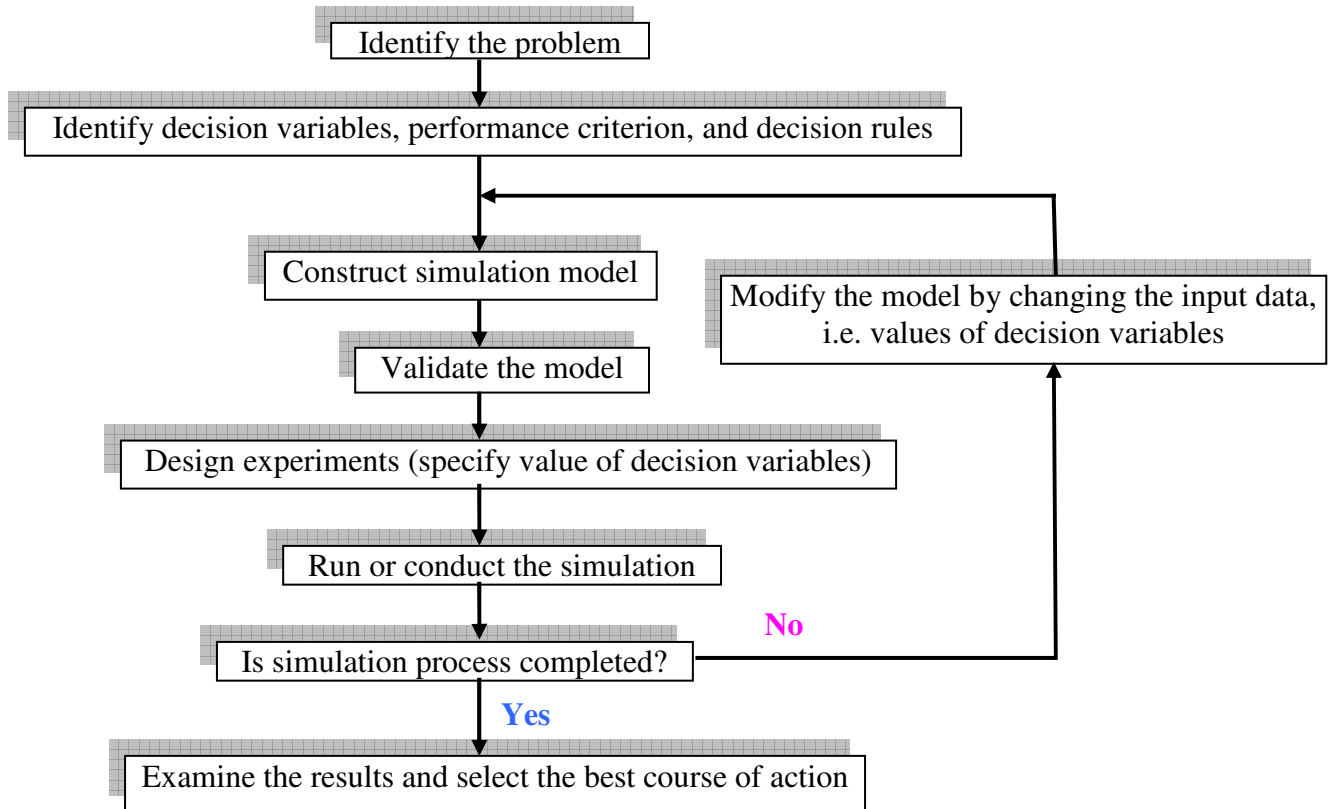


Figure 5-1 Steps of simulation process

A successful simulation of a factory system design needs close cooperation with the factory personnel to ensure the model's correctness and to make the results acceptable to them. With the increasing use of powerful PCs and workstations, graphic simulation and animation of manufacturing systems is possible. Its operation can then be viewed in real time and interactive simulation can be conducted. This type of simulation is most useful for debugging, fine manipulation, and material flow observance [1].

## 5.2 Developing simulation models

A simulation model is a surrogate for actually experimenting with a manufacturing system, which is often infeasible or not cost-effective. Thus, it is important for a simulation analyst to determine whether the simulation model is an accurate representation of the system being studied, i.e., whether the model is *valid*. It is also important for the model to be *credible*; otherwise, the results may never be used in the decision-making process, even if the model is “valid.” The following are some important ideas/techniques for deciding the appropriate level of model detail (one of the most difficult issues when modeling a complex system), for validating a simulation model, and for developing a model with high credibility:

- State *definitively* the issues to be addressed and the performance measures for evaluating a system design at the beginning of the study.
- Collect information on the system layout and operating procedures based on conversations with “subject-matter experts”.
- Delineate all information and data summaries in an “assumptions document,” which becomes the major documentation for the model.
- Interact with the manager (or decision-maker) on a regular basis to make sure that the correct problem is being solved and to increase model credibility.
- Perform a structured walk-through (before any programming is performed) of the conceptual simulation model as embodied in the assumptions document before an audience of managers, etc.
- Use sensitivity analyses to determine important model factors, which have to be modeled carefully.
- Simulate the existing manufacturing system (if there is one) and compare model performance measures (e.g., throughput and average time in system) to the comparable measures from the actual system.

#### ❖ *Timed Petri Nets and Token Game Simulation*

A PN approach to analyzing a system consists of two parts: modeling with PN and analysis of the PNM by either analytical methods or simulation. Simulating a PN using the token is one of the several methods to conduct PN simulation. Timed PNs (TPNs) are used for the performance evaluation of a system. *Instantaneous description (ID)*, which is useful for the quantitative and behavioral analysis of the system, defines the state of a TPN and is a four tuple  $ID = (m, F, Q, A)$  where:

$m$  is a marking;

$F$  is a binary selector function,  $F: T \rightarrow \{0, 1\}$ . If  $F(t) = 1$ ,  $t$  is enabled, otherwise disabled;

$Q: T \rightarrow R^+$  is remaining firing time function where  $R^+$  is the set of all positive integers. If  $Q(t)=q$ , there is  $q$  amount of time to complete firing  $t$ .  $Q$  is a cumulatively decreasing time function;

$A: T \rightarrow R^+$  is active time function. If  $A(t) = q'$ ,  $t$  is said to be active for  $q'$  amount of time.  $A$  is a cumulatively increasing time function [11].

