EFFECT OF IMPROVING ENERGY EFFICIENCY ON SYSTEM RELIABILITY

A THESIS

submitted by

SHOURI P. V.

under the guidance of

Dr. SREEJITH P. S.

in partial fulfilment of the requirements for the award of the degree

of

DOCTOR OF PHILOSOPHY
(Faculty of Engineering)

DIVISION OF MECHANICAL ENGINEERING
SCHOOL OF ENGINEERING
COCHIN UNIVERSITY OF SCIENCE & TECHNOLOGY
COCHIN - 682 022

MARCH 2007

DECLARATION

I hereby declare that the thesis entitled **"EFFECT OF IMPROVING ENERGY EFFICIENCY ON SYSTEM RELIABILITY"** submitted by me to the Cochin University of Science and Technology, Cochin in partial fulfillment of the requirements for the award of the degree of Doctor of Philosophy have not been submitted and will not be submitted to any other University or Institute for the award of any degree, diploma, associateship, fellowship or other similar title of recognition.

Cochin,
01-03-2007

P.v. Shouri

Shouri P.V.
Ph.D Research Scholar (Full Time),
School of Engineering,
Cochin University of Science and
Technology, Cochin 682022.

THESIS CERTIFICATE

This is to certify that the thesis entitled **"EFFECT OF IMPROVING ENERGY EFFICIENCY ON SYSTEM RELIABILITY"** submitted by **Shouri P.V.** to the Cochin University of Science and Technology, Cochin in partial fulfilment of the requirements for the award of the degree of Doctor of Philosophy is a bonafide record of research work carried out by him under my supervision. The contents of this thesis have not been submitted and will not be submitted to any other University or Institute for the award of any degree.

Cochin,
Date: 03.03.2007.

Dr. Sreejith P.S.
Principal and Professor & Head of
Mechanical Engineering (Research Guide),
School of Engineering,
Cochin University of Science and
Technology, Cochin 682 022.

ACKNOWLEDGEMENT

I wish to express my sincere gratitude to Dr. Sreejith P.S., Principal and Professor & Head of Mechanical Engineering, School of Engineering, Cochin University of Science and Technology for his guidance, help and encouragement throughout the period of this thesis work. He has been a friend, a teacher and a guide to me.

I thank all the faculty members of School of Engineering for the cooperation extended towards me.

I also thank Sri. Azeem K., Assistant Manager (Central Engineering Service), Kerala Chemicals and Proteins Ltd., Cochin, Kerala, Sri. Lal Varghese, Assistant Engineer (Boiler Operations), Travancore Titanium Products Ltd., Trivandrum, Kerala and Sri. Rajan A.M., Managing Director, Cryptoms Confectioners Pvt. Ltd., Idukki, Kerala for helping me in securing the data from industries.

I also wish to place on record my sincere thanks to my parents and family for the cooperation and support extended towards me.

Finally I wish to place on record my sincere thanks to one and all who helped me in the completion of this work.

Shouri P.V.

ABSTRACT

Key words: Availability; Breakeven availability; Reliability; Reliability allocation; Process system value

In the present scenario of energy demand overtaking energy supply top priority is given for energy conservation programs and policies. Most of the process plants are operated on continuous basis and consumes large quantities of energy. Efficient management of process system can lead to energy savings, improved process efficiency, lesser operating and maintenance cost, and greater environmental safety. Reliability and maintainability of the system are usually considered at the design stage and is dependent on the system configuration. However, with the growing need for energy conservation, most of the existing process systems are either modified or are in a state of modification with a view for improving energy efficiency. Often these modifications result in a change in system configuration there by affecting the system reliability. It is important that system modifications for improving energy efficiency should not be at the cost of reliability. Any new proposal for improving the energy efficiency of the process or equipments should prove itself to be economically feasible for gaining acceptance for implementation. In order to arrive at the economic feasibility of the new proposal, the general trend is to compare the benefits that can be derived over the lifetime as well as the operating and maintenance costs with the investment to be made. Quite often it happens that the reliability aspects (or loss due to unavailability) are not taken into consideration. Plant availability is a critical factor for the economic performance evaluation of any process plant.

The focus of the present work is to study the effect of system modification for improving energy efficiency on system reliability. A generalized model for the valuation of process system incorporating reliability is developed, which is used as a tool for the analysis. It can provide an awareness of the potential performance improvements of the process system and can be used to arrive at the change in process system value resulting from system modification. The model also arrives at the pay back of the modified system by taking reliability aspects also into consideration. It is also used to study the effect of various operating parameters on system value. The concept of breakeven availability is introduced and an algorithm for allocation of component reliabilities of the modified process system based on the breakeven system availability is also developed. The model was applied to various industrial situations.

TABLE OF CONTENTS

CHAPTER 2 LITERATURE SURVEY

CHAPTER 3 PROCESS VALUATION MODEL INCORPORATING RELIABILITY

Table of Contents (Contd.)

Table of Contents (Contd.)

LIST OF TABLES

LIST OF FIGURES

List of Figures (Contd.)

NOMENCLATURE

A/P	annual rate given the present value
A_a	achievable availability
A_{BEP}	breakeven availability of the modified process system
A_i	steady state availability
A_m	process system availability before modification
A_o	operational availability
A_S	process system availability after modification
b	pay back period (years)
C	cost of process system components and equipments (Rs)
C_m	cost of modification (Rs)
g	acceleration due to gravity (m/sec^2)
H	system operating hours in a year
i	interest rate
k	expected percentage growth of operating and maintenance cost per year
m	mass flow rate of steam (kg/sec)
MAMT	mean active maintenance time (hours)
MDT	mean down time (hours)
MTBF	mean time between failure (hours)
MTBM	mean time between maintenance operations (hours)
MTTR	mean time to repair (hours)
n	life of the process system in years
O_m	yearly operation and maintenance cost of the process system after modification (Rs)

O_S	yearly operation and maintenance cost of the process system before modification (Rs)
P/A	present value given annual rate
P_f	pumping pressure (kgf/cm^2)
Q_b	energy in the steam at the boiler outlet (kW)
Q_f	energy in the fuel supplied to the boiler (kW)
Q_l	energy loss in the line due to heat dissipation from the surface of the pipe, water loss, steam loss etc (kW)
Q_r	energy in the condensate recovered from the condensate return (kW)
Q_u	theoretical useful energy required to accomplish the given task (kW)
Q_w	energy in the feed water at the boiler inlet (kW)
R	hourly production rate (units/hr)
R(t)	reliability expressed as a function of time
RBD	reliability block diagram
U	unit price of the process output (Rs/unit)
V	process system value (Rs)
V_C	change in process system value (Rs)
Z(t)	failure rate expressed as a function of time
μ	constant mean repair rate (hr $^{-1}$)
Δh	change in enthalpy of the steam between inlet and outlet of the turbine (kJ/kg)
η_b	boiler efficiency
η_g	generator efficiency
η_l	efficiency of the steam line

η_m	efficiency of the pumping system after modification
η_o	overall steam system efficiency
η_r	factor of unrecovered condensate
η_s	efficiency of the pumping system before modification
η_t	turbine efficiency
η_u	useful task efficiency
λ	constant failure rate (hr^{-1})

CHAPTER 1

INTRODUCTION

There are three principal forms of energy used in industrial processes namely electricity, direct-fired heat, and steam. Electricity is used in many different ways, including mechanical drive, heating, and electrochemical reactions. Direct-fired energy directly transfers the heat of fuel combustion to a process. Steam provides process heating, pressure control, mechanical drive, component separation, and is a source of water for many process reactions [United States DOE, 2004]. Industrial energy efficiency has emerged as one of the key issues in developing countries and there is a growing need to bring about improvement in the efficiency of energy use in the industrial sector.

In India the industrial energy consumption is about 40% of the total energy in the country [Ming Yang, 2006]. The studies by Ming Yang [2006] pointed out that electricity tariffs in the industrial sector in India are quite high and this encourages industrial entities to develop captive power plants themselves. This is particularly true where there are power shortages. As a result, small power plants or units have been quickly developed in the industrial sector. The small and decentralized captive power plants, however, are less efficient than the large centralized power plants from the national economy viewpoint. Ming Yang [2006] also brought out the inadequacies in the national energy policy. For instance, one of the industrial concerns that was analyzed imported a second-hand oil fired 2.6 MW cogeneration power facility from Germany. The equipment was made in the 1970s and it had been phased out in Germany in 1993 due to the high cost of operation and environment pollution. The energy efficiency policy and capital investment policies and measures in India did not prevent such old and inefficient equipment being purchased and installed in India.

Steam has many performance advantages that make it an indispensable means of delivering energy. These advantages include low toxicity, ease of transportability, high efficiency, high heat capacity, and low cost with respect to the other alternatives. Steam holds a significant amount of energy on a unit mass basis that can be extracted as mechanical work through a turbine or as heat for process use. Since most of the heat content of steam is stored as latent heat, large quantities of heat can be transferred efficiently at a constant temperature, which is a requirement in many process heating applications. Steam is also used in many direct contact applications. For example, steam is used as a source of hydrogen in steam methane reforming, which is an important process for many chemical and petroleum refining applications. Steam is also used to control the pressures and temperatures of many chemical processes. Other significant applications of steam are to strip contaminants from a process fluid, to facilitate the fractionation of hydrocarbon components, and to dry all types of paper products. The many advantages that are available from steam are reflected in the significant amount of energy that industry uses to generate it. Hence, the focus in majority of the industrial energy conservation programs will be on steam systems. Typical methods for improving the steam system efficiency includes proper insulation of steam lines, use of waste heat recovery devices like economizers and air pre-heaters, return of condensate to boiler, minimizing boiler blowdowns, recovering heat from boiler blowdown, use of vapour recompression to recover low-pressure waste steam, flashing of high-pressure condensate to regenerate low-pressure steam, replacing pressure-reducing valves with backpressure turbo generators, and considering steam turbine drives for rotating equipment.

Measures taken to improve energy conservation can have an adverse impact on system reliability. For example, although heat recovery from flue gas and other wastes reduce flue gas temperature and there by improve steam system efficiency in some cases this may lead to condensation there by creating severe corrosion problems. Similarly, minimizing boiler blow-down can substantially reduce energy losses, as the temperature of the blow-down liquid is the same as that of the steam generated in the boiler. Minimizing blow-down will also reduce make up water and chemical costs. However, this tendency of bringing down the blow-down rate can have adverse effect on reliability of the system, as insufficient blow-down may lead to formation of deposits and there by increase system failures. In order to take care of this automatic blow-down control system can be installed. In this case reliability of this additional element also has to be considered.

Returning hot condensate to the boiler minimizes the requirement of feed water, saves fuel, and chemical treatment costs. However, it calls for reliable condensate pumping system. Failure of condensate removal from the condenser can lead to system failure causing severe process quality problems. It can also lead to piping failure. The increase of number of essential components can only lead to reduction in overall process reliability.

Most of the industrial processes invariably use pumps for transportation of fluids in and out as well as within the plants. Proper sizing of the pump and motor is of utmost importance in minimizing the energy consumption. Pumping configuration also has a bearing on reliability and efficiency. Around 70% of the total electrical energy in the industrial sector is consumed by motors.

It is evident that many opportunities exist for improving energy efficiency of industrial processes. This include replacement of existing components with more efficient ones, adding efficiency- boosting controls to existing components and process modifications. While modifying the process systems for improving energy efficiency, often the focus is on immediate demands of the equipment and the broader issue of how the system parameters affect the equipment is overlooked. Similarly, a common engineering approach is to break a system into subsystems, optimize the design of these subsystems, and assemble these subsystems to form the system. Although this approach is very simple, often the focus is limited to subsystems and does not consider the overall change in system configuration. With the growing importance given for the systems approach, it is necessary to give equal focus on reliability and energy efficiency while a system is modified or redesigned. A systems approach recognizes that process efficiency and reliability are equally important.

Whenever a system is modified for improving energy efficiency there is bound to be a change in either of (1) the process system configuration or (2) the process system components or both #1 and #2. The modification thus affects the failure rate and thereby the system availability and reliability. The present work attempts to find the impact of system modification for improving energy efficiency on process system reliability, with emphasis on steam systems. A generalized tool for process system valuation by incorporating reliability was developed and the tool was used to study the impact of modification on various process plants.

CHAPTER 2

LITERATURE SURVEY

2.1 Introduction

Process industries depend heavily on energy resources to provide fuel and power for the conversion of raw materials into usable products. How efficiently energy is used, as well as the cost and availability of energy, consequently have a substantial impact on the competitiveness and economic health of the manufacturers. More efficient use of energy lowers production costs, conserves limited energy resources, and increases productivity. The more efficient use of energy also has positive impacts on the environment – reductions in fuel use translate directly into fewer emissions of pollutants such as sulfur oxides, nitrogen oxides, and particulates, as well as greenhouse gases such as carbon dioxide.

Energy efficiency can essentially be defined as the effectiveness with which energy resources are converted into usable work. Thermal efficiency is commonly used to measure the efficiency of energy conversion systems. While there are many ways to determine thermal efficiency, it is basically the ratio of net work output to the total heat supplied. Energy efficiency varies dramatically across industries and manufacturing processes, and even between plants manufacturing the same products. Efficiency can be limited by mechanical, chemical, or other physical parameters, or by the age and design of equipment. Operating and maintenance practices also play an important role in deciding the efficiency of a system. Regardless of the reason, less than optimum energy efficiency means that as equipment is used, only a small fraction of the energy is converted to useful work – a major fraction is released as lost energy. In the manufacturing sector, these energy losses amount to several crores of rupees every year. Given this resource and cost perspective, it is clear that increasing the efficiency of energy use could result in substantial benefits to both industry and the nation. Unfortunately, the sheer complexity of the thousands of processes used in the manufacturing sector makes this a daunting task. There are, however, significant opportunities to address energy efficiency in energy systems that are used across many different industries, such as steam generators, onsite power systems, fired heaters, heat exchangers, compressors, motors, pumps, and others. In addressing these issues of energy efficiency, it is important that reliability aspects are also taken into consideration. It is important that these two factors, that is, reliability and energy efficiency should go hand in hand.

2.2 Energy efficiency evaluation tools

The primary sources of energy, such as heavy oil, natural gas and other conventional sources are limited resources formed by geological processes through solar energy accumulation into the earth over millions of years. Because of their fluctuations in reserves and prices and due to the increased costs of power stations, it is very important to consider new measures for energy conservation [Imad & Mahmoud, 2005]. Energy-related problems are likely to become more and more important in the forthcoming millennium. To improve energy-utilization efficiency, people analyze energy-utilization features of a process with the aid of theoretical method of mathematics as well as graphics, etc., and try to find out the location, quantity and reason of energy-loss, e.g. adopting the thermodynamic analysis method graphically [Zheng et al., 2004]. Typical graphical tools used to evaluate the energy utilization efficiencies are the Sankey diagram, also called as the enthalpy flow diagram and the Grassman diagram, also called the exergy-flow diagram [Nobuzawa, 1987]. The energy-utilization situation of the system can be visually understood by the branch and the width of each input and output flow in the Sankey diagram. Similarly, the Grassmann diagram is a graphic analysis tool to show the input and the output relations of the exergy balance. It obviously illustrates the quantities and directions of exergy-flow to evaluate the energy-utilization efficiencies. The energy-utilization diagram was proposed by Ishida et al. [1982]. The diagram not only can be used in heat exchange process, but also in other energy conversion processes, such as chemical reaction, compression, expansion and so on. Ishida [1983] also presented a graphic tool, which is called the thermodynamic compass. Zheng et al. [1986] presented Energy-utilization diagrams for two types of LNG power-generation systems. These graphical thermodynamic analysis methods are all fairly simple and visual. However, they are inadequate in describing the structure characteristics of a process scheme and embodying the energy supply–demand relation between utilities and the energy-consuming processes from the view of process technology, and indicating the energy recovery or utilization relation of the concrete equipment or stream, as well as showing the stream balance relations either, because they do not combine with the process scheme closely. Zheng et al. [2004] proposed a new graphic method that can visually reveal the features of energy transformation and the system losses to find out the energy-utilization shortage and energy-saving opportunities, through describing the energy supply–demand relation between utilities and energy-consumption processes. Studies related with exergy analysis on combustion and energy conversion processes were conducted by Kudo et al [1984], Taniguchi et al. [1984], Fiaschi & Manfrida [1998], Facchini et al. [2000] and Hiroshi et al. [2005].

The pinch technology was proposed by Linnhoff [1979]. This thermodynamic analysis method was suitable for heat-exchange net integration. In 1990s, the pinch analysis was widely used. Though its primary rules are still on thermodynamic basics and the point is still carrying on program study before design, its application expand to many fields, such as design for distillation, heat pumps, turbines, furnaces, and decision-making for process schemes, as well as non-energy target (such as investment, sewage and pollution treatment etc.). It has become a general method of energy integration of processes and utility systems [Gaggioli, 1999].

Tonon et al. [2006] presented an effective tool for evaluating the performance of energy conversion processes from different points of view. A set of indicators that can support decision-making on energy conversion were presented that include:

First Law efficiency, which evaluates how the energy content of input resources (both renewable and non-renewable) is exploited using first law balances.

Raw energy conversion coefficient, which quantifies the level of utilization of raw resources (non-renewable resources, fossil fuels). Its numerical value can range between first law efficiency (no renewable energy used) and + ∞ (best use, no raw energy used at all). In comparison with first law efficiency, raw energy conversion coefficient highlights how much raw energy can potentially be saved if renewables are substituted for fossil fuels to get the same products.

Second Law efficiency, which evaluates system performance in converting input exergy ('fuel' exergy) into exergy associated with the delivered products.

Potential second law efficiency, which assesses the potential additional exergy efficiency deriving from exploiting the outlet flows that exist as streams but are not considered as useful products and effectively used. These products are normally useful only if particular conditions occur (consider, for example, the heat released with flue gases when low temperature heat is not needed nearby).

Profit index, which provides a direct measure of the investment performance by measuring the profit associated with the plant operation at the end of the economic life referred to the initial investment.

Internal rate of return, which assesses the ability to report profits. It expresses the value of the discount rate at which the investment involves no economic benefit. The greater this value, the more competitive the investment.

Cost of products, which determines the efficiency in using the economic resources to get the products. In order to compare different products (heat and electricity for example), the cost is expressed on exergy basis.

Exergo-economic factor, which compares the plant capital cost against the cost of the irreversibilities linked with the process. In fact, the latter involves increased amounts of energy and material (and thus increased costs) in order to get the same products, if compared with ideal processes. In principle, the exergo-economic factor may vary between 0 and 1.

2.3 Energy conservation in steam systems

A major fraction of the energy consumption in process industries is related with steam systems. A steam system consists of two main units: the steam generator or boiler and the load circuit. Fig. 2.1 gives a schematic of the steam circuit. Improving the efficiency of steam systems alone will provide substantial benefits to the industry. A great deal of information on the generation and utilization of steam, accumulated over the years, is available in the literature. Typically, O'Callaghan [1993] has provided a detailed checklist of measures for control of energy consumption in steam systems. Estop & Croft [1990] has highlighted energy conservation techniques for steam systems for heat and power applications. Equipment manufacturers like Babcock and Wilcox Company [1978]

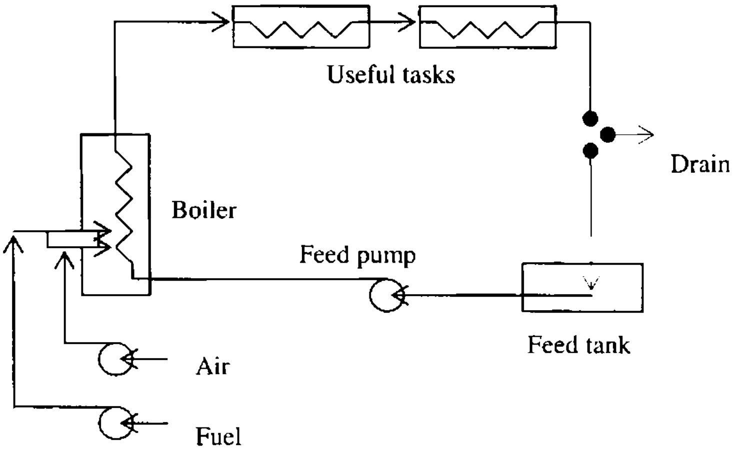

Figure 2.1 Schematic of a steam system

have also documented their experience on the production and use of steam. Based on the above experiences, the factors affecting steam circuit efficiency can be qualitatively classified as follows:

a) Boiler

Combustion

1) Furnace pressure (draft)
2) Air to fuel ratio
3) Atomization efficiency
4) Turbulence (mixing)
5) Furnace temperature
6) Effectiveness of controls

Heat transfer

1) Water composition
2) Flue gas side resistance
3) Geometry/view factor
4) Area of heat transfer

b) Load circuit

Heat transfer

1) Area of heat transfer
2) Thermal resistance on the water-steam side
3) Steam quality

Dispersion

1) Line leakage
2) Thermal dispersion
3) Pressure drop
4) Loss through steam traps
5) Loss through deaerator

Condensate/liquid return

1) Filtered return for contaminated liquid
2) Direct return
3) Presence of condensate polishing unit

Siddhartha Bhatt [2000] proposed a method for determining the overall efficiency or circuit efficiency of the steam systems. The circuit efficiency is defined as the product of the various sub-system efficiencies. By doing so, losses and efficiencies of each segment in the system can be determined independently. This would provide a clue as to where to act on improving the energy efficiency of the system.

The overall steam system efficiency is given by

$$\eta_o = \frac{\eta_b \eta_l \eta_u}{\eta_r} \tag{2.1}$$

The efficiency of the boiler, steam line, useful task and the factor of unrecovered condensate can be obtained as

$$\eta_b = \frac{Q_b - Q_w}{Q_f} \tag{2.2}$$

$$\eta_l = \frac{Q_b - Q_l}{Q_b} \tag{2.3}$$

$$\eta_u = \frac{Q_u}{Q_b - Q_l} \tag{2.4}$$

$$\eta_r = \frac{Q_b - Q_r}{Q_b} \tag{2.5}$$

Ideally, a closed loop feedback control of the useful load by the steam generator is desirable wherein the steam supply responds to the rapid fluctuation in the useful task requirements. In the absence of accurate tracking of the tasks due to lack of communication between the source (steam) and the loads (end tasks), steam is wasted and the various losses will increase thereby increasing the fuel consumption.

A boiler should always be supplied with more combustion air than is theoretically required, in order to ensure complete combustion and safe operation. If the air rate is too low, there will be a rapid build up of carbon monoxide in the flue gas and, in extreme cases, smoke will be produced (i.e. unburned carbon particles). At the same time, boiler efficiency is very dependent on the excess air rate. Excess air should be kept at the lowest practical level to reduce the quantity of unneeded air that is heated and exhausted at the stack temperature [West, 2002]. Therefore, the excess air should be optimized to increase the system efficiency. In order to complete combustion, the desired air flow in a fan is determined by the employment of one of the following:

a) Inlet damper control

b) Inlet vane control

c) Variable speed control

Engin [2004] presented a study on energy conservation opportunities with a variable speed controller in a boiler house. The modern boiler systems are designed, equipped and practiced with the described method at present time. It is particularly effective when operating conditions call for frequent low load periods [Ronald, 1997]. The study also indicated that a reduction in excess air also tends to decrease the stack gas temperature. This is primarily due to the higher flame temperature, which improves radiation heat transfer rates in the boiler.

The exit flue gas temperature of a conventional boiler is usually higher than 150°C, sometimes as high as 200°C, to avoid low temperature corrosion. At such temperatures, the water vapor entrained in the flue gases does not condense, and the latent heat cannot be reclaimed, which leads to a considerable heat loss. Since the 1970s, condensing boilers have been developed and have found wide applications in Europe and North America. In such a boiler, the exit flue gas is reduced to such a low temperature that the water vapour can be condensed, and the latent heat released can be recovered. As such, the thermal efficiency of the boiler can be significantly increased. Reported works in this area are from Field [1974], Noir & Houlmann [1982], Gordon [1983], Thomson [1983], Streatfield [1984], Thorn [1987] and Shook [1991]. If both sensible heat and latent heat can be recovered by adding a condensing heat exchanger, the efficiency of the boiler can be increased by as much as 10%. Dann [1984] concluded in his paper that the potentially high operating efficiencies offered by condensing boilers can be achieved in practice, and this will ensure that for both new and replacement central heating installations, the condensing boiler will provide substantial savings in running costs when compared to the more conventional boiler. Most of the energy saving benefit of using condensing boilers can be achieved without recourse to excessive additional heat emitter surface or sophisticated controls. However, further developments in systems and controls for these appliances should be performed, and optimization of such schemes is necessary. The investigation of Searle & Shiret [1986] and Pickup [1983] showed that many parameters of design and installation influence the performance of condensing boilers in the field. These parameters include pipe work design, controls, hot water cylinder design and boiler and system sizing, but the system designs for high efficiency condensing boilers do not need to be very different from current good practice for existing non-condensing boilers. Defu et al. [2004] presented the recoverable heat and the efficiency improvement potential of different heat recovery schemes at various exit flue gas temperatures based on combustion and heat transfer calculations. The payback period method has been used to analyze the feasibility of retrofitting a conventional gas fired boiler into a condensing boiler in a heating system. The results show that the most economical exit flue gas temperature is 40-55°C when a conventional natural gas fired boiler is retrofitted into a condensing boiler simply by adding a condensing heat exchanger.

2.4 Energy analysis and payback

Several methods have been suggested to perform analyses of energy conversion systems and supply information from different viewpoints. In the area of energy investigations, especially worth mentioning are the Life cycle assessment (LCA) method presented by Valero [1998], its exergetic version ExLCA proposed by Cornelissen et al. [1999] and the thermoeconomic theory presented by Lazzaretto et al. [1998], Lozano & Valero [1993] and Tsatsaronis & Winhold [1985]. This was further extended to include environmental implications by Badino & Baldo [1998]. The cumulative exergy cost accounting (CExC) was proposed by Szargut [1999], the extended exergy accounting (EEA) by Sciubba [1999], the environomic theory by Von Spakovsky & Frangopoulos [1993] and the emergy accounting by Odum [1995].

Researchers at Lawrence Berkeley National Laboratory have used life-cycle costing in United States Department of Energy's rulemaking for residential central air conditioners [Rosenquist, 2002]. The life-cycle cost consists of two main components: (1) the first cost of buying and installing equipment, and (2) the operating costs summed over the lifetime of the equipment, discounted to the present.

$$Life-cycle\cos t = installation\cos t + \frac{\sum_{n=1}^{lifetime} operating\cos t}{(1+i)^n} \tag{2.6}$$

Recently the United States department of energy initiated a rulemaking process to consider whether to amend the existing energy efficiency standards for residential furnaces and boilers. The approach involves comparing the total life-cycle cost (LCC) of owning and operating a more efficient appliance with the LCC for a baseline design. James Lutz et al. [2006] presented the method used to conduct the LCC analysis and also presented the estimated change in LCC associated with more energy-efficient equipment. The LCC calculated in this analysis expresses the costs of installing and operating a furnace or boiler for its lifetime starting in the year 2012 - the year a new standard may take effect. The analysis also calculated the payback period for energy-efficiency design options. The pay back period represents the number of years of operation required to pay for the increased efficiency features. It is the change in purchase expense due to an increased efficiency standard divided by the change in annual operating cost that results from increased efficiency.

The payback period equation is expressed as

$$Payback_{option} = \frac{Equipment\cos t_{option} - Equipment\cos t_{base}}{Operation\cos t_{base} - Operation\cos t_{option}} \tag{2.7}$$

where, base is the base case design, and option is the design option being considered.

Lekov et al. [2003] also presented payback period calculations for furnaces and boilers based on the United States department of energy test procedure. The test procedure uses specific, prescribed values to calculate annual energy consumption. At the time the test procedure was written, these values were considered to be relatively typical of conditions in US homes.

2.5 Reliability and availability

Process availability is a critical driver for the economic performance of a production plant. Over the years efforts have been made to address plant reliability and maintainability issues at the conceptual stage of design so as to improve the plant availability at the operational stage [Vassiliadis & Pistikopoulos, 1999; Grievink et al., 1993]. The plant/unit availability can be divided into several subtypes: operational, achievable and inherent. For a plant, the operational availability reflects the system availability considering both unplanned and planned maintenance time as well as time lost through operational logistics and administration. An achievable availability reflects the availability considering unplanned and planned maintenance time. The inherent or steady state availability of a plant measures the availability to be expected when reflecting unscheduled (corrective) maintenance only. Ireson [1996] defines these frequently-used terms:

$$\text{Steady state availability, } A_i = \frac{MTBF}{MTBF + MTTR} \tag{2.8}$$

$$\text{Achievable availability, } A_a = \frac{MTBM}{MTBM + MAMT} \tag{2.9}$$

$$\text{Operational availability, } A_o = \frac{MTBM}{MTBM + MDT} \tag{2.10}$$

where, MTBF, MTTR, MTBM, MAMT and MDT refers to mean time between failure, mean time to repair, mean time between maintenance operations, mean active maintenance time, and mean down time respectively.

Davidson [1998] pointed out three factors to achieve growing availability: increasing the time to failure; decreasing down-time due to repairs or scheduled maintenance; and accomplishing the above two in a cost-effective manner. As availability increases, the capability for making money increases because the equipment is in service for longer periods of time. The common approach to improve inherent availability at the design stage is to use different reliability analysis tools/methods such as a reliability block diagram [Henley & Gandhi, 1975], a Petri net simulation [Cordier et al., 1997], a fault tree analysis [Thangamani et al., 1995], etc. all of which allow for availability assessments on a selected process system with given unit/component reliability and maintainability data. The results of these availability studies provide useful qualitative and quantitative information that can be used later to evaluate operational performance and can be further used in improving achievable availability.

Availability, which is generally defined as the ability of an item to perform its required function at a stated function of time or over a stated period of time, is determined by reliability and maintainability of an item. Usually, the item reliability is given in terms of failure or probability density distribution such as normal, Weibull, exponential distribution, etc. The exponential distribution density function is widely used in the literature to reduce the computational burden of the resulting problem because the parameter MTBF becomes time-independent in this case [Goel et al., 2002]. In recent years, reliability and availability have expanded their influence in various industries and fields, thus serve as an integral quality element in the organization system and manufacturing process. To maintain the reliability of sophisticated systems to a higher level, the system's structural design or system components of higher reliability shall be required, or both of them are performed simultaneously [Henley & Kumampto, 1985]. Many information systems were built and a wide variety of methods were used for the reliability design [Chen & Hsu, 2006; Liu & Yang, 1999; Moon et al., 1998; Varde et al., 1998]. However, a well-defined knowledge system for reliability design and availability optimization was not found in the literature.

Typical approaches to achieve higher system reliability are: (1) increasing the reliability of system components, and (2) using redundant components in various subsystems in the system [Kuo & Prasad, 2000; Hsieh et al., 1998]. In the reliability literature, these methods are commonly posed as reliability optimization problems. Depending on the choice of decision variables, creating redundancy (adding parallel units), increasing component's reliability or both, the reliability optimization problem can be formulated as a redundancy allocation, a reliability allocation or a mixed optimal problem, respectively. Information on different formulations and solution procedures are presented by Kuo et al. [2001].

2.6 Defining the failure rate function

Understanding the dynamic behaviour of system reliability becomes an important issue in either scheduling the maintenance activities or dealing with the improvement in the revised system design. In doing so the failure or hazard rate function should be addressed. Bathtub curve is usually adopted to represent the general trend of hazard rate function. Many studies were concentrated on depicting the geometric shape of bathtub curve. The early contributors in this area include Shooman [1968], Thomas [1973], Bain [1974], Smith &Bain [1975], Gaver[1979], Hijroth [1980], Dhillon [1981], Lawless[1982], Jaisingh et al [1987], Haupt & Schabe [1992], Schabe [1994], Xie & Lai [1996], and Edelstein [1998].

Wang et al [2002] proposed a general form of bathtub shape hazard function in terms of reliability. The relation between hazard rate and reliability of a system follows the definition

$$Z(t) = -\frac{1}{R(t)}\frac{dR(t)}{dt} \tag{2.11}$$

Usually the reliability decreases monotonically with time and thus there is a one to one correspondence between reliability and time. That is, the hazard rate function can also be expressed as

$$Z(t) = -\frac{1}{R(t)} \frac{1}{dt / dR(t)} = Z(R) \tag{2.12}$$

Thus, instead of the usual procedure of estimating Z (t) the relationship of Z(R) based on the available data was defined. The change of expression Z (t) to Z(R) has certain advantages. First, the equation of dynamic reliability takes an autonomous form; particularly it belongs to a general type of logistic equation encountered very often in ecological science [Edelstein, 1988]. Therefore good experience can be guided from these studies. Secondly, the hazard rate is investigated in finite domain (1, 0) as comparing with that in infinite domain of time sequence.

Wang et al. [1993] developed reliability models that can be applied for development of new mechanical product with modified function requirements. Wang et al. [1996] also developed reliability models for material fracture due to crack growth.

2.7 Integrating reliability, availability, maintainability and supportability

Physical products and systems wear, tear and deteriorate with age and use. Markeset & Kumar [2001] pointed out that due to costs and technological limitations, it is almost impossible to design a system that is maintenance free. Breakdowns ensue mainly due to inappropriate designs. Other factors, such as human error, statutory requirements, unreliability and the required quality of the end-product, influence the maintenance procedure that should be applied. Blanchard & Fabrycky [1998] stated that maintenance needs for a system are more or less decided by its design and manufacturing procedure. Bartow & Prochan [1975], Kumar [1990] Blanchard et al. [1995], Coffin [1998], and Dhillon [1999] presented discussions on RAMS analysis for various types of products and applications under varying conditions. Eti et al. [2007] presented an analysis for integrating reliability, availability, maintainability and supportability with risk analysis in a thermal power-station .Barringer [1999] studied mechanical integrity and risk analysis for refineries and chemical plants. Warburton et al. [1998] demonstrated a methodology for predicting mechanical-failure characteristics. Moss [1985] described how to design to achieve least maintenance-expense through the use of life-cycle cost analysis. Markeset & Kumar [2001] considered the need to compensate for product unreliability, loss of product performance, reduced product output quality and lack of usability. The early space-programmes studied process failures in man/machine systems. Root-cause failure analysis, risk analysis, failure evaluation, categorization as well as oversight methods, such as management oversight risk trees (MORTs) along with reliability analyses, have been developed. Failure-pattern recognition developed into the identification and study of failure modes. Emphasis has shifted from performing repairs – the traditional focus of maintenance – to understanding the cause of failure [August, 1999]. Key aspects of the initial findings include (i) devising the technique known as stem focus; (ii) recognition of the complexity as an important attribute in modern failure classification by modes; (iii) assessment of failure effects on systems; and (iv) numerical and statistical data evaluation of large equipment populations.

Consideration of systems with randomly failing repairable components is of interest in many engineering fields and the contributors in this area include Barlow & Proschan

[1975], Page & Gondran [1986], Vaurio & Tammi [1995], Lewis [1996], and Vaurio [1997]. Armen et al. [2007] considered the class of coherent systems composed of randomly failing repairable components. Components were assumed to fail independently of each other and with constant mean failure rates; the repair of each component commences immediately after its failure and has a random duration, independent of the states of other components, with an exponential distribution. Furthermore, stationary conditions are assumed so that the probabilistic characteristics of the components and the system are invariant of a translation in time. With constant mean component failure and repair rates, stationary conditions are achieved after the effect of the initial system state has died out. The derived results are appropriate for consideration of the steady-state or limiting state of the system. Under these assumptions and conditions, closed form expressions are derived for the system availability, the mean rate of system failures, the mean duration of system downtime after each failure, and a lower bound to the system reliability as functions of the mean rate of failure and the mean duration of repair of each component. The closed-form solutions are used to derive rates of change of these system performance measures with respect to the component parameters, which are then used to formulate a set of component importance measures in the context of upgrading the performance of the system.

2.8 Setting reliability goals

Setting reliability requirements is a cornerstone of any reliability strategy. Requirements are set in such a way as to meet companies' business goals and minimize the financial risks associated with the loss of production, health and safety risks and risks to the environment. While a number of treatments [Wang et al., 2001; Kececioglu, 1991] related to the reliability allocation stage do exist, little discussion is available regarding the rigorous transformation of customers' requirements into a system reliability goal. The reliability requirements specify the expected function, performance, environment and other operating conditions. They may be purely qualitative: if, for example, suppliers are required to eliminate or reduce the risk (the likelihood of failure or the consequences of failure or both) associated with certain critical failure modes. The reliability requirements may also have a quantitative component: if for example the mean time to failure (MTTF) is specified for components and systems whose failures are characterized by a constant hazard rate. An alternative method for setting quantitative reliability requirements which is closely linked with the business risks is the minimum failure-free operating (MFFOP) model presented by Todinov [2004]. The requirements include two key components: a specified MFFOP interval and a maximum acceptable probability of premature failure.

For the framework of series-parallel system, it is very difficult to find out an optimal solution under multiple constraint conditions [Chern, 1992]. Misra Algorithm proposed by Misra & Sharma [1991] solves problems by integer programming, which serves as an algorithm searching for nearby boundary of the domain of feasible solution. Prasad & Kuo [2000] pointed out that Misra algorithm sometimes cannot yield an optimal solution, and suggested a method of searching for the upper limit of reliability's objective function. Gen et al. [1990; 1993] also studied how to solve the problem by integer programming.

The reliability of a series-parallel system has drawn continuous attention in both problem characteristics and solution methodologies. Nakagawa & Miyazaki [1981] utilized several examples to compare the mean failure rate of these methods. After combining Lagrange multiplier and branch-and-bound technologies, Kohda & Inoue [1982] and Kim & Yum [1993] solved the reliability of a series-parallel system by using heuristic algorithm. Kuo et al. [1987] proposed a heuristic algorithm that obtains rapidly the solution close to the optimal one via Lagrange multiplier. Other large systems, such as those placing limitation on linear resources proposed by Li and Haimes [1992], suggested a three-layer decomposition method for the optimization of system reliability. Mohan & Shanker [1998] selected system components via random selection method according to cost limitation. Hsieh et al. [1998] utilized genetic algorithms to solve various reliability design problems, which include series systems, series-parallel systems and complex (bridge) systems. While considering maximum system reliability and minimal total cost, Li [2001] solved them by multiple fuzzy objective planning. Yalaoui & Chatelet [2005] formulated an approximated function for the reliability allocation problem in a series-parallel system. You & Chen [2005] proposed an efficient heuristic for series-parallel redundant reliability problems. The goal was to determine the combination of components and the quantity of components in each sub system to achieve maximum overall system reliability.