### **5.3 Description of the Software Package to Simulate Petri Nets**

A software package is developed using the token game to conduct PN simulation based on previous related works; especially the work in [11] has been taken as the base for this research and it has major contribution for this particular work to be completed. Figure 5-2 describes the algorithm used in developing the software package. At the beginning of the simulation run, the user is prompted to select the mode of operation, which is either deterministic or stochastic. The software has the following major modules whose functionality is briefly described next.

#### *Read Petri Net*

This module reads an input file that specifies the structure of the PNM. The structure of the PNM means the input and output connectivity between places and transitions including the weights on the connecting arcs, initial marking, and transition timing duration. The timing duration for transitions is given in time units. An input file may also contain information that can be used to give priorities that are used to resolve conflicts during simulation.

#### *Enabled Transitions*

This module scans the whole PNM at each unit of time and finds the transitions that are ready to fire. Thus, this module generates a list of enabled transitions that are enabled to fire with respect to real-time. This list of enabled transitions is defined as an F-function (the machine status) in the terminology of Timed PNs as explained in the earlier section.

#### *Conflict Resolver*

A conflict in a PN model results when an element is shared by two other elements of the system (e.g. a single robot serving two machines that demand service at the same time. In such cases, this module detects the conflicts and resolves it based on the criteria given by a user. During simulation this module determines the transitions that are in conflict and stops the program execution until the conflict is resolved. Once the conflict is resolved, the program execution is resumed. Conflicts can be resolved by giving priorities to transitions. Priorities can either be interactively given during simulation or be entered in the input file. This is because in some PN models conflicts can be determined even before starting simulation. In such cases by giving priorities to resolve conflicts in the input file, user intervention during simulation can be avoided. However, in complex PN models conflicts can be identified only during simulation time. In such cases, this module displays the time of the conflict and the transitions in conflict on the screen. It then prompts the user to enter priorities to resolve

conflicts. Then, based on the information given by the user it resolves the conflict and resumes simulation.

*Minimum time*

This module scans the whole PN model and detects the transition(s) with minimum timing duration to fire as there can be more than one transition with minimum time.

*New marking*

Whenever a transition fires, this module updates the marking of PN model accordingly by using the PN firing rules as explained in the earlier chapters.

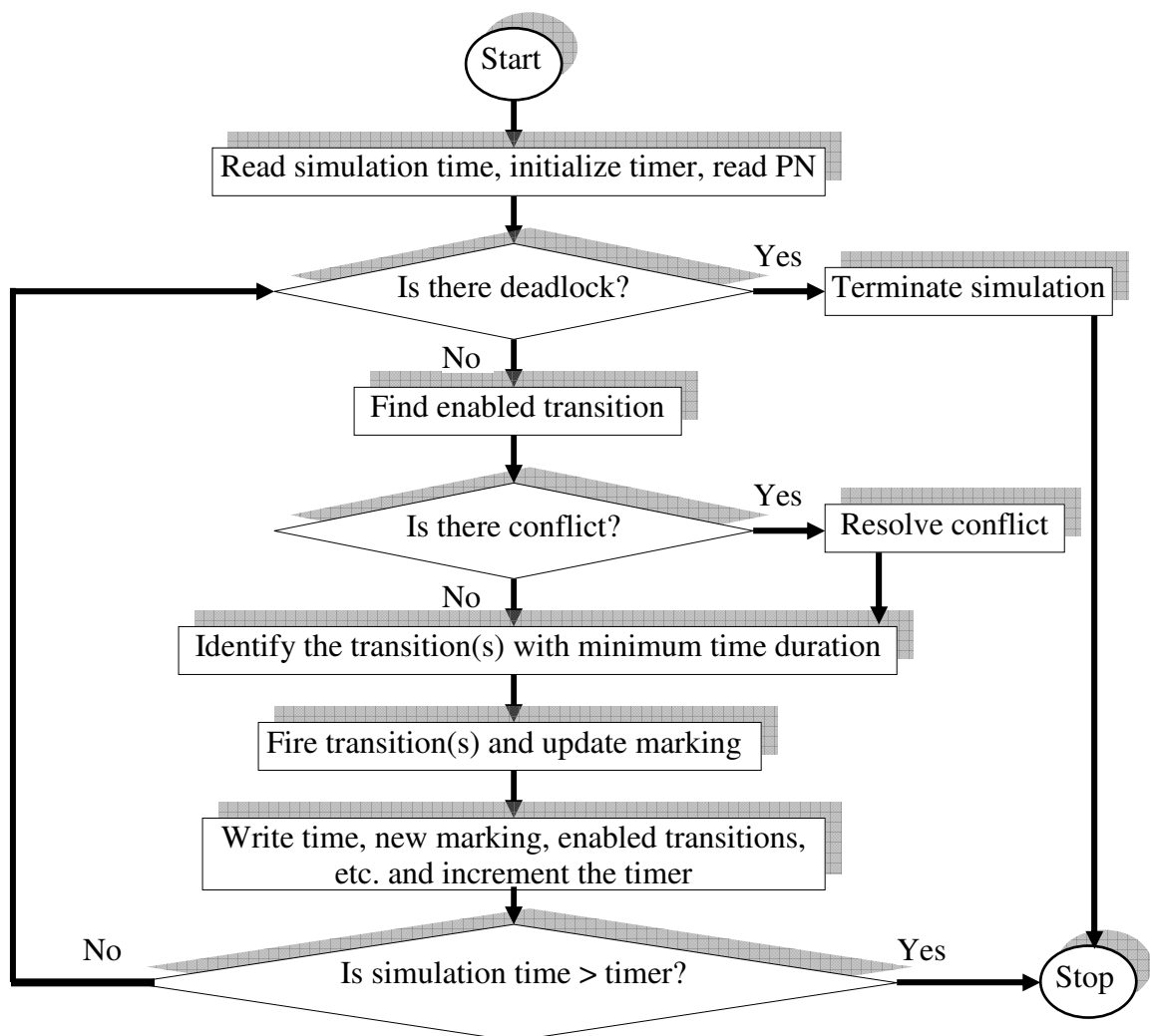


Figure 5-2 Algorithm used for developing software package using Token Game

## 5.4 Application of the simulation

This section of the paper deals with the application of the developed methodology. As it has been already discussed in the preceding sections, the simulation run can be made for both deterministic and stochastic processes. In the deterministic part the processing time of a given operation on a machine is fixed or known whereas in the stochastic part the processing time is assigned to each process on respective machine randomly using random number generation, which is based on the available data for process time.