2.9 Objectives and scope of the thesis

From the above literatures it can be concluded that reliability and energy efficiency are treated as two independent areas. Efforts were mainly on addressing plant reliability and maintainability issues at the conceptual stage of design and this kind of analysis does not give an insight about how these parameters get affected in the event of process system modification. Analysis of energy systems were presented without any considerations on the system reliability and availability. The pay back analysis concerned with energy efficiency improvements has also not considered the impact of change in system configuration and there by the reliability. Considering these factors, there is enough scope for a carrying out detailed study on process systems by relating energy efficiency with reliability. There is also a need for development of a generalized tool for process system valuation by incorporating reliability.

The main objectives of the present work are:

- To conduct reliability study on process plants for evaluating process system reliability and availability
- Development of a tool to study the impact of system modification on system value – Process valuation model incorporating reliability
- To arrive at the change in system value of the modified system by taking availability and reliability into consideration
- To study the impact of process system modification on availability, reliability, and energy efficiency
- To study the effect of improving energy efficiency on system reliability
- To arrive at the pay back period in case of systems whose change in process value is positive after system modification by incorporating the change in system availability.
- To arrive at the breakeven system availability, by fixing a pay back period, in case of process systems whose change in system value is negative after system modification

- To allocate component reliabilities based on the breakeven system availability

2.10 Conclusions

An extensive literature survey was conducted in the areas of energy conservation and reliability. The survey revealed the inadequacy of the literatures relating energy efficiency and reliability. Also, as such no deterministic models are available for decision making regarding system modifications that incorporates reliability and energy together. Considering these aspects the major objectives of the research was drawn.

CHAPTER 3

PROCESS VALUATION MODEL INCORPORATING RELIABILITY

3.1 Introduction

Process system components play a vital role in deciding the process availability. The performance of system components is a critical factor in deciding the availability of process plants. Modification of process systems with an over emphasis on energy conservation can affect the process system reliability and availability and hence it is necessary to study the impact of modification on process system value. Keeping this in view, a model for process system valuation by incorporating reliability is developed. This is a generalized model and can be adapted to suit the various industrial situations. The developed model is used as a tool in the present analysis and arrives at the breakeven availability of the modified system. An algorithm for allocation of the component reliabilities of the modified system based on the breakeven availability is also developed.

3.2 Reliability and availability estimation

Reliability is the probability of the equipment or process functioning without failure, when operated as prescribed for a given interval of time, under stated conditions [Kumar et al, 1992]. High costs motivate seeking engineering solutions to reliability problems for reducing financial expenditures, enhancing reliability, satisfying customers with on-time deliveries through increased equipment availability, and by reducing costs and problems arising from products that fail easily [Barringer, 2000]. Measuring the reliabilities of plant and equipment by quantifying the annual cost of unreliability incurred by the facility puts reliability into a business context. Higher-plant reliability reduces equipment failure costs. Failure decreases production and limits gross profits [Warburton et al., 1998]. Failure is a loss of function when that function is needed – particularly for meeting finance goals. Failure requires a clear definition for organizations striving to make reliability improvements [Barringer, 2000]. Reliability is a measure of the probability for failure-free operation and is often expressed as

$$R(t) = e^{-\int_0^t Z(t)dt} \tag{3.1}$$

Key parameters describing reliability are mean time to failure, mean time between/before repairs, mean life of components, failure rate and the maximum number of failures in a specific time-interval [Barringer & Weber, 1996]

For a component with a constant failure rate equation (3.1) reduces to

$$R(t) = e^{-\lambda t} \tag{3.2}$$

Equation (3.2) is generally used for the calculation of component reliabilities for a given system. In reality, even though this holds good only in-between the period of infant mortality and wear-out, it is often a reasonably good assumption as this time frame is equal to almost the entire lifetime of any equipment.

Also, reliability may be the product of many different reliability terms, such as

$$R(t) = R(t)_{boiler} \times R(t)_{feedwaterpump} \times R(t)_{piping} \times etc. \tag{3.3}$$

for a process system.

The constant failure rate model is widely used in the literature to reduce the computational burden of the resulting problem because the parameter mean time between failure (MTBF) which can be obtained from equation (3.4) becomes time-independent in this case [Goel et al., 2002].

$$MTBF = \int_0^\infty R(t)dt = \int_0^\infty e^{-\lambda t}dt = \frac{1}{\lambda} \tag{3.4}$$

Similarly, with a constant mean repair rate, mean time to repair (MTTR) can be expressed as

$$MTTR = \frac{1}{\mu} \tag{3.5}$$

Availability can be defined as the probability that an item will be available when required, or as the proportion of total time the item will be available for use. The proportion of total time that the item is available is the *steady state availability*. Availability is determined by reliability and maintainability of an item. For a simple unit with a constant failure rate and a constant mean repair rate, the steady state availability can be expressed as

$$A_i = \frac{\mu}{\lambda + \mu} \tag{3.6}$$

Similar to reliability, availability of the process system can be expressed as a function of component availabilities. With the increase of number of essential components in the system, the system reliability will decrease and to achieve high system reliability component reliability values should be very high. A system in which the components are arranged to give parallel reliability is said to be redundant; there is more than one mechanism for the system functions to be carried out. In a system with full active redundancy all but one component may fail before the system fails. A mixed system is one in which the components are connected in series as well as in parallel. The modification of an existing system with a view to improve energy efficiency should consider these factors.

For a given process, reliability block diagram (RBD) can be drawn and can be used to derive the analytic expression for system availability and reliability. In arriving at the process system reliability and availability the following considerations are made.

1) All component failures that occur are assumed to be independent of each other.
2) The process unit, depending upon the case, is logically represented by a series, parallel, or a mixed configuration.
3) Equipments or components with short service periods or components that do not affect the process continuity and can be repaired or replaced within a reasonable time are omitted from the logical configuration.

3.3 Model development

This section describes the development of system valuation model by taking into consideration the system availability, in addition to the other cost elements like investment cost, and maintenance as well as operating cost. The model is based on the following assumptions:

1) Process components are assumed to have a constant failure rate as well as a constant repair rate.

2) Availability under consideration is steady state availability.

3) Interest rate is constant throughout.

4) Depreciation of the plant is not considered.

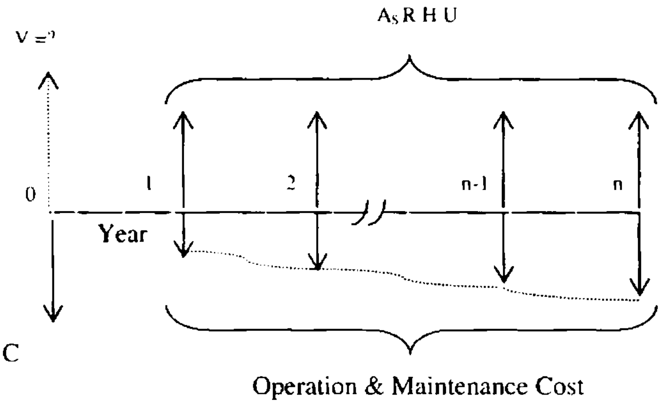

Figure 3.1 Process valuation model

The value of the system is arrived at by considering the present worth of expected future cash flows. The cash flow model developed for system valuation is shown in Fig.3.1. With reference to the cash flow model, the system value can be expressed as

$$V = A_S RHU(P/A,i,n) - C - A_S O_S \left[\frac{1-(1+k)^n (1+i)^{-n}}{i-k} \right] \tag{3.7}$$

The valuation equation (3.7) can be used only for cases where i $\neq$ k and when i = k the equation will get modified as

$$V = A_S RHU(P/A,i,n) - C - \frac{nA_S O_S}{1+i} \tag{3.8}$$

If operation and maintenance cost are assumed to remain constant, the equation for process value will get simplified as

$$V = [A_S RHU - A_S O_S](P/A,i,n) - C \tag{3.9}$$

The quantity (P/A, i, n) in the equation (3.9) is the uniform series present worth factor [James et al., 2004] and can be obtained as

$$(P/A,i,n) = \frac{(1+i)^n - 1}{i(1+i)^n} \tag{3.10}$$

Whenever a process system is to be modified for energy savings, it is important to know the expected change in system value. In this case, the investment for modification, expected annual savings due to modification as well as the change in system availability has to be taken into consideration. Change in process availability results from the change in system configuration. The change in process value can be expressed as

$$V_C = \left[A_m(RHU - O_m) - A_S(RHU - O_S)\right](P/A,i,n) - C_m \tag{3.11}$$

The equation for change in process value can be used to study the impact of system modification on system value and a positive value for V_C is desirable. The equation can also be used to study the effect of variation of operating parameters on the system value.

3.4 Breakeven availability of the modified system

A positive value for V_C implies that the cost of modification can be made up and the equation can be used to arrive at the pay back period. On the other hand, a negative value for V_C implies that the modification will only result in decreasing the earnings out of the system with the passage of time. In this case the equation can be used to calculate the breakeven availability of the modified system, for a given pay back period. The modified system availability should be greater than this breakeven availability for V_C to be positive. The breakeven availability is the value of A_m corresponding to $V_C = 0$, at a given payback period .The breakeven availability of the modified system for a given pay back period can be expressed as

$$A_{BEP} = \frac{C_m(A/P,i,b) + A_S(RHU - O_S)}{RHU - O_m} \tag{3.12}$$

The quantity (A/P i, b) in the equation (3.12) is the uniform series capital recovery factor [James et al., 2004] and can be obtained as

$$(A/P,i,b) = \frac{i(1+i)^b}{(1+i)^b - 1} \tag{3.13}$$

3.5 Reliability allocation in system modification

The system valuation model can be used to develop an algorithm for allocation of component reliabilities of the modified system based on the breakeven system availability. Reliability engineers are often called upon to make decisions as to whether to improve a certain component or components in order to achieve minimum required system reliability. It happens that even by raising the individual component reliability to a hypothetical value of 1, the overall system reliability goal will not be met by improving the reliability of just one component. This requires that the reliability goal has to be apportioned among the system components. The 10-step algorithm developed for reliability allocation of the modified system is listed below:

1) Draw the RBD for the process system before and after modification. Equipments or components with short service periods and those that can be repaired without affecting the process system are omitted from the RBD.
2) Calculate the process system reliability and availability based on the known values of failure rate and repair rate of the components before and after modification.
3) Calculate the break-even availability of the modified system using the equation for breakeven availability.
4) Compare the modified process system availability with the breakeven system availability. If the modified system availability is less than the breakeven system availability, the component reliabilities have to be apportioned in some equitable manner.
5) Increment the system reliability and corresponding to the incremented value obtain the reliability allocation of the individual components.
6) Obtain the respective failure rate of the components corresponding to the allocated component reliabilities.
7) Based on the failure rate corresponding to the allocated component reliabilities and under the assumption that the constant component repair rate does not vary after modification, calculate the component availabilities.
8) Based on the component availabilities obtained in step 7 and based on the modified RBD obtain the process system availability.
9) Compare the process system availability obtained in step 8 with the breakeven system availability.

10) If the difference between the process system availability the breakeven system availability is negative, return to step 5 and continue the iteration till the difference is zero.

The process by which the failure allowance for a system is allocated in some logical manner among its sub-systems and elements is termed reliability allocation [Srinath, 1991]. The purpose of reliability allocation is to establish a goal or objective for the reliability of each component. The principle adopted for apportioning the system allowance is that the failure allowance of each component is directly proportional to the predicted probability of failure.

3.6 Conclusions

A generalized process valuation model that can be used for the analysis of process systems was developed. The concept of breakeven availability was introduced and a 10-step algorithm for allocation of the component reliabilities of the modified system based on the breakeven availability was also presented.

CHAPTER 4

APPLICATION OF PROCESS VALUATION MODEL IN A CAPTIVE POWER PLANT TO STUDY THE IMPACT OF SYSTEM MODIFICATION

4.1 Introduction

The ability to improve continually is desirable. In recent years, the reliabilities of power plants have become increasingly important issues in most developed and developing countries [Eti et al., 2007]. As a result the recent works are focused on integrating reliability, availability, maintainability and supportability (RAMS), as well as risk analysis related with power plants. On the other hand, prevailing low efficiency of the power plants, especially that of captive power plants is a matter of concern. With the growing need for energy conservation most of the process plants are being modified and it is important that in decision making regarding plant modifications and redesigns reliability and energy efficiency have to be considered together. This chapter discusses the adverse effects of system modification conducted in a captive power plant on system reliability. The valuation model is applied to arrive at the change in system value resulting from system modification. The model also calculates the breakeven system availability and based on this the allocation of the component reliabilities were carried out. The effect variation of various parameters like steam flow rate, valuation period, interest rate and power price on process system value was also studied.

4.2 Description of the captive power plant

The process flow diagram and the corresponding RBD of the captive power plant are shown in Figs. 4.1 and 4.2 respectively.

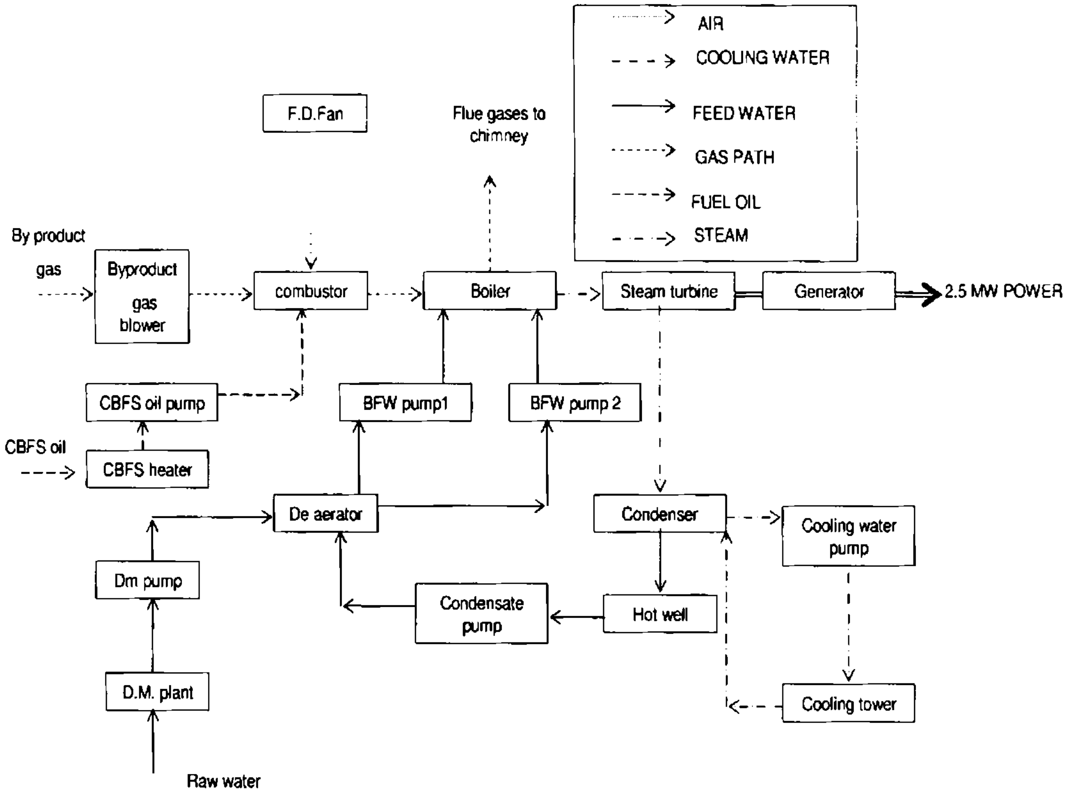

Figure 4.1 Process flow diagram for the captive power plant

The capacity of the power plant is 2.5 MW. The boiler is of Thermax design and is a panel type water tube boiler capable of burning oil and byproduct gas. The steam is generated at 39 kgf/cm^2 and 350°C. The failure data of the power plant components as per the collected data is shown in Table 4.1. Respective availability and reliability values are indicated in Figs. 4.3 and 4.4 respectively.

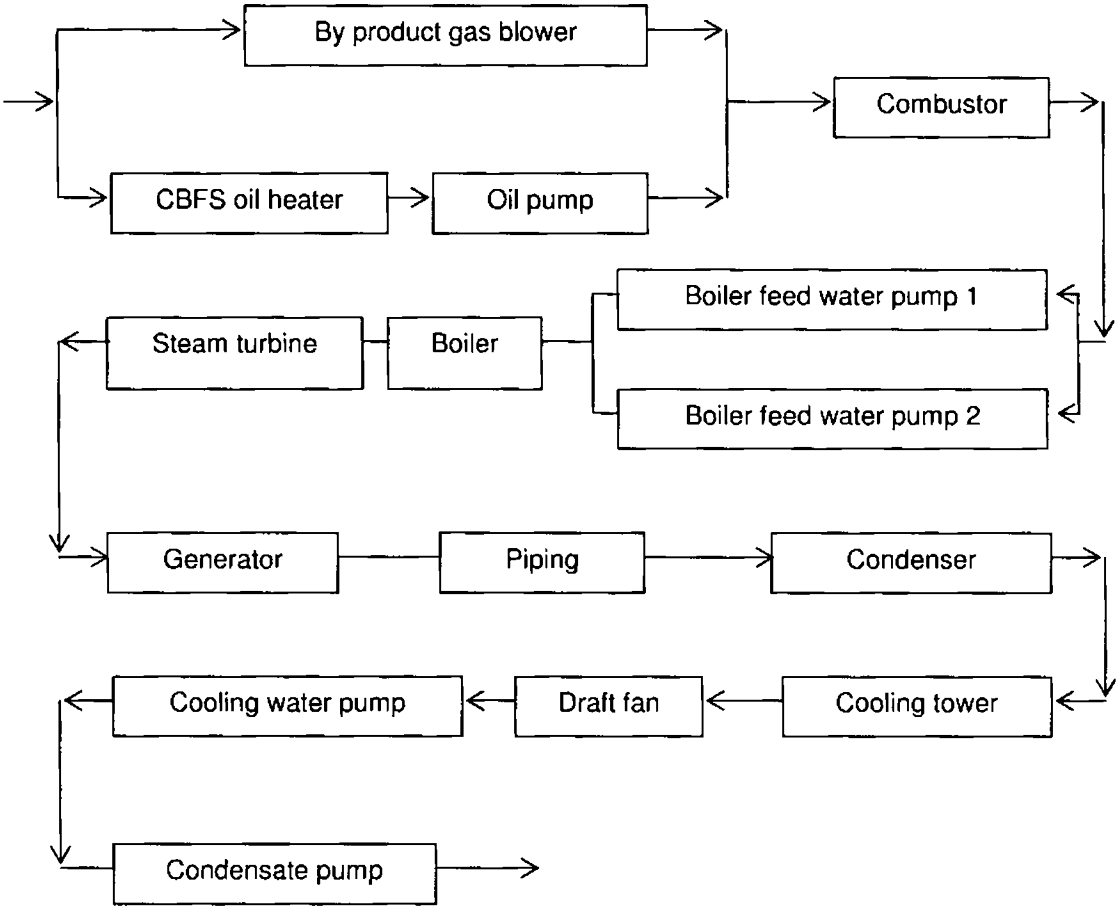

Figure 4.2 RBD for the captive power plant

During the normal course of operation the boiler is fired by the byproduct gas and only if the supply of gas is insufficient the oil is supplied and the oil used is carbon black feed stock oil. A heater is also used for heating the oil. Different equipments present in the system are represented as series and parallel configuration in RBD. It should be noted that the connectivity between equipment in RBD is based on logic and differs from the actual physical configuration. Feed water pumping is carried out by two 25 KW pumps connected in parallel and are running at half loads. The pumping system will fail only if both the pumps fail simultaneously.