The designed methodology or simulation is product/process-based. i.e. it depends on the processes required to produce the product. Two products are selected as case situations for illustrations purpose, which are oil pump and nozzle. Production of oil pump needs five processes on five different machine tools: the lathe, slotting machine, milling machine, heat treatment, and grinding machine; while the nozzle needs the lathe and milling machines only.

Data are collected to get the actual time taken to process the same work at each machine by different machinists.

Table 5-1 Production processes and their respective time for nozzle

Type of machine	Operation	Process time (hr.)	Frequency
Lathe Machine	Turning	2:00	2
		3:10	3
		4:00	3
		5:30	5
		6:00	2
Milling machine	Milling	4:00	2
		5:00	1
		6:40	6
		8:30	3
		9:00	3

Table 5-2 Production processes and their respective time for oil pump

Type of machine	Operation	Process time (hr.)	Frequency
Lathe Machine	Turning	3:00	4
		4:00	6
		5:00	3
		6:00	2
Slotting Machine	Slotting	1:00	1
		2:00	4
		3:00	3
		4:00	6
		5:00	1
Milling machine	Milling	3:00	1
		4:00	5
		5:00	5
		6:30	3
		7:00	1
Crucible furnace	Heat treatment	1:00	1
		1:30	3
		2:00	4
		3:00	5
Surface grinder	Grinding	2:00	4
		3:00	6
		4:00	4
		5:00	1

In the simulation the random machine failure and corresponding time for repair are taken in to account. This is done in order to handle the production interruption that may be caused by the failure and repair of machines. For this part of simulation, data are collected to get the Mean Time to Fail (*MTTF*) and Mean Time to Repair (*MTTR*). Table 5-3 depicts the actual time to fail (up time) and repair (down time) in the month June, 2006. In this month there were 168 working hours (21 working days/month\*8 hours/day).

Table 5-3 MTTF and MTTR of machines in month June, 2006

S.N <sup>o</sup>	TTF (hr.)	Frequency (no. of machines)	TTR (hr.)
1	50	1	12:00
2	90	1	5:00
3	115	2	3:00, 7:00
4	150	2	6:00, 10:00
5	155	1	2:00

Based on the above data the *MTTF* is found to be 117.857 hr. and the corresponding failure rate becomes  $1/MTTF$ , which is equal to 0.008. Then in the program random number is generated at each process time for each machine. Whenever the random number equals 0.008, the machine is subject to failure and needs to be repaired. The time for repair can be calculated from the data, where  $MTTR=6:25$  hrs. By using the relation  $P(r) = 1 - e^{-t_{max}/MTTR}$ ; where,  $P(r)$  stands for the probability of 95% confidence interval, the  $t_{max}$ , which is the maximum repair time, can be obtained and assigned to the failed machine so that the machine process will be delayed for the specified time. Fig.5-3 and 5-4 below are the models developed for the two products mentioned above.

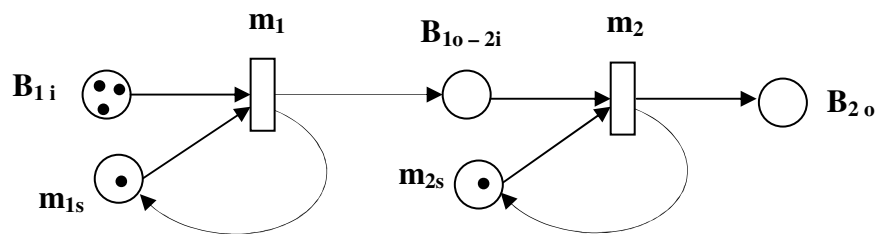


Figure 5-3 a PN model for operations of nozzle production on two machines

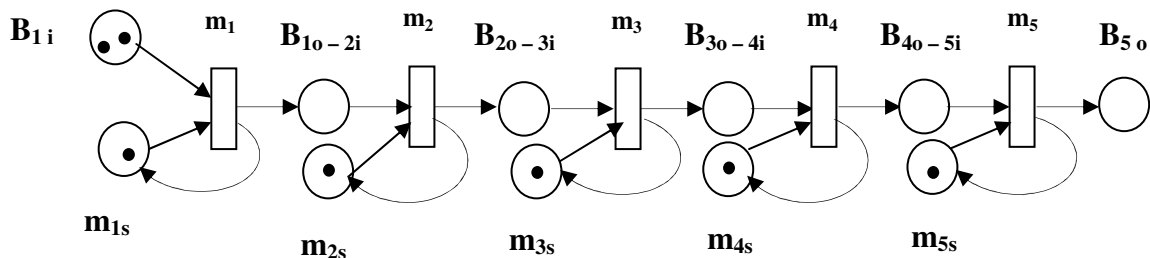


Figure 5-4 a PN model for operations of oil pump production on five machines

For both models the number of tokens in their initial input buffer depends on the number of parts to be produced. By using these models simulation runs are made to observe the various performance parameters of the production operations. The following assumptions are made in this work:

- The machine setup, loading, and unloading times are assumed to be included in the machining (process) time.
- The maintenance of failed machines takes place as soon as the failure takes place.

- Continuous production will be there as long as tokens are available in the input buffer of each machine.
- For all arcs, the arc weight equals one.
- The transfer line (chain) production module is considered.
- The product route can pass through different modules (see Fig.4-1).
- Buffer capacity is assumed to be infinite.

Based on the above assumptions, the sample simulation run for the two products has been made and the inputs and outputs of the program are shown below.

### **1- Inputs and Out puts for oil pump production:**

#### **➤ INPUT**

Select Mode of Operation:

1. Deterministic Mode
2. Stochastic Mode

: 1

Enter number of Machine/Processor: 5  
Number of pre and post conditions: 11

Enter the Input matrix inm[1][1]: 1  
Enter the Input matrix inm[1][2]: 1  
Enter the Input matrix inm[1][3]: 0  
Enter the Input matrix inm[1][4]: 0  
Enter the Input matrix inm[1][5]: 0  
Enter the Input matrix inm[1][6]: 0  
Enter the Input matrix inm[1][7]: 0  
Enter the Input matrix inm[1][8]: 0  
Enter the Input matrix inm[1][9]: 0  
Enter the Input matrix inm[1][10]: 0  
Enter the Input matrix inm[1][11]: 0

Enter the Input matrix inm[2][1]: 0  
Enter the Input matrix inm[2][2]: 0  
Enter the Input matrix inm[2][3]: 1  
Enter the Input matrix inm[2][4]: 1  
Enter the Input matrix inm[2][5]: 0  
Enter the Input matrix inm[2][6]: 0  
Enter the Input matrix inm[2][7]: 0  
Enter the Input matrix inm[2][8]: 0  
Enter the Input matrix inm[2][9]: 0  
Enter the Input matrix inm[2][10]: 0  
Enter the Input matrix inm[2][11]: 0

Enter the Input matrix inm[3][1]: 0  
Enter the Input matrix inm[3][2]: 0  
Enter the Input matrix inm[3][3]: 0  
Enter the Input matrix inm[3][4]: 0  
Enter the Input matrix inm[3][5]: 1  
Enter the Input matrix inm[3][6]: 1  
Enter the Input matrix inm[3][7]: 0  
Enter the Input matrix inm[3][8]: 0  
Enter the Input matrix inm[3][9]: 0  
Enter the Input matrix inm[3][10]: 0  
Enter the Input matrix inm[3][11]: 0

Enter the Input matrix inm[4][1]: 0  
Enter the Input matrix inm[4][2]: 0  
Enter the Input matrix inm[4][3]: 0  
Enter the Input matrix inm[4][4]: 0  
Enter the Input matrix inm[4][5]: 0  
Enter the Input matrix inm[4][6]: 0  
Enter the Input matrix inm[4][7]: 1  
Enter the Input matrix inm[4][8]: 1  
Enter the Input matrix inm[4][9]: 0  
Enter the Input matrix inm[4][10]: 0  
Enter the Input matrix inm[4][11]: 0

Enter the Input matrix inm[5][1]: 0  
Enter the Input matrix inm[5][2]: 0  
Enter the Input matrix inm[5][3]: 0  
Enter the Input matrix inm[5][4]: 0  
Enter the Input matrix inm[5][5]: 0  
Enter the Input matrix inm[5][6]: 0  
Enter the Input matrix inm[5][7]: 0  
Enter the Input matrix inm[5][8]: 0  
Enter the Input matrix inm[5][9]: 1  
Enter the Input matrix inm[5][10]: 1  
Enter the Input matrix inm[5][11]: 0

The input matrix is :

	1	1	0	0	0	0	0	0	0	0	0	
	0	0	1	1	0	0	0	0	0	0	0	
	0	0	0	0	1	1	0	0	0	0	0	
	0	0	0	0	0	0	1	1	0	0	0	
	0	0	0	0	0	0	0	0	1	1	0	

Enter output Matrix otm[1][1]: 0  
Enter output Matrix otm[1][2]: 1  
Enter output Matrix otm[1][3]: 1  
Enter output Matrix otm[1][4]: 0  
Enter output Matrix otm[1][5]: 0  
Enter output Matrix otm[1][6]: 0  
Enter output Matrix otm[1][7]: 0  
Enter output Matrix otm[1][8]: 0  
Enter output Matrix otm[1][9]: 0  
Enter output Matrix otm[1][10]: 0  
Enter output Matrix otm[1][11]: 0

Enter output Matrix otm[2][1]: 0  
 Enter output Matrix otm[2][2]: 0  
 Enter output Matrix otm[2][3]: 0  
 Enter output Matrix otm[2][4]: 1  
 Enter output Matrix otm[2][5]: 1  
 Enter output Matrix otm[2][6]: 0  
 Enter output Matrix otm[2][7]: 0  
 Enter output Matrix otm[2][8]: 0  
 Enter output Matrix otm[2][9]: 0  
 Enter output Matrix otm[2][10]: 0  
 Enter output Matrix otm[2][11]: 0

Enter output Matrix otm[3][1]: 0  
 Enter output Matrix otm[3][2]: 0  
 Enter output Matrix otm[3][3]: 0  
 Enter output Matrix otm[3][4]: 0  
 Enter output Matrix otm[3][5]: 0  
 Enter output Matrix otm[3][6]: 1  
 Enter output Matrix otm[3][7]: 1  
 Enter output Matrix otm[3][8]: 0  
 Enter output Matrix otm[3][9]: 0  
 Enter output Matrix otm[3][10]: 0  
 Enter output Matrix otm[3][11]: 0

Enter output Matrix otm[4][1]: 0  
 Enter output Matrix otm[4][2]: 0  
 Enter output Matrix otm[4][3]: 0  
 Enter output Matrix otm[4][4]: 0  
 Enter output Matrix otm[4][5]: 0  
 Enter output Matrix otm[4][6]: 0  
 Enter output Matrix otm[4][7]: 0  
 Enter output Matrix otm[4][8]: 1  
 Enter output Matrix otm[4][9]: 1  
 Enter output Matrix otm[4][10]: 0  
 Enter output Matrix otm[4][11]: 0

Enter output Matrix otm[5][1]: 0  
 Enter output Matrix otm[5][2]: 0  
 Enter output Matrix otm[5][3]: 0  
 Enter output Matrix otm[5][4]: 0  
 Enter output Matrix otm[5][5]: 0  
 Enter output Matrix otm[5][6]: 0  
 Enter output Matrix otm[5][7]: 0  
 Enter output Matrix otm[5][8]: 0  
 Enter output Matrix otm[5][9]: 0  
 Enter output Matrix otm[5][10]: 1  
 Enter output Matrix otm[5][11]: 1

The output matrix is :

	0	1	1	0	0	0	0	0	0	0	0	0	
	0	0	0	1	1	0	0	0	0	0	0	0	
	0	0	0	0	0	1	1	0	0	0	0	0	
	0	0	0	0	0	0	0	1	1	0	0	0	
	0	0	0	0	0	0	0	0	0	1	1	0	

Enter time duration of processes d[1]: 2  
Enter time duration of processes d[2]: 1  
Enter time duration of processes d[3]: 3  
Enter time duration of processes d[4]: 4  
Enter time duration of processes d[5]: 1

Transition/process durations are: 2 1 3 4 1

Enter Initial Marking m[1]: 4  
Enter Initial Marking m[2]: 1  
Enter Initial Marking m[3]: 0  
Enter Initial Marking m[4]: 1  
Enter Initial Marking m[5]: 0  
Enter Initial Marking m[6]: 1  
Enter Initial Marking m[7]: 0  
Enter Initial Marking m[8]: 1  
Enter Initial Marking m[9]: 0  
Enter Initial Marking m[10]: 1  
Enter Initial Marking m[11]: 0

Initial marking is: 4 1 0 1 0 1 0 1 0 1 0

(4 stand for the number of parts to be produced)

How long the system has to be simulated?