Table 4.1 Power plant failure details

Component No.	Component	MTBF (hours)	MTTR (hours)
1	Byproduct gas blower	2320	8
2	CBFS oil pump	6000	4
3	CBFS oil heater	2000	8
4	Combustor	3500	12
5	Boiler	2200	36
6	Boiler feed water pump 1	8500	3
7	Boiler feed water pump 1	8500	3
8	Generator	5000	24
9	Steam turbine	4000	24
10	Piping	7000	12
11	Condenser	4000	12
12	Cooling tower	5000	16
13	Draft fan	5000	12
14	Cooling water pump	3000	12
15	Condensate pump	4000	12

4.3 System modification

As a part of energy conservation program, it was decided to replace the two 25 kW parallel pumps by a single 30 kW pump which runs at nearly full load. The modification resulted in an expenditure of Rs.1.5 lakhs. Based on the operating voltage and current values the yearly savings in terms of rupees will be Rs. 5.4 lakhs corresponding to 8000 hours of operation A simple tradeoff between the cost of modification and the projected savings will show that the pay back period will only be a few months. However, a more realistic approach will be to take reliability aspects also into consideration and develop valuation model that can be used to check the economic feasibility of this modification.

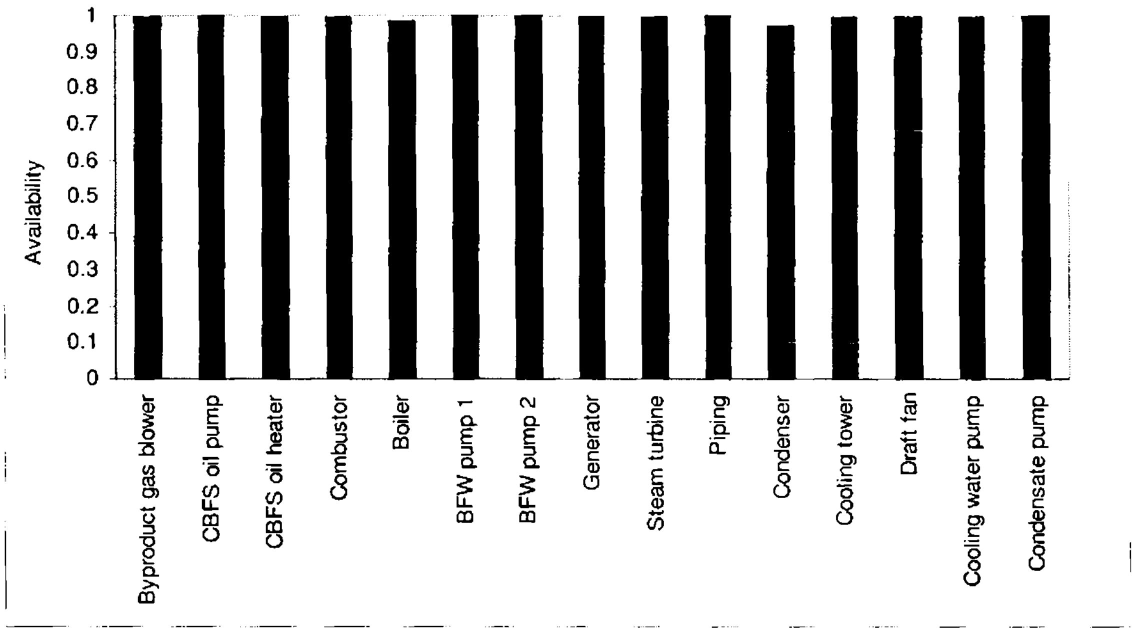

Figure 4.3 Power plant component availabilities

The equation for the change in process value as per the model can be expressed as

$$V_C = \left\{ \Delta h m H U \eta_g \eta_t \left(A_m - A_S\right) - O_S\left(A_m - A_S\right) + \frac{A_m m g p_f H U\left(\eta_m - \eta_S\right)}{100 \eta_m \eta_S} \right\} \left(P / A, i, n\right) - C_m \quad (4.1)$$

If the operating characteristics of the two parallel pumps were assumed to be same, then the equation for breakeven availability takes the form

$$A_{BEP} = \frac{100\eta_m\eta_S\{C_m(A/P,i,b)+A_S(\Delta hmHU\ \eta_g\eta_t - O_S)\}}{100\eta_m\eta_S\{\Delta hmHU\ \eta_g\eta_t - O_S\}+mgp_f HU(\eta_m-\eta_S)} \tag{4.2}$$

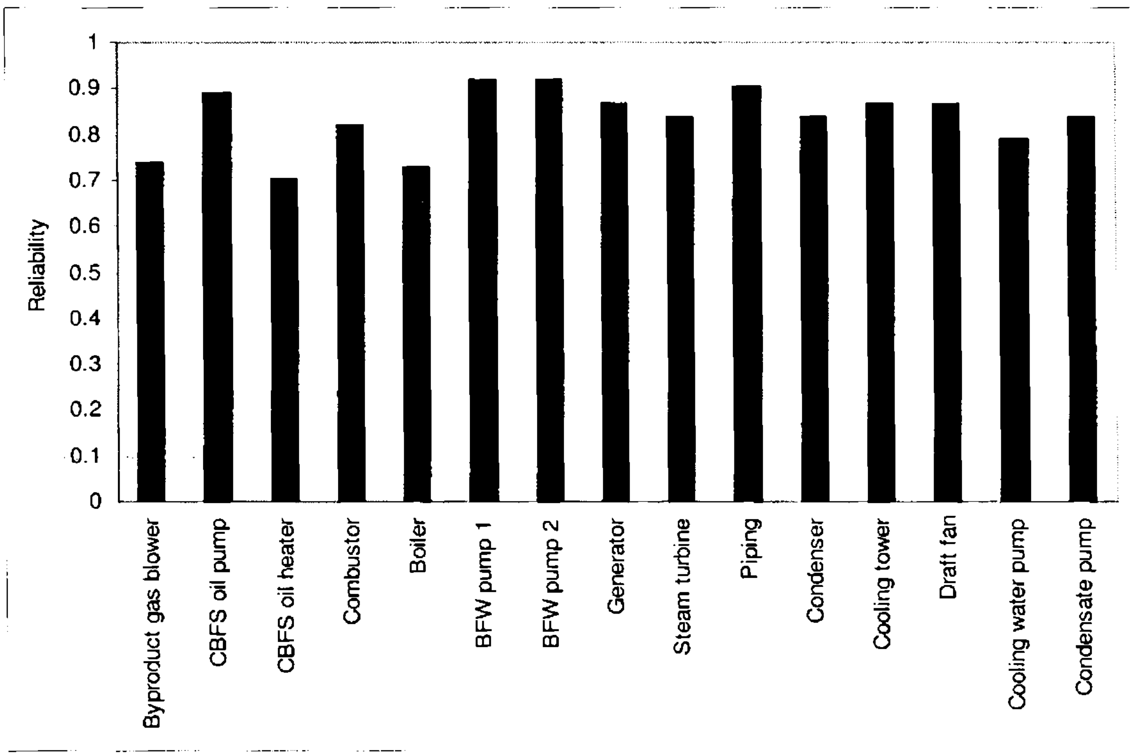

Figure 4.4 Power plant component reliabilities

Looking from the reliability point of view the modification resulted in the elimination of the redundancy for the feed water pumping system. Also, it was observed that the MTBF of the newly installed more efficient pump was relatively low as compared to the earlier pumps. The MTBF of the newly installed pump was found to be 2500 hours and MTTR 15 hours. The piping failure rate also increased and the new MTBF value for the piping system is 3000 hours and the MTTR remaining same. The variation of process value with respect to market price of the power generated, steam flow rate, interest rate, and system life are shown in Figs.(4.5 - 4.8).

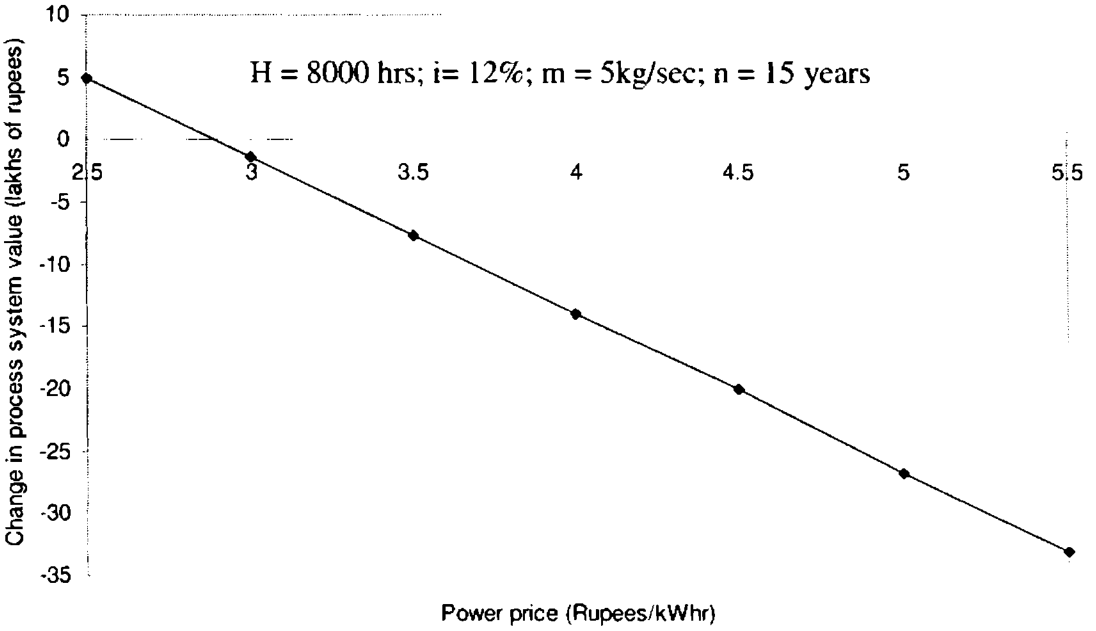

Figure 4.5 Change in process value as a function of power price

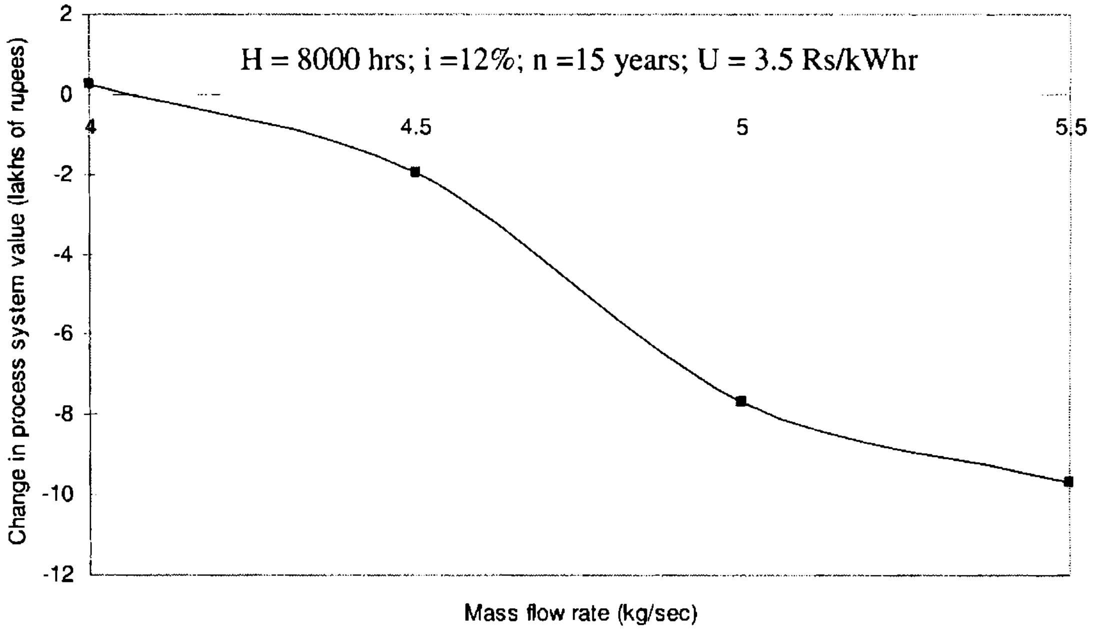

Figure 4.6 Change in process value as a function of steam flow rate

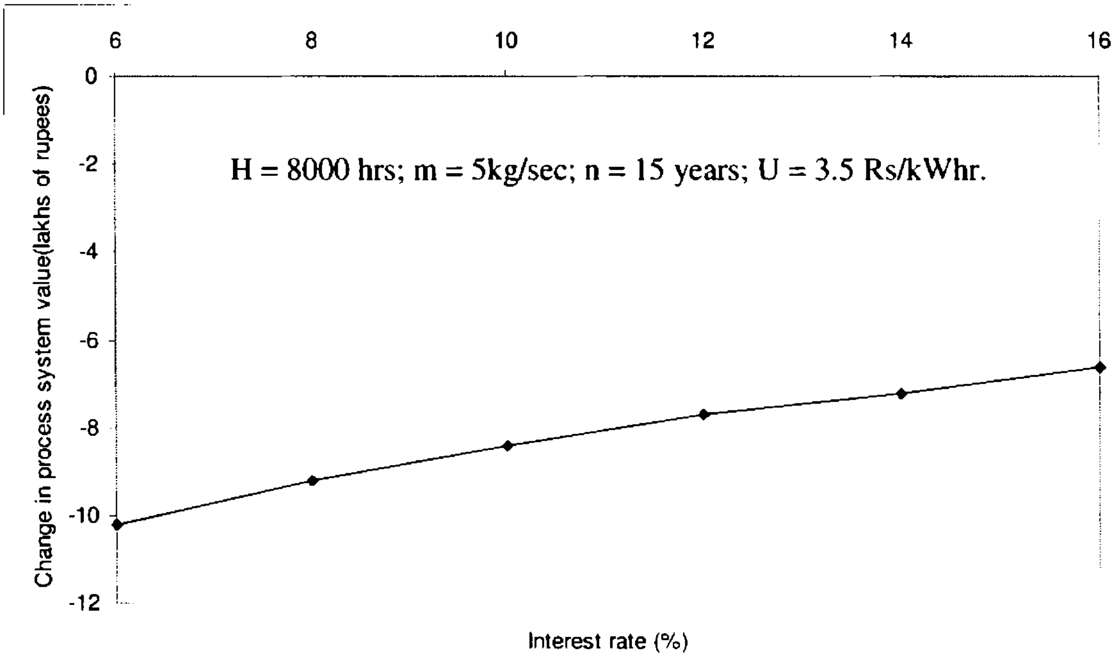

Figure 4.7 Change in process value as a function of interest rate

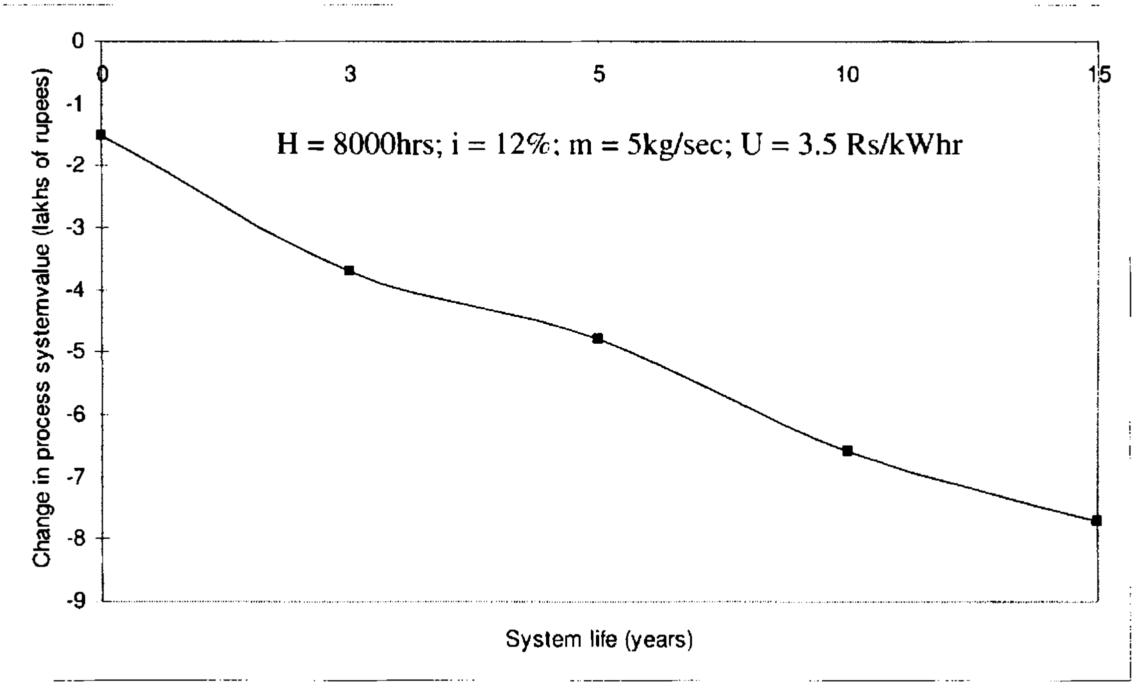

Figure 4.8 Change in process value as a function of system life

Fig. 4.5 indicates that with the increase of market price of power, the change in process value becomes more unfavourable. Fig 4.6 shows that for V_C to be favourable, the steam flow rate should be very much less than the existing flow rate of 5 kg/sec. However, operating at low values of flow rates is not possible. Fig. 4.7 shows a very high rate of return is required to make the value of V_C favourable. Fig. 4.8 indicates that under the existing conditions the earnings out of the process system will only get decreased with the years of operation, when compared to the state before modification and this requires that the reliability and availability of the modified system should be improved upon in order to achieve the pay back. Or else, by fixing a pay back period the valuation model can be used to arrive at the breakeven availability. That is, the change in process system value will be non-negative for all values of $n \geq b$ if the modified system availability is corresponding to the breakeven availability for a given value of b .The effect of variation of process system availability from the breakeven level can be best understood from Fig. 4.9.

The process system availability after modification is 0.94554896, whereas the breakeven availability for a payback period of 3 years is 0.947525914. In order to attain the break even availability for the modified system, one option is to improve the reliability of the modified component. In the present situation the break even availability can be achieved, say by improving the feed water pumping reliability by around 10%. The corresponding improvement in MTBF will be more than 50%. However, rather than significantly improving reliability of a single component - in this instance feed water pump - what is more preferable is to improve the reliability of all the components in some equitable manner. The reliability improvements needed will be very small and the algorithm for allocation of breakeven availability can be made use of. Starting from the existing system reliability of the modified system the reliability goal is increased in steps and this reliability goal is apportioned among the system components.