Please give time units: 25

➤ **OUT PUT :**

TIME: 0  
MARKING: 4 1 0 1 0 1 0 1 0 1 0  
MACHINE STATUS: 1 0 0 0 0  
PROCESSING TIME: 2 0 0 0 0  
TOTAL ELAPSED TIME: 0 0 0 0 0

TIME: 1  
MARKING: 4 1 0 1 0 1 0 1 0 1 0  
MACHINE STATUS: 1 0 0 0 0  
PROCESSING TIME: 1 0 0 0 0  
TOTAL ELAPSED TIME: 1 0 0 0 0

TIME: 2  
MARKING: 3 1 1 1 0 1 0 1 0 1 0  
MACHINE STATUS: 1 1 0 0 0  
PROCESSING TIME: 2 1 0 0 0  
TOTAL ELAPSED TIME: 2 0 0 0 0

TIME: 3  
MARKING: 3 1 0 1 1 1 0 1 0 1 0  
MACHINE STATUS: 1 0 1 0 0  
PROCESSING TIME: 1 0 3 0 0  
TOTAL ELAPSED TIME: 3 1 0 0 0

TIME: 4  
MARKING: 2 1 1 1 1 1 0 1 0 1 0  
MACHINE STATUS: 1 1 1 0 0  
PROCESSING TIME: 2 1 2 0 0  
TOTAL ELAPSED TIME: 4 1 1 0 0

TIME: 5  
MARKING: 2 1 0 1 2 1 0 1 0 1 0  
MACHINE STATUS: 1 0 1 0 0  
PROCESSING TIME: 1 0 4 0 0  
TOTAL ELAPSED TIME: 5 2 2 0 0

TIME: 6  
MARKING: 1 1 1 1 1 1 1 1 0 1 0  
MACHINE STATUS: 1 1 1 1 0  
PROCESSING TIME: 2 1 6 4 0  
TOTAL ELAPSED TIME: 6 2 3 0 0

TIME: 7  
MARKING: 1 1 0 1 2 1 1 1 0 1 0  
MACHINE STATUS: 1 0 1 1 0  
PROCESSING TIME: 1 0 8 3 0  
TOTAL ELAPSED TIME: 7 3 4 1 0

TIME: 8  
MARKING: 0 1 1 1 2 1 1 1 0 1 0  
MACHINE STATUS: 0 1 1 1 0  
PROCESSING TIME: 0 1 7 2 0  
TOTAL ELAPSED TIME: 8 3 5 2 0

TIME: 9  
MARKING: 0 1 0 1 2 1 2 1 0 1 0  
MACHINE STATUS: 0 0 1 1 0  
PROCESSING TIME: 0 0 9 5 0  
TOTAL ELAPSED TIME: 8 4 6 3 0

TIME: 10  
MARKING: 0 1 0 1 2 1 1 1 1 1 0  
MACHINE STATUS: 0 0 1 1 1  
PROCESSING TIME: 0 0 8 8 1  
TOTAL ELAPSED TIME: 8 4 7 4 0

TIME: 11  
MARKING: 0 1 0 1 2 1 1 1 0 1 1  
MACHINE STATUS: 0 0 1 1 0  
PROCESSING TIME: 0 0 7 7 0  
TOTAL ELAPSED TIME: 8 4 8 5 1

TIME: 12  
MARKING: 0 1 0 1 1 1 2 1 0 1 1  
MACHINE STATUS: 0 0 1 1 0  
PROCESSING TIME: 0 0 9 10 0  
TOTAL ELAPSED TIME: 8 4 9 6 1

TIME: 13  
MARKING: 0 1 0 1 1 1 2 1 0 1 1  
MACHINE STATUS: 0 0 1 1 0  
PROCESSING TIME: 0 0 8 9 0  
TOTAL ELAPSED TIME: 8 4 10 7 1

TIME: 14  
MARKING: 0 1 0 1 1 1 1 1 1 1 1  
MACHINE STATUS: 0 0 1 1 1  
PROCESSING TIME: 0 0 7 12 1  
TOTAL ELAPSED TIME: 8 4 11 8 1

TIME: 15  
MARKING: 0 1 0 1 0 1 2 1 0 1 2  
MACHINE STATUS: 0 0 0 1 0  
PROCESSING TIME: 0 0 0 15 0  
TOTAL ELAPSED TIME: 8 4 12 9 2

TIME: 16  
MARKING: 0 1 0 1 0 1 2 1 0 1 2  
MACHINE STATUS: 0 0 0 1 0  
PROCESSING TIME: 0 0 0 14 0  
TOTAL ELAPSED TIME: 8 4 12 10 2

TIME: 17  
MARKING: 0 1 0 1 0 1 2 1 0 1 2  
MACHINE STATUS: 0 0 0 1 0  
PROCESSING TIME: 0 0 0 13 0  
TOTAL ELAPSED TIME: 8 4 12 11 2

TIME: 18  
MARKING: 0 1 0 1 0 1 1 1 1 1 2  
MACHINE STATUS: 0 0 0 1 1  
PROCESSING TIME: 0 0 0 16 1  
TOTAL ELAPSED TIME: 8 4 12 12 2

TIME: 19  
MARKING: 0 1 0 1 0 1 1 1 0 1 3  
MACHINE STATUS: 0 0 0 1 0  
PROCESSING TIME: 0 0 0 15 0  
TOTAL ELAPSED TIME: 8 4 12 13 3

TIME: 20  
MARKING: 0 1 0 1 0 1 1 1 0 1 3  
MACHINE STATUS: 0 0 0 1 0  
PROCESSING TIME: 0 0 0 14 0  
TOTAL ELAPSED TIME: 8 4 12 14 3

TIME: 21  
MARKING: 0 1 0 1 0 1 1 1 0 1 3  
MACHINE STATUS: 0 0 0 1 0  
PROCESSING TIME: 0 0 0 13 0  
TOTAL ELAPSED TIME: 8 4 12 15 3

TIME: 22  
 MARKING: 0 1 0 1 0 1 0 1 1 1 3  
 MACHINE STATUS: 0 0 0 0 1  
 PROCESSING TIME: 0 0 0 0 1  
 TOTAL ELAPSED TIME: 8 4 12 16 3

TIME: 23  
 MARKING: 0 1 0 1 0 1 0 1 0 1 4  
 MACHINE STATUS: 0 0 0 0 0  
 PROCESSING TIME: 0 0 0 0 0  
 TOTAL ELAPSED TIME: 8 4 12 16 4

\*\*\*\*\*Program terminated \*\*\*\*\*

The Bottleneck Machine is: M4  
 Machine Utilization of m[1] is: 18.18%  
 Machine Utilization of m[2] is: 9.09%  
 Machine Utilization of m[3] is: 27.27%  
 Machine Utilization of m[4] is: 36.36%  
 Machine Utilization of m[5] is: 9.09%  
 The Cycle Time is : 5.75 hr  
 The output rate is: 0.17

End of sequence.

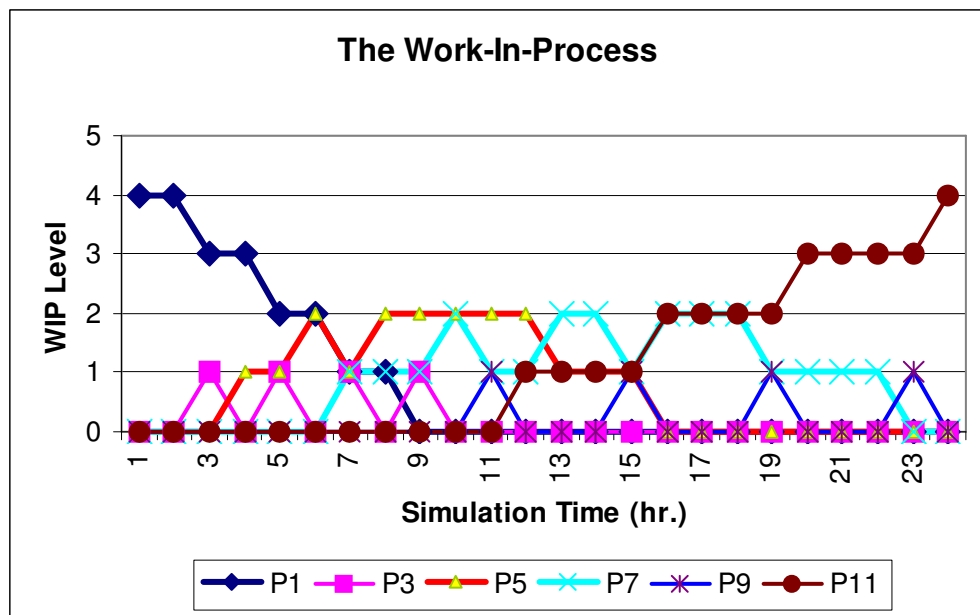


Figure 5-5 The WIP at Input and Output buffers of each machine

Where: P1, P3, P5, P7, and P9 are input buffers of M1, M2, M3, M4, and M5 respectively; and P11 is output buffer of M5.

## 2- Input and Out put for nozzle production

### ➤ INPUT:

Select Mode of Operation:

Figure 5-  Deterministic Mode

Figure 6-  Stochastic Mode

: 1

Enter number of Machine/Processor: 2

Number of pre and post conditions: 5

Enter the Input matrix inm[1][1]: 1

Enter the Input matrix inm[1][2]: 1

Enter the Input matrix inm[1][3]: 0

Enter the Input matrix inm[1][4]: 0

Enter the Input matrix inm[1][5]: 0

Enter the Input matrix inm[2][1]: 0

Enter the Input matrix inm[2][2]: 0

Enter the Input matrix inm[2][3]: 1

Enter the Input matrix inm[2][4]: 1

Enter the Input matrix inm[2][5]: 0

The input matrix is :

$$\begin{array}{c|ccccc|} 1 & 1 & 0 & 0 & 0 & \\ \hline 0 & 0 & 1 & 1 & 0 & \end{array}$$

Enter output Matrix otm[1][1]: 0

Enter output Matrix otm[1][2]: 1

Enter output Matrix otm[1][3]: 1

Enter output Matrix otm[1][4]: 0

Enter output Matrix otm[1][5]: 0

Enter output Matrix otm[2][1]: 0

Enter output Matrix otm[2][2]: 0

Enter output Matrix otm[2][3]: 0

Enter output Matrix otm[2][4]: 1

Enter output Matrix otm[2][5]: 1

The output matrix is :

$$\begin{array}{c|ccccc|} 0 & 1 & 1 & 0 & 0 & \\ \hline 0 & 0 & 0 & 1 & 1 & \end{array}$$

Enter time duration of processes d[1]: 2

Enter time duration of processes d[2]: 3

Transition/process durations are: 2 3

Enter Initial Marking m[1]: 4  
Enter Initial Marking m[2]: 1  
Enter Initial Marking m[3]: 0  
Enter Initial Marking m[4]: 1  
Enter Initial Marking m[5]: 0

Initial marking is: 4 1 0 1 0

*(4 stand for the number of parts to be produced)*

How long the system has to be simulated?