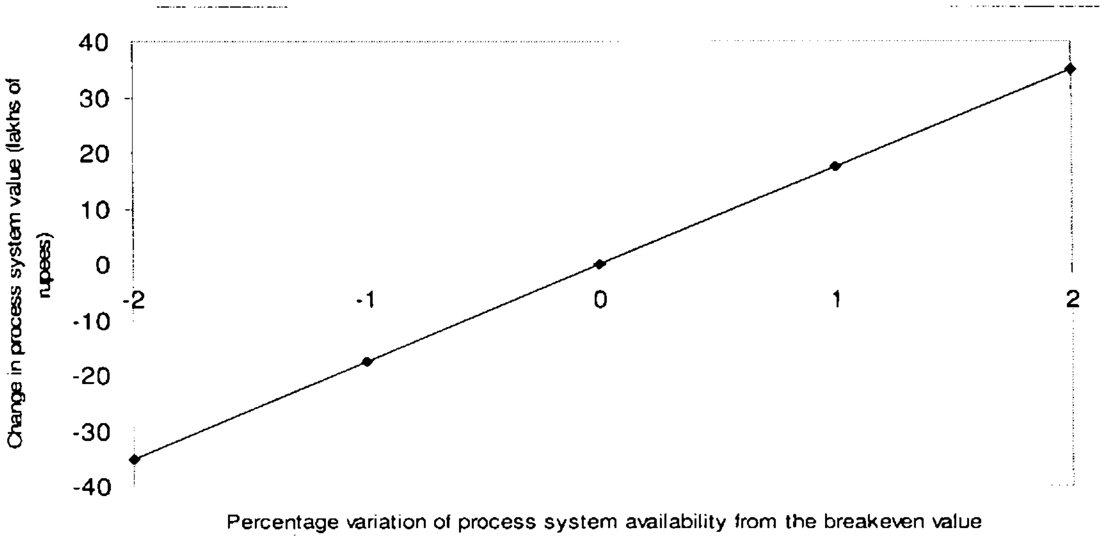

Figure 4.9 Effect of variation of process system availability from the breakeven value on the change in system value

Based on these new component failure rates and under the assumption that MTTR of the components does not vary the component availabilities and there by the system availability is obtained. The procedure is carried out until the system availability is matched with the calculated value of breakeven system availability. The iteration sequence is shown in Fig. 4.10 and the improvements in component reliabilities required to attain the breakeven system availability is presented in Table 4.2. It can be seen that the percentage improvement in feed water pumping reliability is only about 1% as oppose to 10% before allocation. Relative improvements in MTBFs of the components are shown in Fig. 4.11. The relative improvements in MTBF required for the modified system components to achieve the breakeven system availability is very minute and is of the order of around 4% and can be achieved by proper planning of preventive maintenance procedures. Byproduct gas blower, carbon black feed stock oil pump, and oil heater together make up the fuel supply system and the effective failure rate is obtained by using the reliability equations. The use of the algorithm requires that the system be converted into an all series system.

The variation of change in process value with respect to system life before and after reliability allocation can be seen in Fig.4.12. It can be seen that corresponding to the break even point change in process value is zero. Below this point V_C will be negative and above this it will be positive.

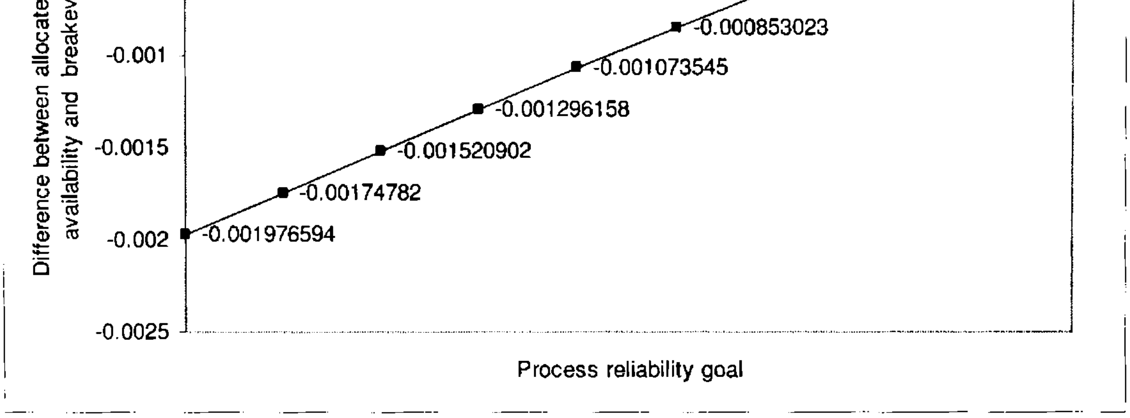

Figure 4.10 Iteration for achieving the breakeven system availability

Table 4.2 Reliability and availability goals for the power plant

Component No.	Component	% Improvement in reliability	% Improvement in availability
1	Fuel supply system	0.385038743	6.00714E-05
2	Combustor	0.755080978	0.01285321
3	Boiler	1.203942368	0.060593049
4	Feed water pump	1.058707378	0.022437772
5	Generator	0.52795998	0.017970853
6	Steam turbine	0.660384936	0.022437772
7	Piping	0.881480959	0.014987196
8	Condenser	0.660384936	0.011251184
9	Cooling tower	0.52795998	0.01199896
10	Draft fan	0.52795998	0.009006132
11	Cooling water pump	0.881480959	0.014987196
12	Condensate pump	0.660384936	0.011251184

It can be seen from the allocated values of reliability that components which already have high reliability requires only relatively small improvements. Fuel supply system generator, cooling tower and draft fan has relatively high MTBFs and as such reliability improvements required also are very low. On the other hand components like boiler and feed water pump require more improvements. The reliability values are calculated for 700 hours.

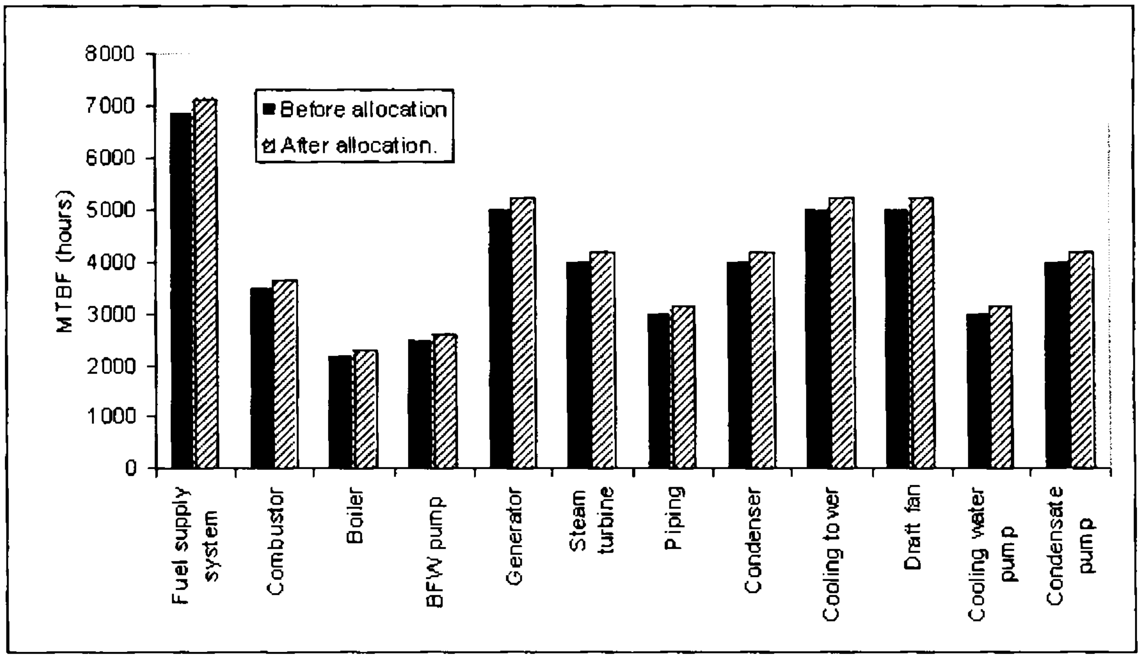

Figure 4.11 Component MTBF before and after allocation

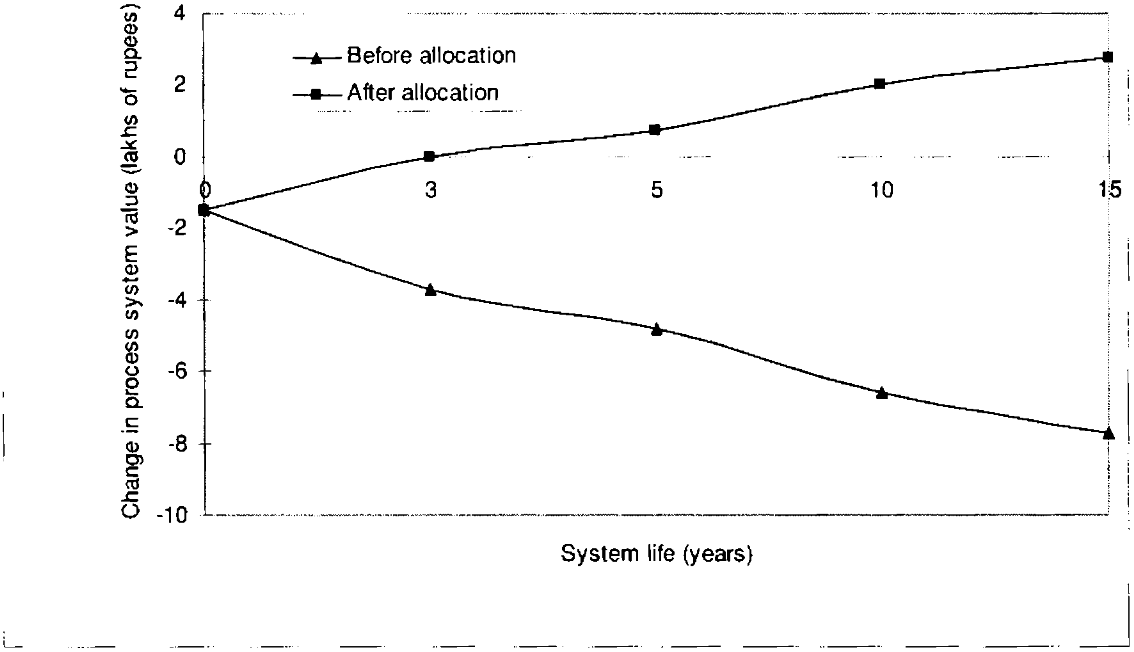

Figure 4.12 Change in process system value before and after allocation

The impact of system modification for energy efficiency on reliability is presented in Fig 4.13. Even though there is a very high improvement in pumping system efficiency there is not much improvement in the overall system efficiency. Also it is evident that the variation of energy efficiency and reliability is exactly in the opposite direction.

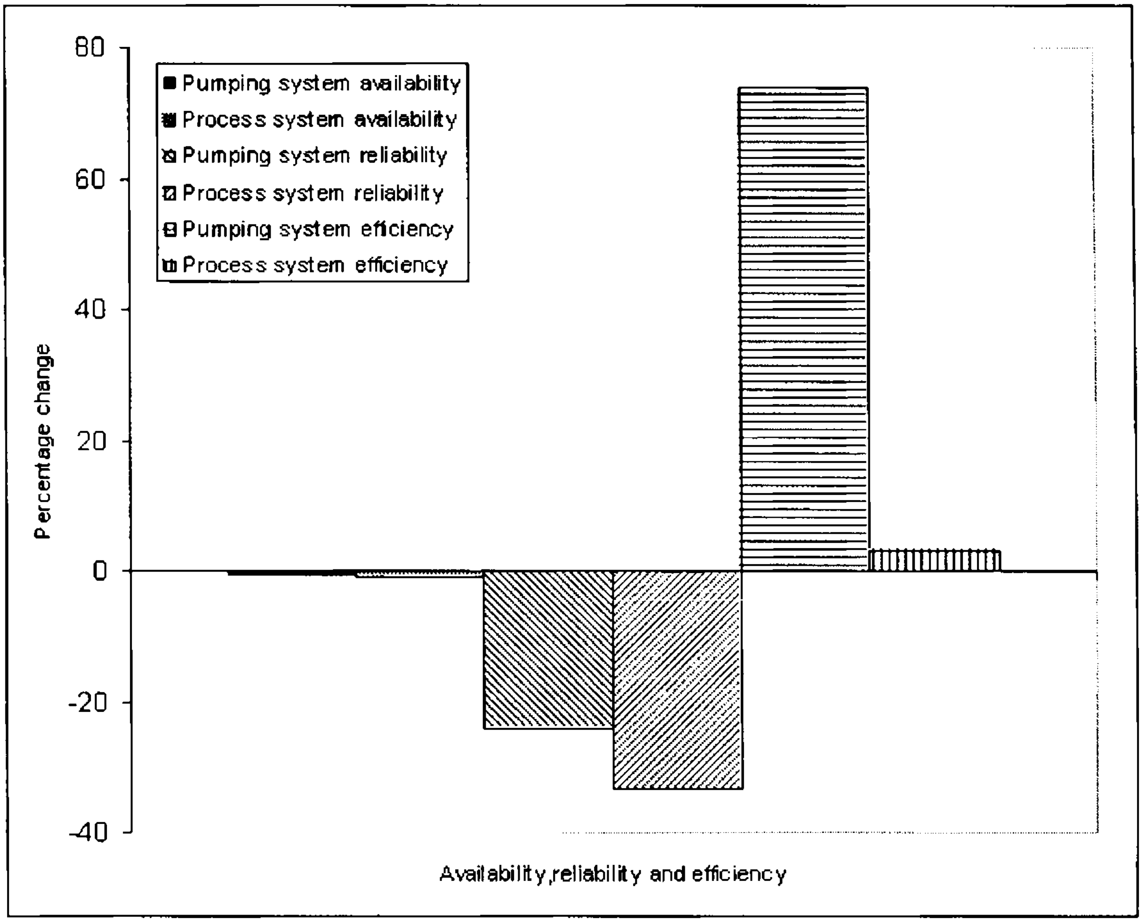

Figure 4.13 Effect of improving energy efficiency on process system reliability

4.4 Conclusions

The impact of system modification for improving energy efficiency was studied using the model. The change in system value as result of modification was not found to be positive and the component reliabilities had to be reallocated to achieve the breakeven level of system availability. It was found that the improvement in energy efficiency was at cost of system reliability. The impact of other operating parameters on process system value was also studied.

CHAPTER 5

APPLICATION OF VALUATION MODEL IN A GELATIN PLANT AND MODEL VALIDATION

5.1 Introduction

Valuation model was applied in a gelatin manufacturing plant. The objective was to find the variation of energy efficiency and reliability and also to study how the process value is affected by the relative magnitude of the variation of these parameters. The production data from the gelatin plant is made use off in validating the model.

5.2 Process details in a gelatin plant

The model was applied to study the effect of plant modification in a concentrator part of a gelatin manufacturing plant. Fig 5.1 shows the concentrator part of the plant. Dilute gelatin solution is received in a feed tank. A circulation stream is maintained through the first effect of the concentrator consisting of heat exchanger HE 1 and separator SEP 1 by the circulation pump 2. Gelatin solution from feed tank is pumped to this circulation stream by pump 1. This solution is heated by steam coming from steam header through pressure reducing valve (PRV). The heated solution gets concentrated by the evaporation of water. A part of this medium concentration gelatin is fed to the circulation stream of second effect of the evaporator. Again the second effect of the concentrator consists of

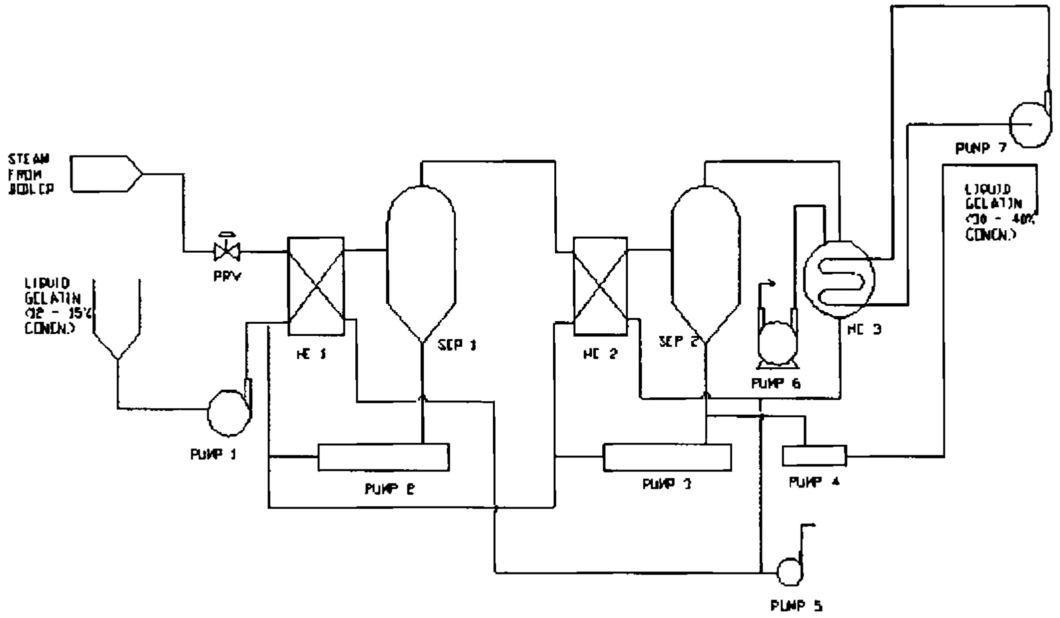

Figure 5.1 Concentrator part of a gelatin plant before modification

heat exchanger HE 2 and separator SEP 2 and the circulation is maintained by pump 3. The feeding quantity to first effect is balanced with the sum of water quantity evaporated and gelatin quantity bled out. The heating medium for second evaporator is the vapour generated by the first effect. In second effect evaporated vapour is removed from separator to a condenser HE 3, where it is condensed. Here the concentration maintained is higher and part of this concentrated gelatin solution is taken out by pump 4 and fed to next section. The steam condensate together with the vapour condensates are removed from system by pump 5. All this evaporation is carried out at vacuum pressure so as to keep temperatures down. This vacuum is maintained by pump 6 by removing non condensable gases from condenser. The heat rejected at condenser is removed by circulating water pumped by pump 7. Steam at a pressure of 40kgf/cm^2 was brought down to 3 kgf/cm^2 by means of a pressure reduction valve (PRV) and then further supplied to the heat exchanger HE 1.

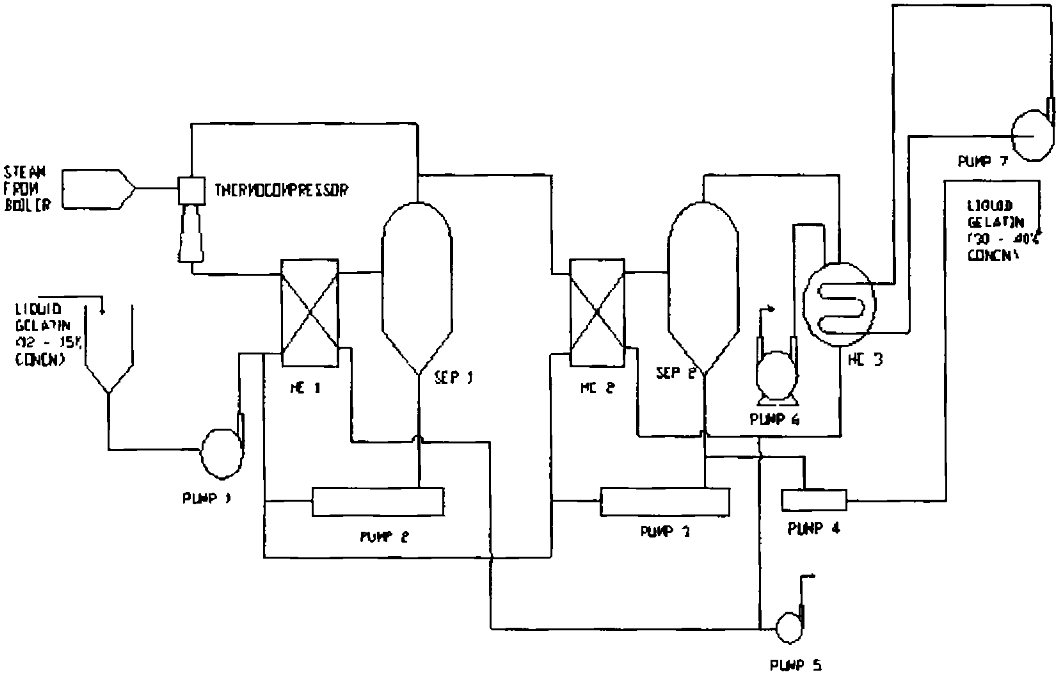

Figure 5.2 Concentrator part of a gelatin plant after modification

5.3 Process modification

The modification for improvement in energy efficiency was carried out by introduction of a thermocompressor instead of PRV. Thermo compressors use a high-pressure steam source to recover the energy from the low-pressure source, thereby providing considerable savings in energy cost. This is accompanied by change in circulation flow rates maintained in the two effects and varying heat transfer areas. Part of the vapour generated in first effect at low pressure is sucked by the thermocompressor to generate medium pressure steam. This process is powered by high pressure steam that is the motive force from steam header. The modification costed about Rs. 2 crores including the cost of thermocompressor and replacement of old boiler by a new one. The savings based on fuel consumption is about 33 kg per hour of furnace oil. The concentrator part after modification is shown in Fig.5.2 and the RBD corresponding to the modified process system is shown in Fig 5.3.

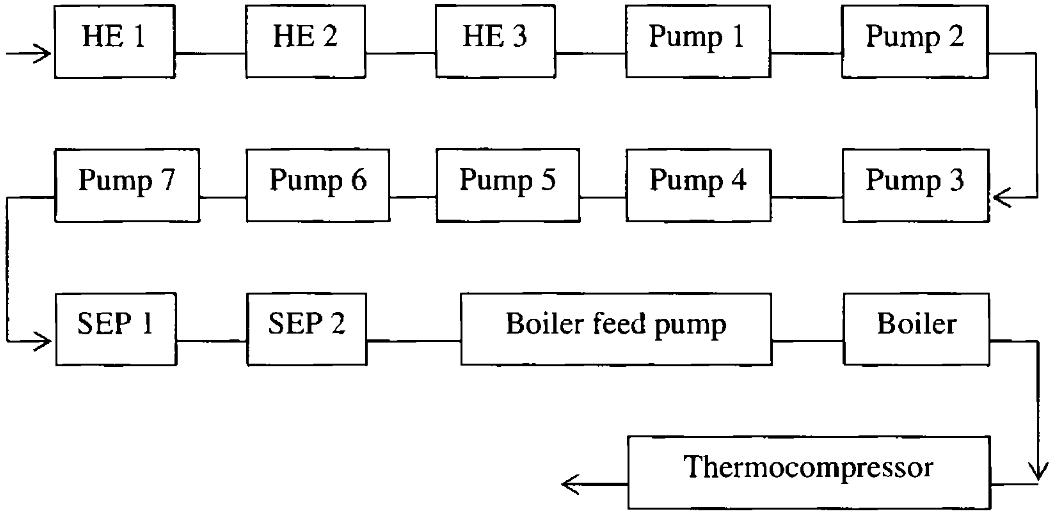

Figure 5.3 RBD corresponding to the modified gelatin plant

The failure data of the process system before modification is shown in Table 5.1. Corresponding component availabilities and reliabilities are shown in Figs. 5.4 and 5.5 respectively. After modification the PRV was replaced by a thermocompressor and the corresponding MTBF and MTTR is 6000 hours and 36 hours respectively. Also the old boiler was replaced by a new boiler with MTBF and MTTR equal to 4500 and 18 hours respectively.

Table 5.1 Failure data of the concentrator part before modification

Component No.	Component	MTBF (hours)	MTTR (hours)
1	Heat exchanger 1	4020	8
2	Heat exchanger 2	4510	8
3	Heat exchanger 3	4480	8
4	Separator 1	5540	8
5	Separator 2	5580	8
6	Pump 1	4500	4
7	Pump 2	5100	6
8	Pump 3	5063	6
9	Pump 4	5190	6
10	Pump 5	4409	4
11	Pump 6	4510	4
12	Pump 7	4409	4
13	Boiler feed water pump	6206	4
14	Boiler	6900	24
15	PRV	6000	4

It is evident from Figs. 5.4 and 5.5 that a component with a relatively high reliability can have a relatively low availability if repair time is high. For instance, in the case of boiler and feed water pump, the boiler exhibits a high reliability compared to that of the feed water pump but reverse is the case with availability.

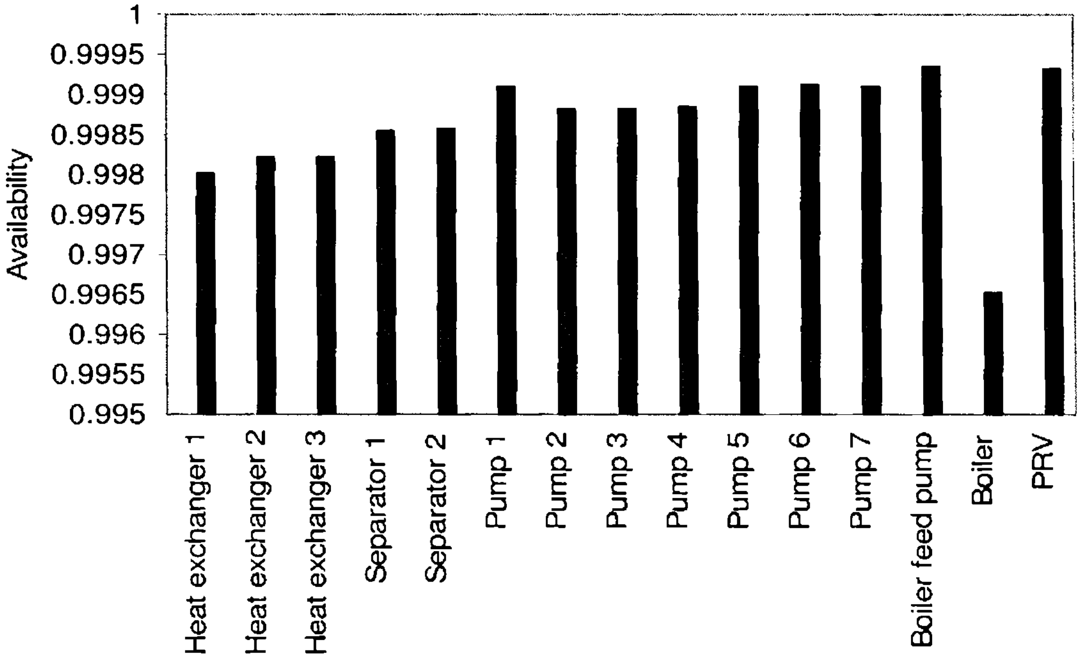

Figure 5.4 Concentrator part availabilities

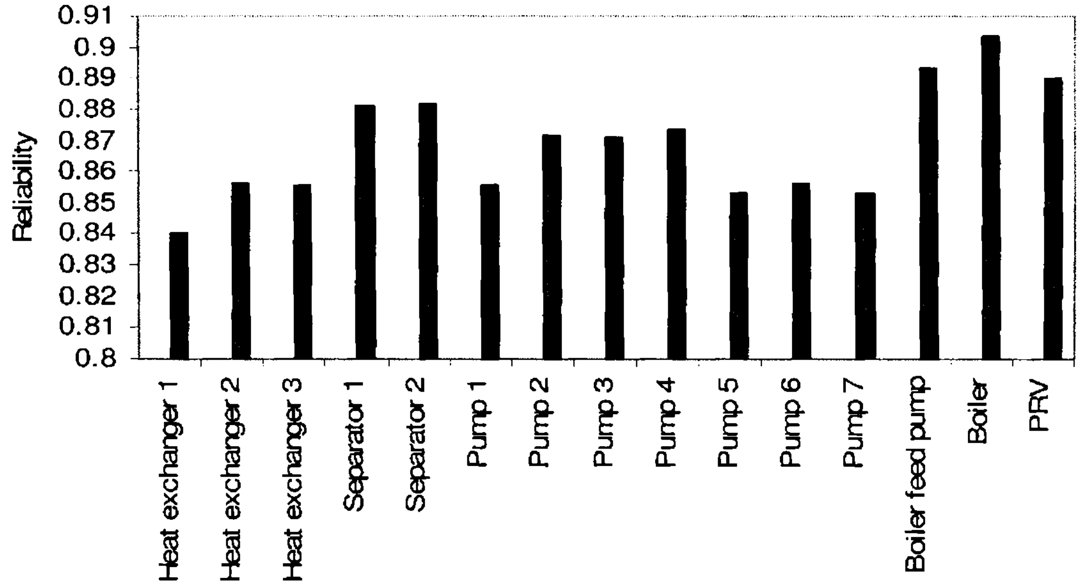

Figure 5.5 Concentrator part reliabilities

Table 5.2 Calculation of change in process system value and payback

Expected life of the system, n (Years)	15
System operating hours in a year	7000
Unit price of the output, U (Rs/kg)	50
Production rate, R (kg/hr)	1215
Cost of modification, C_m (Rs)	20000000
Operation and maintenance cost before modification corresponding to system operating hours in a year , O_S (Rs/Year)	402295400
Operation and maintenance cost after modification corresponding to system operating hours in a year , O_m (Rs/Year)	388286400
System availability before modification, A_S	0.979897466
System availability after modification, A_m	0.974196001
(P/A,i,n) corresponding to the life of the system	6.8108
Change in Process Value, V_c (Rs)	72059982
Payback Period, Years	1.7248809

The change in operation and maintenance cost after modification corresponding to the system operation period of 7000 hours shown in Table 5.2. The change in process system value calculation is also shown and the pay back period is arrived at using the model. The reduction in operation cost results from the reduction in fuel consumption and the corresponding energy calculations are shown in Table 5.3.The variation of change in process value after modification as a function of system life is shown in Fig. 5.6. The variation of reliability and availability in relation with change in energy efficiency is in the opposite direction.

Table 5.3 Energy and efficiency calculations for concentrator part

Particulars	Before Modification	After Modification
Steam rate (kg/hr.)	1250	825
Energy in the feed water at the boiler inlet (kW), Q_W	123.9504	81.787
Energy in the Steam at the boiler outlet (kW), Q_b	971.8128	635.9816
Fuel supplied (kg/hr.)	97.6	64.4
Energy in the fuel supplied to the boiler (kW), Q_f	1081.733	713.7667
Boiler efficiency, η_b	78.38%	77.64%
Energy loss in the line due to heat dissipation from the surface of pipes, water loss, steam loss etc. (kW), Q_l	266	147
Efficiency of the steam line η_l	72.63%	76.89%
Theoretical useful energy required to accomplish the given task (kW), Q_u	250	250
Useful task efficiency η_u	35.42%	55.13%
Energy in the condensate recovered from the condensate return, (kW), Q_r	123.95	81.79
Factor of unrecovered condensate, η_r	87.24%	87.14%
Overall steam system efficiency	23.11%	35.02%

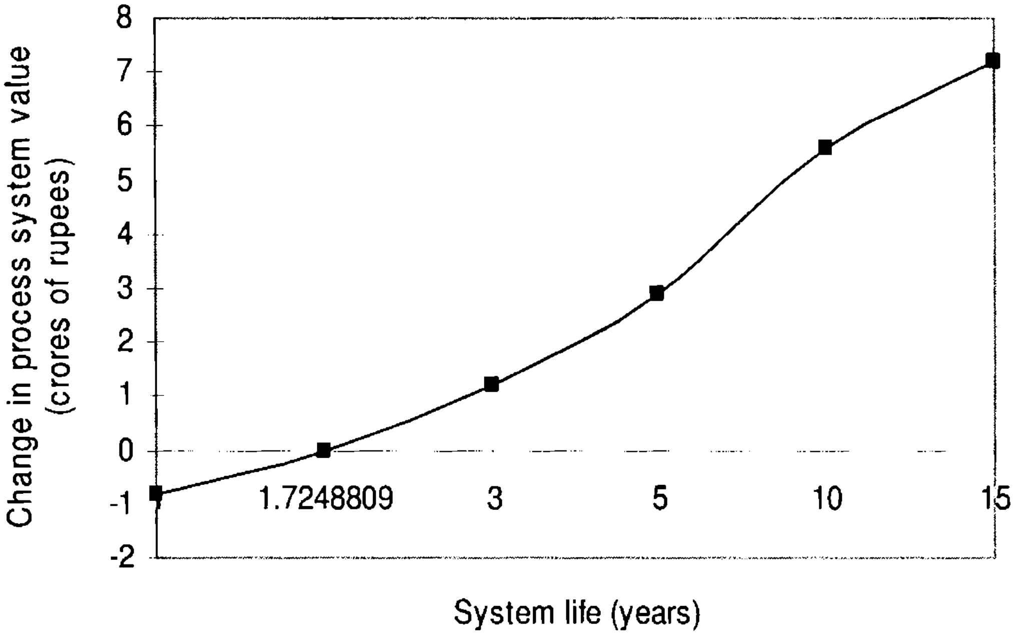

Figure 5.6 Change in process value with system life for gelatin plant

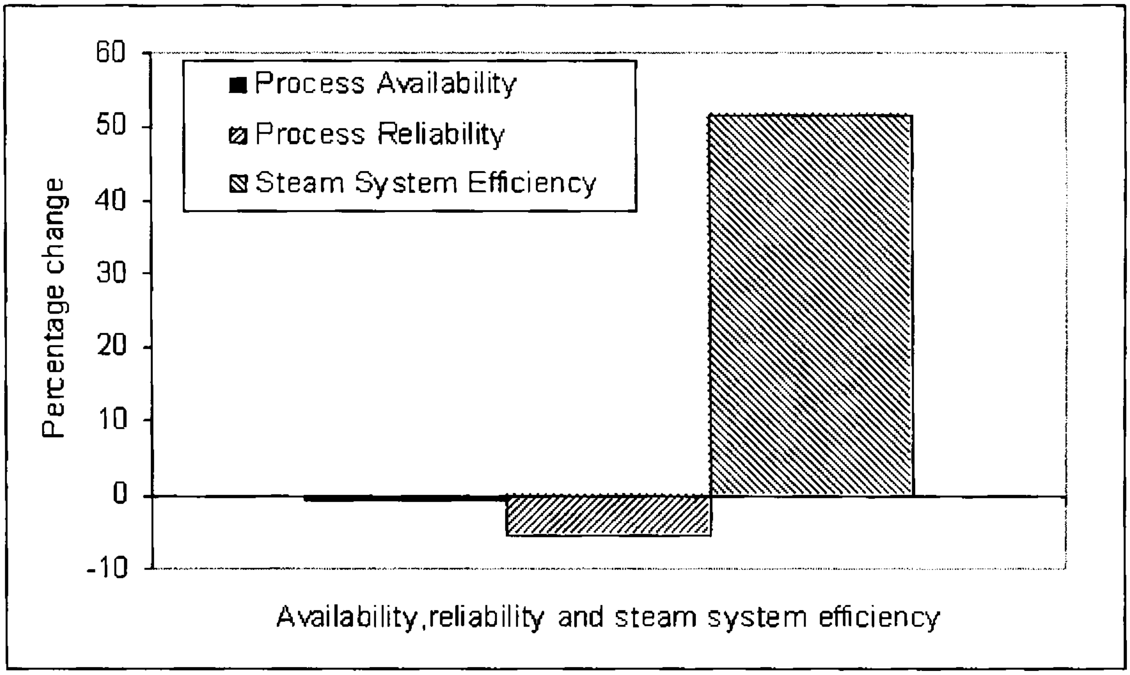

Figure 5.7 Impact of modification on availability, reliability and energy efficiency

Table 5.4 Production data in the gelatin plant after modification

Month &Year	Monthly Production after modification (kg)	Change in production (kg)	Change in production (Rs)	Decrease in Operation & maintenance cost after modification (Rs)	Net Benefit (Rs)
Oct 04	707130	-7210	-360500	1464116	1103616
Nov	707130	-7210	-360500	1464116	1103616
Dec	713763.9	-576.1	-28805	1169665	1140860
Jan 05	713836.8	-503.2	-25160	1166430	1141270
Feb	699840	-14500	-725000	1787688	1062688
Mar	710775	-3565	-178250	1302330	1124080
Apr	727542	13202	660100	558114.4	1218214
May	729000	14660	733000	493400	1226400
Jun	670680	-43660	-2183000	3081976	898976
Jul	641520	-72820	-3641000	4376264	735264
Aug	656100	-58240	-2912000	3729120	817120
Sept	692550	-21790	-1089500	2111260	1021760
Oct	692550	-21790	-1089500	2111260	1021760
Nov	707130	-7210	-360500	1464116	1103616
Dec	691821	-22519	-1125950	2143617	1017667
Jan 06	692550	-21790	-1089500	2111260	1021760
Feb	703485	-10855	-542750	1625902	1083152
Mar	677970	-36370	-1818500	2758404	939904
Apr	729000	14660	733000	493400	1226400
				Total	**20008123**

Even though there is a decrease in availability and reliability of the process system after modification the change in process value is very much favourable and this shows the importance of the relative magnitude of the change in reliability and energy efficiency in decision making. With the increase of energy efficiency the operating cost will come down. However, operating cost itself is related with availability. Also, corresponding to the decrease in availability there will be a reduction in the production and there by revenue. The pay back period is calculated by considering these factors. Fig. 5.7 shows the impact of modification on reliability, availability and energy efficiency.

5.4 Model validation

The model was validated using the actual production data from plant. Table 5.4 gives the actual production figures obtained from the plant after modification. Monthly production and operating cost figures are compared with the average values for the year before modification. It can be seen that after modification the change in production for most of the months is negative. However, the relative magnitude of loss due to decrease in production is less compared to the savings in the operating cost. The pay back period obtained as per the model is 1.7248809 years (or approximately 20.7 months) which is very close to 19 months obtained as per the actual data.

5.5 Conclusion

Valuation model was applied in a gelatin manufacturing plant. The impact of modification on improvements in the concentrator part of the plant was studied. It was found that even though there is an improvement in efficiency of the modified steam system the reliability and availability had come down. Inspite of this decrease in reliability and availability the change in process value was positive indicating the importance of relative magnitude of the variation of these parameters in decision making. The model was validated using the production data available from the plant and the pay back arrived using the model closely agrees with that of the actual value.

CHAPTER 6

APPLICATION OF VALUATION MODEL IN A CHOCOLATE MANUFACTURING COMPANY

6.1 Introduction

The valuation model can be applied to a variety of situations to study the impact of system modification. In the present case, the model is used to study the impact of modification in a steam system of a chocolate manufacturing company with a view for improving process system reliability. The algorithm for breakeven availability also is made use of in achieving reliability goals.

6.2 Process details

The RBD for the chocolate manufacturing is shown in Fig. 6.1. Glucose (approximately 40%) and sugar (approximately 60%) is cooked in a cooker, wherein heat required for cooking is supplied by the steam. The steam is generated in a 9 kgf/cm^2 water tube boiler at a rate of 0.0566 kg/sec. The cooked products are then cooled in a cooling table and then send to a rope sizer and then further to the forming machine, where the rope sized product is cut into the required shape and size. Then the products are conveyed to a scrap remover and to a wrapping machine to get the desired product. The boiler is fired by diesel oil and the steam after supplying heat to the process is condensed and returned to the boiler as feed water.