Please give time units:15

➤ **OUTPUT:**

TIME: 0  
MARKING: 4 1 0 1 0  
MACHINE STATUS: 1 0  
PROCESSING TIME: 2 0  
TOTAL ELAPSED TIME: 0 0

TIME: 1  
MARKING: 4 1 0 1 0  
MACHINE STATUS: 1 0  
PROCESSING TIME: 1 0  
TOTAL ELAPSED TIME: 1 0

TIME: 2  
MARKING: 3 1 1 1 0  
MACHINE STATUS: 1 1  
PROCESSING TIME: 2 3  
TOTAL ELAPSED TIME: 2 0

TIME: 3  
MARKING: 3 1 1 1 0  
MACHINE STATUS: 1 1  
PROCESSING TIME: 1 2  
TOTAL ELAPSED TIME: 3 1

TIME: 4  
MARKING: 2 1 2 1 0  
MACHINE STATUS: 1 1  
PROCESSING TIME: 2 4  
TOTAL ELAPSED TIME: 4 2

TIME: 5  
MARKING: 2 1 1 1 1  
MACHINE STATUS: 1 1  
PROCESSING TIME: 1 3  
TOTAL ELAPSED TIME: 5 3

TIME: 6  
MARKING: 1 1 2 1 1  
MACHINE STATUS: 1 1  
PROCESSING TIME: 2 5  
TOTAL ELAPSED TIME: 6 4

TIME: 7  
MARKING: 1 1 2 1 1  
MACHINE STATUS: 1 1  
PROCESSING TIME: 1 4  
TOTAL ELAPSED TIME: 7 5

TIME: 8  
MARKING: 0 1 2 1 2  
MACHINE STATUS: 0 1  
PROCESSING TIME: 0 3  
TOTAL ELAPSED TIME: 8 6

TIME: 9  
MARKING: 0 1 2 1 2  
MACHINE STATUS: 0 1  
PROCESSING TIME: 0 2  
TOTAL ELAPSED TIME: 8 7

TIME: 10  
MARKING: 0 1 2 1 2  
MACHINE STATUS: 0 1  
PROCESSING TIME: 0 1  
TOTAL ELAPSED TIME: 8 8

TIME: 11  
MARKING: 0 1 1 1 3  
MACHINE STATUS: 0 1  
PROCESSING TIME: 0 0  
TOTAL ELAPSED TIME: 8 9

TIME: 12  
MARKING: 0 1 1 1 3  
MACHINE STATUS: 0 1  
PROCESSING TIME: 0 0  
TOTAL ELAPSED TIME: 8 10

TIME: 13  
MARKING: 0 1 1 1 3  
MACHINE STATUS: 0 1  
PROCESSING TIME: 0 0  
TOTAL ELAPSED TIME: 8 11

TIME: 14  
MARKING: 0 1 0 1 4  
MACHINE STATUS: 0 0  
PROCESSING TIME: 0 0  
TOTAL ELAPSED TIME: 8 1

\*\*\*\*\*Program terminated\*\*\*\*\*

The Bottleneck Machine is: M2  
 Machine Utilization of m[1] is: 40.00%  
 Machine Utilization of m[2] is: 60.00%  
 The Cycle Time is : 3.5 hr  
 The output rate is: 0.28

End of sequence

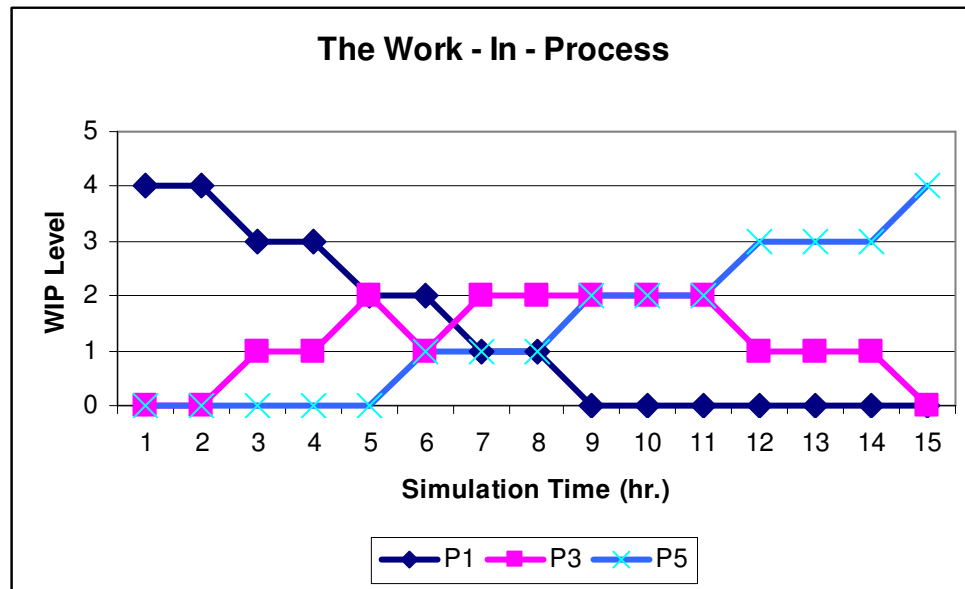


Figure 5-6 The WIP at Input and Output buffers of each machine

Where: P1 and P3 are input buffers of M1 and M2 respectively; and P5 is output buffer of M2.

The outputs of the simulation runs show that how poor the existing performance of the factory is; as it has been already mentioned earlier, the data that are used for simulation are directly taken from the factory. Hence the outputs show the actual performance of the factory. Therefore, the information made available by the out puts gives an opportunity to the production manager or process planner or any concerned personnel to look for alternatives and ways in order to improve the performance.

## **CHAPTER SIX**

### **6. CONCLUSIONS AND RECOMMENDATIONS**

#### **6.1 Conclusions**

Petri nets are being increasingly studied world wide by several researchers and industrial practitioners to address a variety of issues related to manufacturing from their specification, modeling, designing, performance analysis, and scheduling to real-time control and monitoring. Although PNs and related technologies have been successfully applied in European and Japanese industries, its application in third world countries, like Ethiopia, where traditional production systems are being employed is not yet practical. However, by demonstrating the efficiencies of PN-aided approaches to solving problems in manufacturing, industrial application of PNs can be promoted. Motivated by these facts, the present work discusses the application of PNs and proposes it as a tool and methodology for modeling simulation and performance analysis of manufacturing systems based on the previous related works, for the factory to loose its competitiveness in the market. Then, based on the fact that PNs are suitable to solve variety of problems in manufacturing systems, it presents the application of PNs as integrated tool and methodology in manufacturing systems.

In this work, simulation and performance analysis is found to be the potential area for exploring both theoretical and practical application of PNs. By studying the various problems of AEC in the stated area with PNs this work makes an attempt to analyze performance of the factory. Although the research best works in automated manufacturing area, its contribution in traditional manufacturing system like that of AEC is significant in the study of the main factors that attribute to the said problems of the factory such as un able to meet due date, big variation between estimated and actual production/machining time, under/over cost estimation and so on. Therefore, by making use of this research work it is possible to avoid these and other related problems.

The present work widens the knowledge of PN literature among our engineers and managers who are responsible for design and implementation of modern manufacturing system and initiates for further work in this area.

## **6.2 Recommendations**

The purpose of this work is to analyze the overall manufacturing performance of the factory, indicate the key factors that contributed to the poor performance, create awareness for the need of continuous performance analysis, and finally implement or use the proposed methodology to improve the manufacturing performance by avoiding/minimizing the short comings of the factory.

This research work proposes a methodology that can be implemented or practiced with existing layout, facility and data of the production system. The only requirement is having engineers who are familiar with PN modeling and capable of operating the software. Therefore, the organization will be benefited a lot by the implementation of the proposed methodology.