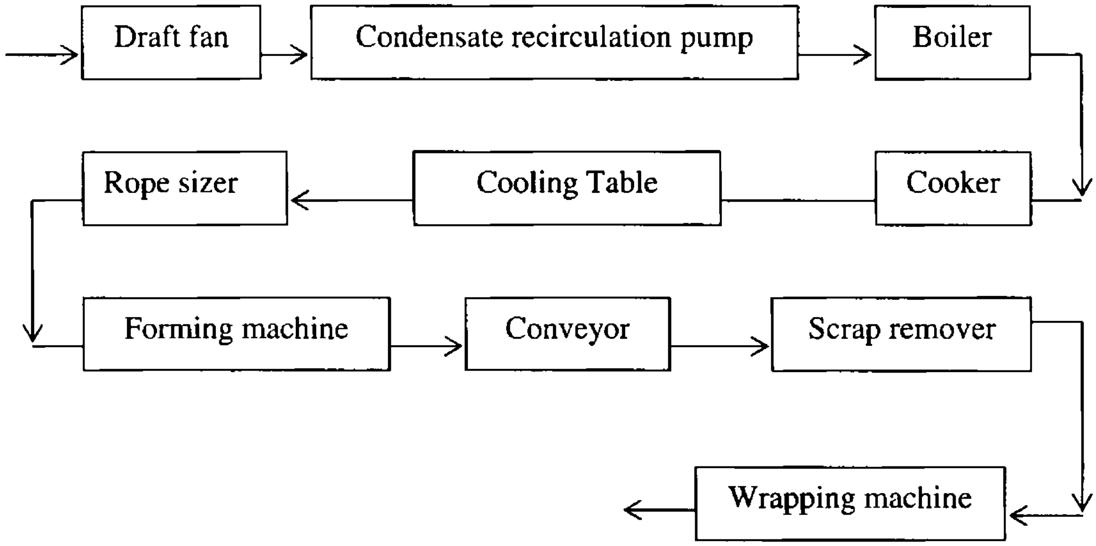

Figure 6.1 RBD for the chocolate manufacturing process

Table 6.1 Component failure data in the chocolate manufacturing plant

Component No.	Component	MTBF (hours)	MTTR (hours)
1	Draft fan	4000	3
2	Condensate recirculation pump	1750	4
3	Boiler	4500	12
4	Cooker	3500	8
5	Cooling table	6000	5
6	Rope sizer	4000	4
7	Forming machine	6000	4
8	Conveyor	4250	4
9	Scrap remover	6000	3
10	Wrapping machine	3500	5

The component failure and repair data of the plant are presented in Table 6.1 and the respective reliabilities and availabilities are shown in Figs. 6.2 and 6.3.

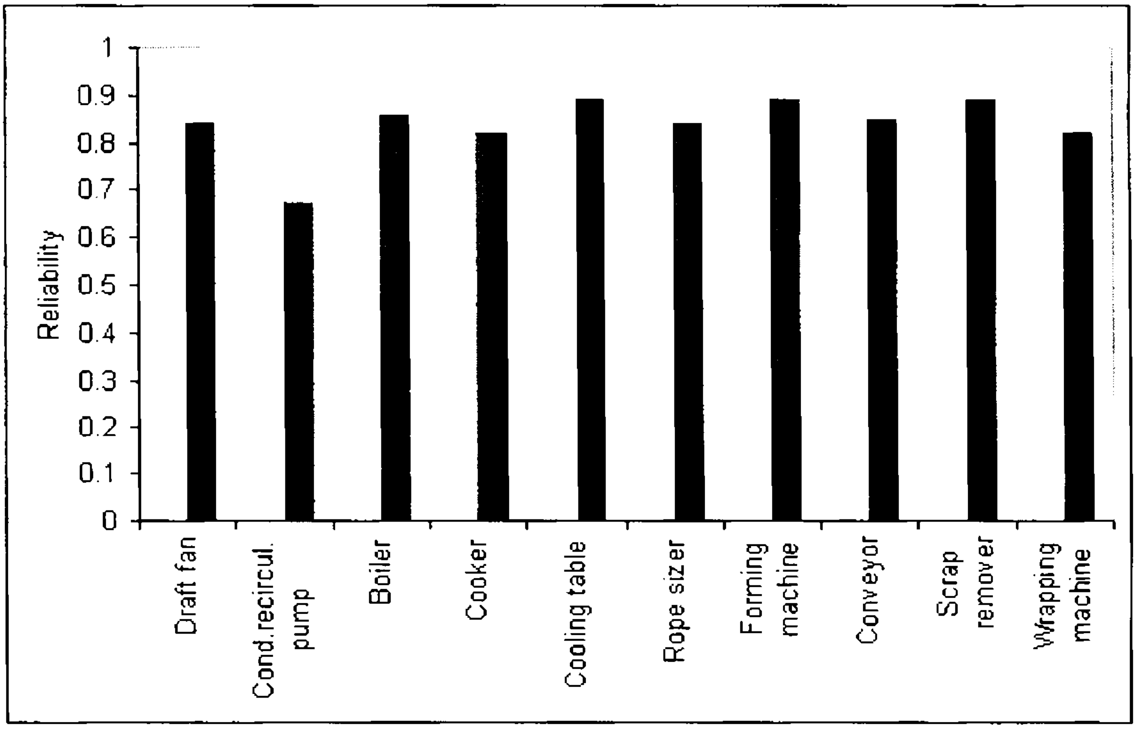

Figure 6.2 Component reliabilities for the chocolate plant

The reliability values are calculated for 700 hours and data indicates (Fig. 6.2) that the condensate pumping reliability is lowest resulting from a low MTBF. However low repair rate make availability relatively high. On the other hand high MTTR makes the boiler availability low in comparison with the other components.

6.3 System modification

Condensate recovery is an attractive method of improving steam system efficiency. In the present situation, the condensate which is at a temperature of around 85° C was recovered and used as feed water. However due to frequent failures of the condensate pumping system, the company decided to use fresh water, rather than the condensate recovered, as feed water to the boiler. The resulting modification costed around Rs. 30000 and also an additional 1.5 litres of fuel consumption per hour. The feed water pump MTBF after modification is 6000 hours against 1750 hours of the condensate recirculation pump. MTTR for pump remains as 4 hours.

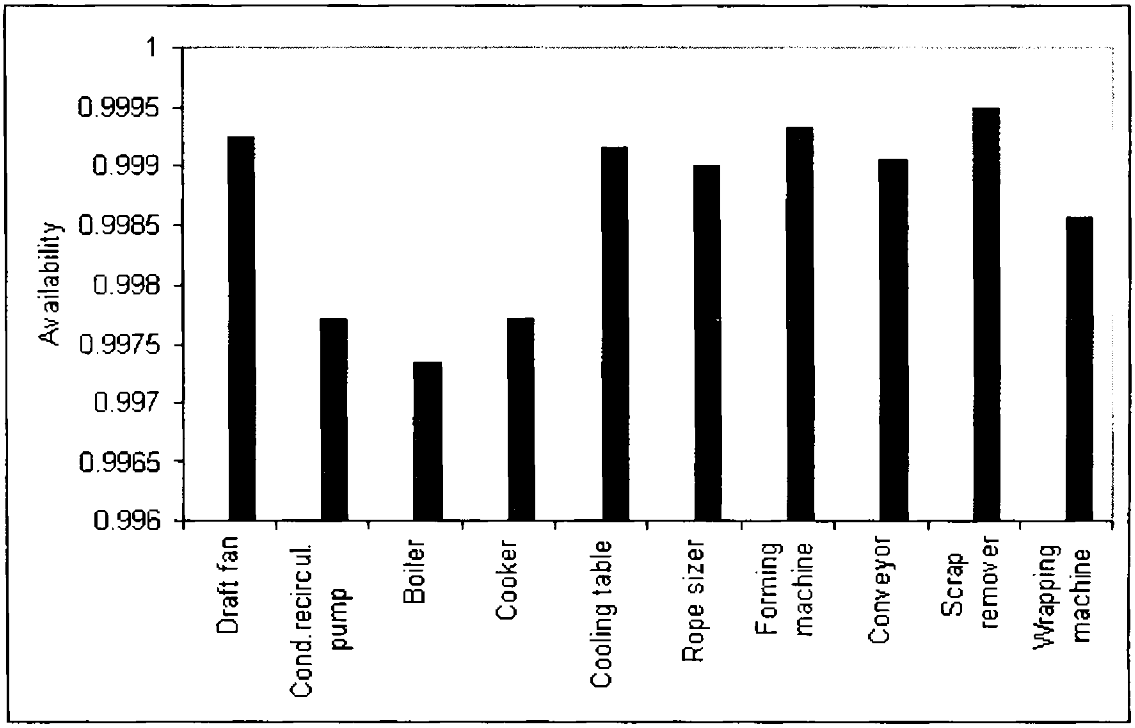

Figure 6.3 Component availabilities for the chocolate plant

The impact of modification in terms of reliability, availability and energy efficiency is shown in Fig. 6.4. The change in process system value works out to be negative which is indicative of the wrong decision made. In fact, returning condensate is a common practice in new plant design and efforts should have been to improve the reliability of the condensate pumping rather than eliminating it. The energy and efficiency calculations are presented in Table 6.2.and the variation of change in process system value with system life is shown in Fig. 6.5.

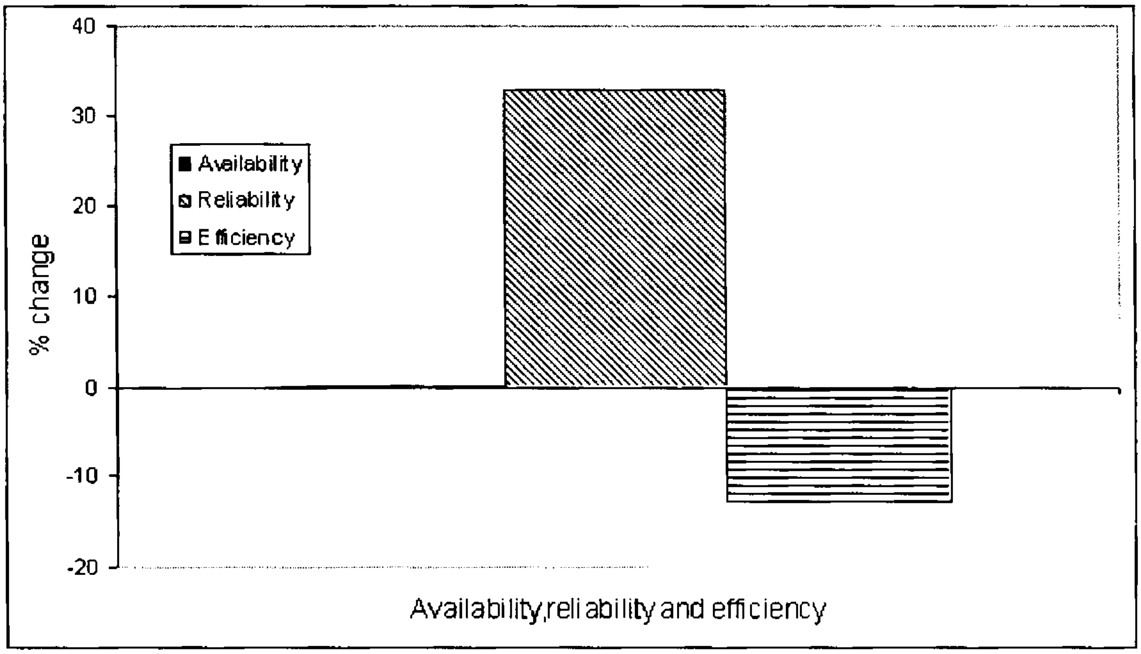

Figure 6.4 Variation of availability, reliability and energy efficiency

It is evident that even though there is around 32% improvement in process system reliability the improvement in availability is only around 0.16%. On the other hand, there is around 13% dip in the overall steam system efficiency there by affecting the process system value. This requires the breakeven availability to be calculated for a given pay back period. Corresponding to a pay back of 2 years the breakeven availability works out to be 0.994752398, whereas the system availability after modification is only 0.988339043.

Table 6.2 Energy and efficiency calculations for the chocolate plant

Particulars	Before Modification	After Modification
Steam rate (kg/sec)	0.05667	0.05667
Energy in the feed water at the boiler inlet (kW), Q_W	20.23	7.14
Energy in the Steam at the boiler outlet (kW), Q_b	157.087	157.087
Fuel supplied (kg/hr.)	15.64	17
Energy in the fuel supplied to the boiler (kW), Q_f	150.50	164.64
Boiler efficiency, η_b	90.93%	91.07%
Energy loss in the line due to heat dissipation from the surface of pipes, water loss, steam loss etc. (kW), Q_l	16.91	30
Efficiency of the steam line η_l	89.24%	80.90%
Theoretical useful energy required to accomplish the given task (kW), Q_u	41.67	41.67
Useful task efficiency η_u	29.72%	32.79%
Energy in the condensate recovered from the condensate return, (kW), Q_r	20.23	0
Factor of unrecovered condensate, η_r	87.12%	100%
Overall steam system efficiency	27.68%	24.157%

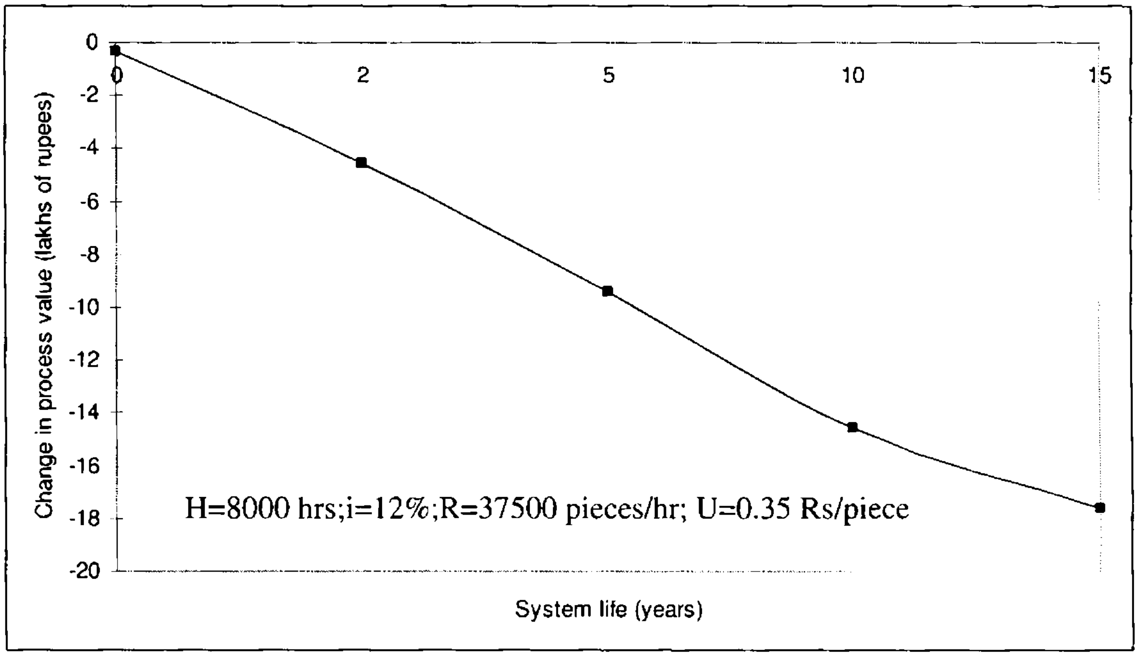

Figure 6.5 Change in process value vs. system life

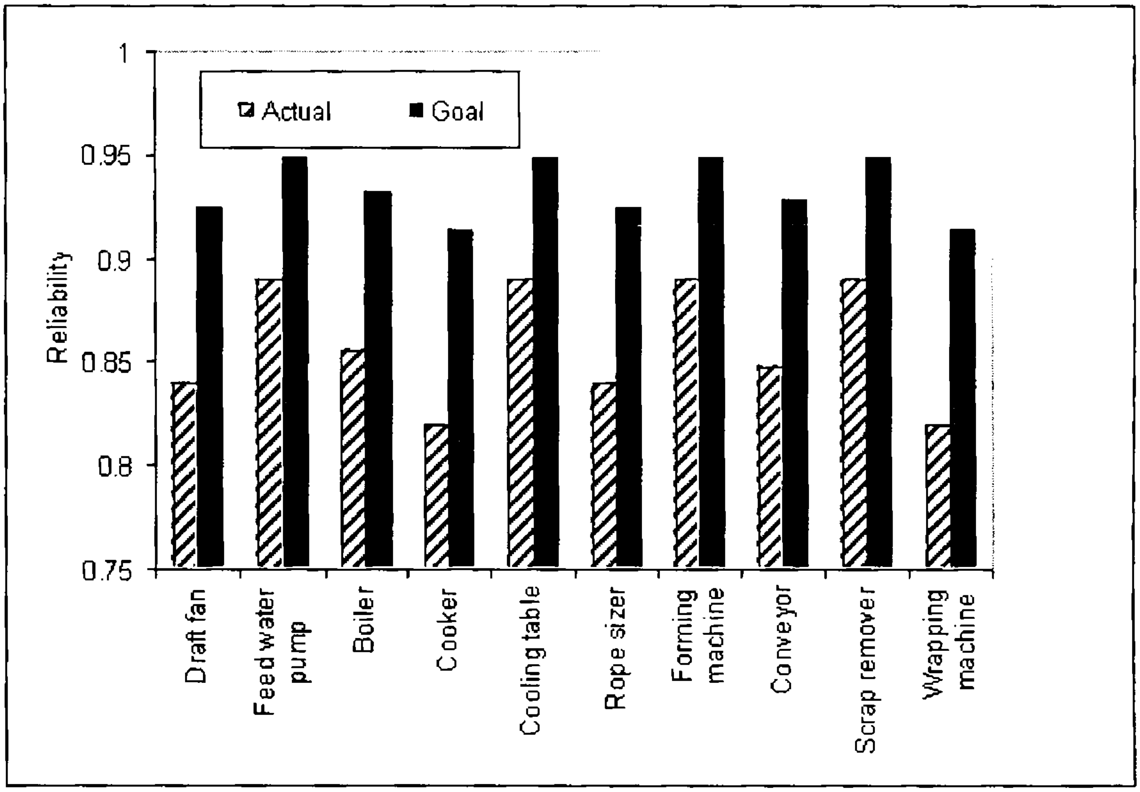

Fig 6.6 Reliability goals for the chocolate plant

Fig. 6.5 indicates that as a result of modification the earnings out of the process system will only decrease with the passage of time. In order to reverse the trend the breakeven availability need to be allocated among the components and the reliability goals corresponding to the allocation are shown in Fig. 6.6. The improvement in process value after allocation is shown in Fig. 6.7.