In addition to the implementation of the proposed methodology, there are many other key issues that the organization needs to revise or consider for otherwise the expected improvement or change may remain to be a nightmare. One of the issues that require serious attention and consideration is the traditional manufacturing practice of the factory, which must be changed. This is the basic factor that comprises many other related ones, which are attributed to the poor performance of the factory. Amongst the best illustrations is the production/machining time. In the factory the machining time of various operations is estimated based on personal experience of individuals. It has been observed that in each and every machining operation there exists variation between the estimated and actual times. It is this time, which is taken as a base for production cost estimation and resource allocation. As a matter of fact this factor has a massive impact on the profitability of the factory. Although the problem seems significant, its solution is nothing but the real technological or engineering application of calculation, which is used to compute the exact machining time. For all machining operations, there are readily available formulae, which are developed through series of experiments and researches made for many years. Thus use of the formulae to calculate machine time will reduce the current variance between the estimated and actual operation time, the probable loss of the factory, and the due date problem as well. The calculation of process time of various operations should consider the present state of existing facilities and worker skill and other related factors of the factory. Unless he suggested solution may not work.

Finally, the following recommendations are made based on the findings of the study:

- The factory should revise its organizational structure, must strive to be competent, and create conducive environment for improved productivity by fulfilling the necessary infrastructures.
- Process planning should be done according to its technological principle and procedure.
- Resource (human and equipment /facility) utilization of this factory is at its lowest stage. This is the other key factor that has direct relation with performance and has to be improved.
- Motivation of workers and bridging the gap between the lower level workers and the management is the other factor that needs attention.
- It is necessary to continuously train workers in order to change the so long existed traditional production system and to cope up the dynamic technological change taking place from day to day.
- The factory should follow aggressive market strategy and hence its strategies starting from the top (strategic plan) to the operational level plan should be revised in order to achieve the goals and objectives of the factory.
- Integration of various departments and workshops is also necessary.
- The traditional market and demand forecasting must be replaced by the scientific techniques.

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## Appendix

### A. Input data for *deterministic* part of the simulation (for PN model in fig. 5-3)

Select Mode of Operation:

1. Deterministic Mode
2. Stochastic Mode

**: 1**

Enter number of Machine/Processor: **2**

Number of pre and post conditions: **5**

Enter the Input matrix  $inm[1][1]$ : **1**

Enter the Input matrix  $inm[1][2]$ : **1**

Enter the Input matrix  $inm[1][3]$ : **0**

Enter the Input matrix  $inm[1][4]$ : **0**

Enter the Input matrix  $inm[1][5]$ : **0**

Enter the Input matrix  $inm[2][1]$ : **0**

Enter the Input matrix  $inm[2][2]$ : **0**

Enter the Input matrix  $inm[2][3]$ : **1**

Enter the Input matrix  $inm[2][4]$ : **1**

Enter the Input matrix  $inm[2][5]$ : **0**

The input matrix is:

$$\begin{array}{c|ccccc|} 1 & 1 & 0 & 0 & 0 & \\ \hline 0 & 0 & 1 & 1 & 0 & \end{array}$$

Enter output Matrix  $otm[1][1]$ : **0**

Enter output Matrix  $otm[1][2]$ : **1**

Enter output Matrix  $otm[1][3]$ : **1**

Enter output Matrix  $otm[1][4]$ : **0**

Enter output Matrix  $otm[1][5]$ : **0**

Enter output Matrix  $otm[2][1]$ : **0**

Enter output Matrix  $otm[2][2]$ : **0**

Enter output Matrix  $otm[2][3]$ : **0**

Enter output Matrix  $otm[2][4]$ : **1**

Enter output Matrix  $otm[2][5]$ : **1**

The output matrix is:

$$\begin{array}{c|ccccc|} 0 & 1 & 1 & 0 & 0 & \\ \hline 0 & 0 & 0 & 1 & 1 & \end{array}$$

Enter Time duration  $d[1]$ : **2**

Enter Time duration  $d[2]$ : **1**

Transition/process durations are: **2 1**

Enter Initial Matking m[1]: **8**  
Enter Initial Matking m[2]: **1**  
Enter Initial Matking m[3]: **0**  
Enter Initial Matking m[4]: **1**  
Enter Initial Matking m[5]: **0**

Initial marking is: 8 1 0 1 0

How long the system has to be simulated?

Please give time units:**15**

**B. Input data for *stochastic* part of the simulation** (for PN model in fig. 5-3)

1. Deterministic Mode
2. Stochastic Mode

: **2**

Enter number of Machine/Processor: **2**  
Number of pre and post conditions: 5

Enter the Input matrix inm[1][1]: **1**  
Enter the Input matrix inm[1][2]: **1**  
Enter the Input matrix inm[1][3]: **0**  
Enter the Input matrix inm[1][4]: **0**  
Enter the Input matrix inm[1][5]: **0**

Enter the Input matrix inm[2][1]: **0**  
Enter the Input matrix inm[2][2]: **0**  
Enter the Input matrix inm[2][3]: **1**  
Enter the Input matrix inm[2][4]: **1**  
Enter the Input matrix inm[2][5]: **0**

The input matrix is :

	1	1	0	0	0	
	0	0	1	1	0	

Enter output Matrix otm[1][1]: **0**  
Enter output Matrix otm[1][2]: **1**  
Enter output Matrix otm[1][3]: **1**  
Enter output Matrix otm[1][4]: **0**  
Enter output Matrix otm[1][5]: **0**

Enter output Matrix otm[2][1]: **0**  
Enter output Matrix otm[2][2]: **0**  
Enter output Matrix otm[2][3]: **0**  
Enter output Matrix otm[2][4]: **1**  
Enter output Matrix otm[2][5]: **1**

The output matrix is :

$$\begin{array}{c|ccccc|} 0 & 1 & 1 & 0 & 0 & | \\ 0 & 0 & 0 & 1 & 1 & | \end{array}$$

1. Lathe.
2. Milling.
3. Grinder.
4. Heat Treatment.
5. Slotting.

Select the machine number: **1**

The Probability of machine

4.00	2	0.13	0.13
6.00	4	0.27	0.40
7.00	3	0.20	0.60
8.00	5	0.33	0.93
12.00	1	0.07	1.00
1	0.0800		

Select the machine number: **2**

The Probability of machine

9.00	1	0.09	0.09
10.00	1	0.09	0.18
11.00	2	0.18	0.36
12.00	6	0.55	0.91
13.00	1	0.09	1.00
2	0.2900		

Transition/process durations are: 4 11

Enter Initial Marking m[1]: **8**

Enter Initial Marking m[2]: **1**

Enter Initial Marking m[3]: **0**

Enter Initial Marking m[4]: **1**

Enter Initial Marking m[5]: **0**

Initial marking is: 8 1 0 1 0

How long the system has to be simulated?

Please give time units: **20**

***N.B Numbers written in bold are those to be entered by the user.***