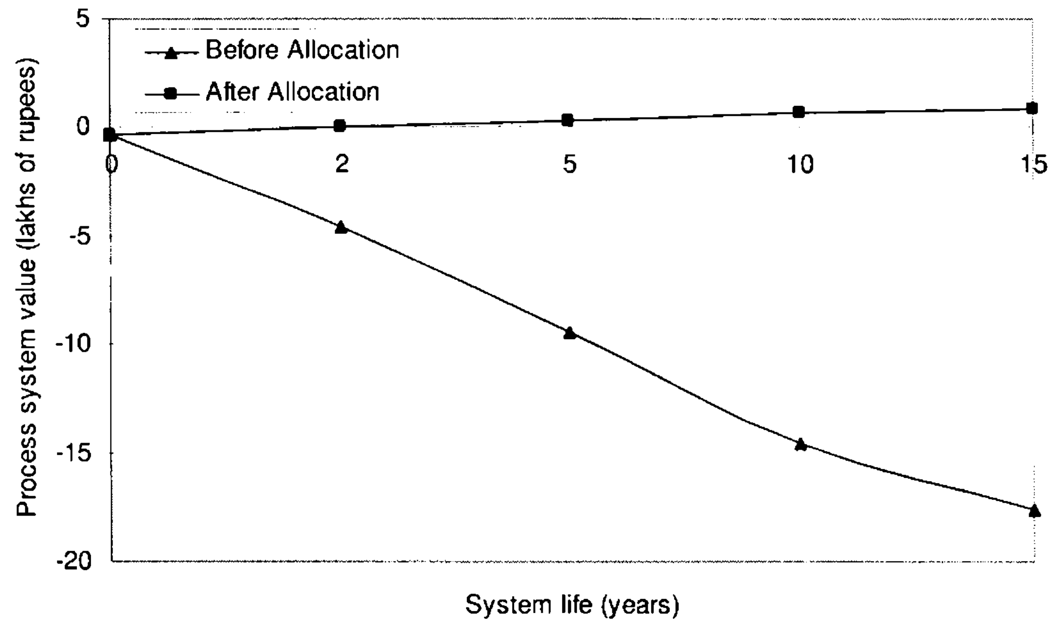

Figure 6.7 System value before and after allocation for chocolate plant

It can be seen from the Fig. 6.6 that the improvements in component reliabilities required, even after allocation, are very high. This again point towards the wrong decision made regarding the elimination of condensate recovery. The improvements in component MTBF are also more than 100%. Hence other options like increasing the cost of the product should be looked into in order to make the change in process value favourable. Fig 6.8 shows the variation of process system value with the unit price of the chocolate.

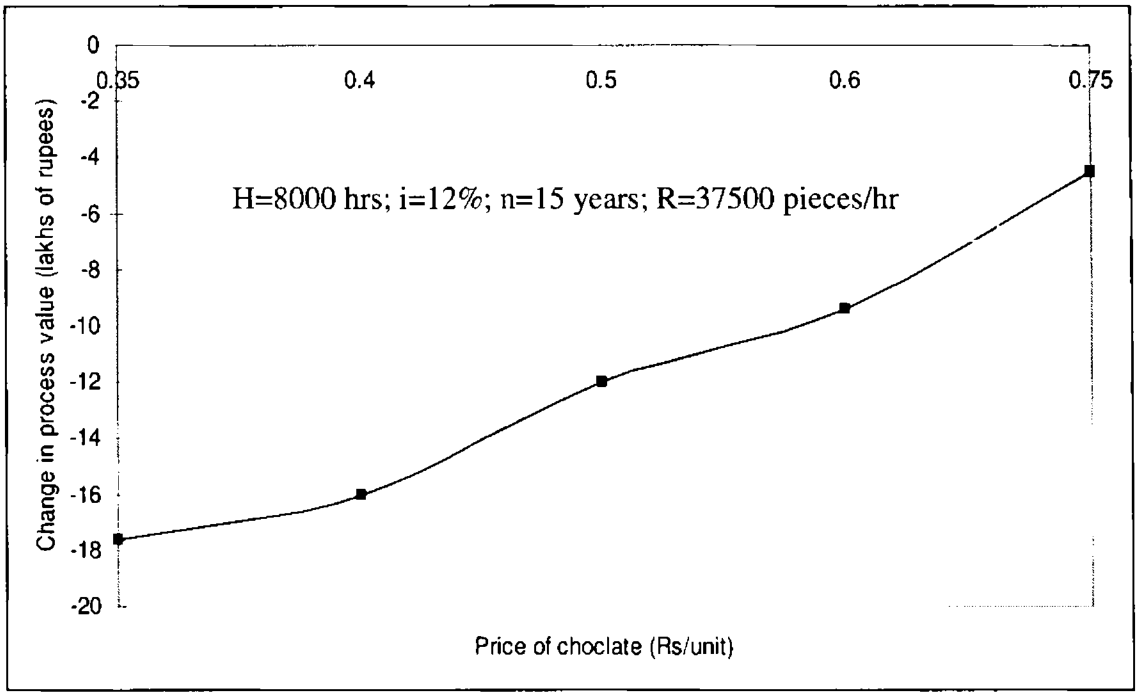

Figure 6.8 Change in process value vs. price of the chocolate

6.4 Conclusions

The model was used to study the impact of process modification in a steam system of a chocolate manufacturing company. The efforts to improve reliability had resulted in lowering of steam system efficiency. The change in process system value also was found to be negative there by indicating the inaccuracy in decision making regarding plant modification. The decision to eliminate the condensate recovery in no way can be substantiated. The breakeven value of the modified was calculated and the component reliability goals were also calculated. However it was found that the percentage improvements in the reliability of the components and also the improvements in respective MTBFs are quite high. Other alternatives like increasing the selling price of the product should be looked into in order to make good of the decrease in process system value.

CHAPTER 7

CONCLUSIONS

Process reliability study was conducted at different industrial situations in order to study the impact of system modification with a view for improving energy efficiency on system reliability. The developed valuation model was used as a tool for the analysis. The concept of breakeven availability was introduced and based on this an algorithm was also developed to allocate component reliability goals. The major research findings are listed below.

1) Modification of a system with a view for improving energy efficiency need not necessarily improve process system availability and reliability and vice versa.
2) A huge improvement in efficiency of a subsystem need not necessarily have the same effect on the overall system efficiency. On the other hand, the consequence of the decrease in the subsystem reliability and availability may have a serious impact on the overall system availability and reliability.
3) 73% improvement in feed water pumping system efficiency resulted in 24% reduction of pumping reliability and 0.6% decrease in availability. The impact of this modification on captive power plant is a 3% increase in thermal efficiency at the cost of 33% process system reliability and 0.8% process system availability.

4) The impact of modification on the process system value will depend on the relative value of the change in reliability and availability vs. energy efficiency.

5) In the case of power plant the change in process system value is negative as magnitude of the loss due to unavailability and unreliability is more than monetary benefit resulting from improvement in efficiency.

6) Decrease in process system reliability and availability after modification need not necessarily make the change in system value negative, provided that the monetary benefits resulting from improvement in energy efficiency are relatively more than the loss due to unavailability and unreliability.

7) Modification at concentrator part of a gelatin plant resulted in a reduction of 5% reliability and 0.6% availability for an increase of 51% efficiency and the resulting change in system value works out to be positive.

8) Increase in process system reliability and availability at the cost of energy efficiency can make the change in process system value negative if the magnitude of loss due to inefficiency is greater than the benefits resulting from high reliability and availability.

9) In the case of chocolate manufacturing company a 33% improvement in reliability and 0.16% improvement in availability resulted in about 13% reduction of efficiency and a negative change in process value of Rs. -17.6 lakhs for a system life of 15 years.

10) A modified system with a negative change in process value requires the breakeven availability to be allocated among the components. The breakeven

value of availability need not be necessarily greater than the process system availability before modification. The improvements in reliabilities required is more for those components that already have a low value for reliability.

REFERENCES

1. Armen, D. K., O. D. Ditlevsen and J. Song. (2007) Availability, reliability and downtime of systems with repairable components. Reliability Engineering and System Safety 92:231–242.
2. August, J. Reliability-centered maintenance. (1999) Penn Well Publishing; Tulsa, Oklahoma.
3. Babcock and Wilcox Co. (1978) Steam: Its Generation and Use. B & W, New York.
4. Badino, V. and G. L. Baldo. (1998) LCA, instructions for use. Bologna: Progetto Leonardo Edition (in Italian).
5. Bain, I. J. (1974) Analysis of linear failure rate life testing distribution. Technometrics 16:551-60
6. Barlow, R. and F. Proschan. (1975) Statistical theory of reliability and life testing probability models. Rinehart and Winston Inc., New York.
7. Barringer, H.P. (1999) Practical reliability for refinery and chemical plants. Barringer & Associates. Humble.
8. Barringer, P.E. and P. D. Weber (1996). Life-cycle cost tutorial. Gulf Publishing Company, Houston, TX.
9. Barringer, P.E. (2000) Reliability engineering principles. Barringer & Associates, Humble.

10. Bartow, R.E. and F. Prochan. (1975) Statistical theory of reliability and life testing. Rinehart and Winston Inc. NY (USA).

11. Blanchard, B.S. and W.J. Fabrycky. (1998) Systems engineering and analysis. Prentice-Hall, Upper Saddle River, NJ.

12. Blanchard, B. S., D. F. Verna and E .L. Peterson. (1995) Maintainability: a key to effective serviceability and maintenance management. John Wiley and Sons, New York (USA).

13. Chen, T.C. and T.C. Hsu. (2006) A GAs based approach for mining breast cancer pattern. Expert Systems with Applications, 30:674–681.

14. Chern. M. S. (1992) On the computational complexity of reliability redundancy allocation in a series system. Operations Research Letters 11: 309–315.

15. Coffin, K. (1998) Evaluating customer support during new product development: an explorative study. International Journal of Operations & Production Management 21(3):21–222.

16. Cordier, C., M. Fayot, A. Leroy and A. Petit. (1997) Integration of process simulations in availability studies. Reliability Engineering & System Safety 55; 105–16.

17. Cornelissen, R.L., E. N. Marquart and G.G. Hirs. (1999) The value of the exergetic life cycle assessment besides the LCA. International Proceedings of ECOS '99, Tokyo, Japan, p. 282–6.

18. Dann, R. (1984) Domestic heating systems and controls for condensing boilers. Heat Ventilat Engr 58(668):1–14.

19. Davidson, J. (1998) The reliability of mechanical systems. Mechanical

Engineering Publications Limited, Instiution of Mechanical Engineers, London.

20. Defu, C., Y. Liu and C. Gao. (2004) Evaluation of retrofitting a conventional natural gas fired boiler into a condensing boiler. Energy Conversion and Management 45:3251–3266.

21. Dhillon, B. S. (1981) Life distributions. IEEE Transactions on Reliability R30:457-9.

22. Dhillon, B. S. (1999) Engineering maintainability: how to design for reliability and easy maintenance. Gulf Publishing, Houston, USA.

23. Edelstein, K. L. (1988) Mathematical models in biology. Random House, New York.

24. Engin, Ozdemir. (2004) Energy conservation opportunities with a variable speed controller in a boiler house. Applied Thermal Engineering 24:981–993.

25. Estop, T.D. and D.R. Croft. (1990) Energy Efficiency. Longman Scientific and Technical, Essex.

26. Eti, M. C., S. O. T. Ogaji and S. D. Probert. (2007) Integrating reliability, availability, maintainability and supportability with risk analysis for improved operation of the Afam thermal power-station. Applied Energy 84: 202–221.

27. Facchini, B., F. Daniele and M. Giampolo. (2000) Exergy analysis of combined cycles using latest generation gas turbines. Journal of Engineering for Gas Turbine Power, 122;233-238.

28. Fiaschi, D. and G. Manfrida. (1998) Exergy analysis of the semi-closed gas turbine combined cycle. Energy Conversion and Management 39:1643–1652.

29. Field, A.A. (1974) Reclaiming latent heat in flue gases. Heating-piping-air

conditioning 46(11):85–7.

30. Gaggioli, R. A. (1999) Reflections on the history and future of exergy. Proceedings of the ECOS'99, Tokyo. p. 5–13.

31. Gaver, D. P. and M. Acar. (1979) Analytical hazard representation for use in reliability, mortality and simulation studies. Communications in Statistics-Simulation and Computation B8 (2):91-111.

32. Gen, M., K. Ida and J.U. Lee. (1990) A Computational algorithm for solving 0-1 goal programming with GUB structures and its application for optimization problems in system reliability – Part 3. Electronics and Communications in Japan 73:88–96.

33. Gen, M., K. Ida, Y. Tsujimura and C.E. Kim. (1993) Large-scale 0-1 fuzzy goal programming and its application to reliability optimization problem. Computers and Industrial Engineering 24:539–549.

34. Goel, H. D., J. Grievink, P. M. Herder and M. P. C. Weijnen. (2002) Integrating reliability optimization into chemical process synthesis, Reliability Engineering and System Safety 78:247–258.

35. Gordon, J. S. (1983) Heat recovery with condensing heat exchangers. American Dyestuff Reporter 72(10):23–4.

36. Grievink, J., K. Smit, R. Dekker and C. F. H. Van Rijn. (1993) Managing reliability and maintenance in the process industry. Conference on Foundation of Computer Aided Operations, FOCAP-O, Colorado, USA. p. 133–57.

37. Haupt, E. and H. Schabe. (1992) A new model for life time distribution with bathtub shaped failure rate. Microelectronics Reliability 32(5):633-9.

38. Henley, E. J. and H. Kumampto. (1985) Design for reliability and safety control. Prentice-Hall, New Jersey,

39. Henley, E. J. and S. L. Gandhi. (1975) Process reliability analysis. American Institute of Chemical Engineers Journal 21: 677–86.

40. Hijroth, U. (1980) A reliability distribution with increasing, decreasing, constant and bath-tub shaped failure rates. Technometrics 22(1):99-107.

41. Hiroshi, T., K. Mouri, T. Nakahara and N. Arai. (2005) Exergy analysis on combustion and energy conversion Processes. Energy 30: 111–117.

42. Hsieh, Y.C., T. C. Chen and D. L. Bricker. (1998) Genetic algorithm for reliability design problems. Microelectronics Reliability 38:1599–605.

43. Imad, H. I. and M. M. Mahmoud. (2005) Energy effciency improvement procedures and audit results of electrical, thermal and solar applications in Palestine. Energy Policy 33 651–658

44. Ireson, W. G. (1996) Handbook of reliability engineering and management. McGraw-Hill, New York (USA).

45. Ishida, M., K. Kawamura. (1982) Energy and exergy analysis of a chemical process system with distributed parameters based on the energy-direction factor diagram. Industrial & Engineering Chemistry Process Design and Development 21:690–702.

46. Ishida, M. (1983) Hierarchical structure analysis based on energy and exergy transformation of a process system. Proceedings of the International Conference on Efficiency and Costing: Second Law Analysis of Process, Washington. p. 179–211.

47. Jaisingh, L. R., W. J. Kolarik and D. K. Dey. (1987) A flexible bathtub hazard model for non-repairable systems with uncensored data. Microelectronics reliability 27(1): 87-103.

48. James, L. R., D. D. Bedworth and U. R. Sabah. (2004) Engineering economics, Tata Mcgraw-Hill Publishing Company Ltd., New Delhi.

49. James Lutz, A. Lekov, P. Chan, C. D. Whitehead, S. Meyers and J. McMahon. (2006) Life-cycle cost analysis of energy efficiency design options for residential furnaces and boilers. Energy 31:311–329.

50. Kececioglu, D. (1991) Reliability Engineering Handbook, vol. 2. Prentice-Hall, Englewood Cliffs, NJ.

51. Kim, J. H. and B. J. Yum. (1993) A heuristic method for solving reliability redundancy optimization problems in complex systems. IEEE Transactions on Reliability 42(4):572–578.

52. Kohda, T. and K. Inoue. (1982) A reliability optimization method for complex systems with the criterion of local optimality. IEEE Transactions on Reliability R31 (1):109–111.

53. Kudo., K, H. Taniguchi, T. Matsumura and Q. R. Huang. (1984) Exergy analysis of thermo-electric power station. Journal of Thermal and Nuclear Power in Japan 35(1):31–40.

54. Kumar, D., B. Klefsjo and U. Kumar. (1992) Reliability analysis of power-transmission cables of electric loaders using a proportional-hazard model. Reliability Engineering & System Safety 37:217–22.

55. Kumar, U. (1990) Reliability analysis of a load-haul-dump machine, PhD

Thesis, Lulea University of Technology, Lulea.

56. Kuo, W., H. Lin H., Z. Xu, and W. Zhang. (1987) Reliability optimization with the Lagrange multiplier and branch-and-bound technique. IEEE Transactions on Reliability, 36:624–630.

57. Kuo, W., V. R. Prasad, F.A. Tillman and C. Hwang. (2001) Optimal reliability design. Cambridge University Press, Cambridge.

58. Kuo, W. and V. R. Prasad. (2000) An annotated overview of system-reliability optimization. IEEE Transactions on Reliability 49(2):176–87.

59. Lawless, J. F. (1982) Statistical models and methods for life time data. Wiley, New York.

60. Lazzaretto, A., A. Macor, A. Mirandola and A. Stoppato. (1998) Potentialities and limits of exergoeconomics methods in the design, analysis and diagnosis of energy conversion plants. Proceedings of the International Conference on Advances in Energy Studies, Porto Venere, Italy: MUSIS. p. 515–30.

61. Lekov, A., G. Stevens, J. Lutz and S. Meyers. (2003) Cost and energy consumption of energy efficiency design options for residential furnaces and boilers, Report No. LBNL-52762. Berkeley, CA: Lawrence Berkeley National Laboratory.

62. Lewis, E. E. (1996) Introduction to reliability engineering. Wiley, New York.

63. Li, D. and Y. Y. Haimes. (1992) A decomposition method for optimization of large-system reliability. IEEE Transactions on Reliability, 41:183–188.

64. Li, Z. L. (2001) Availability allocation of series-parallel system solved from object-oriented planning, Unpublished Master's Thesis, Feng-Chia University,

Taichung, Taiwan.

65. Linnhoff, B. (1979) Thermodynamic analysis in the design of process networks. Ph.D. Thesis. University of Leeds, UK.

66. Liu, T. I., and X. M. Yang. (1999) Design for quality and reliability using expert system and computer spreadsheet. Journal of the Franklin Institute, 336(7):1063–1074.

67. Lozano, M. A. and A. Valero. (1993) Theory of the exergetic cost. Energy 18(9):939–60.

68. Markeset, T. and U. Kumar. (2001) Integration of RAMS information in design processes – a symposium. 20–24 January, Tampa, FL.

69. Ming Yang. (2006) Energy efficiency policy impact in India: case study of investment in industrial energy efficiency. Energy Policy 34:3104–3114.

70. Misra, K. B. and U. Sharma. (1991) An efficient algorithm to solve integer programming problems arising in system reliability design. IEEE Transactions on Reliability 40(1): 81–91.

71. Mohan, C. and K. Shanker. (1998) Reliability optimization of complex systems using random search technique. Microelectronics and Reliability, 28(4), 513–518.

72. Moon,Y. B., C. K. Divers and H. J. Kim. (1998) AEWS: an integrated knowledge-based system with neural networks for reliability prediction. Computers in Industry, 35(2), 101–108.

73. Moss, M. A. (1985) Design for minimal maintenance expense. Marcel Dekker Inc. New York (USA).

74. Nakagawa, Y. and S. Miyazaki. (1981) An experimental comparison of the heuristic methods for solving reliability optimization problems. IEEE Transactions on Reliability, 30:81–184.

75. Nobuzawa, T. (1987) Introduction to exergy. Ohm Co, Tokyo.

76. Noir, D. and N. Houlmann. (1982) European technology in condensing flue-gas systems. In: Symposium on Condensing Heat Exchangers Proceedings, vol. II, March 3–4, Atlanta, GA. pp. 10.1–10.15.

77. O'Callaghan, P. W. (1993) Energy Management, McGraw-Hill Co, Berkshire.

78. Odum, H. T. (1995) Environmental accounting emergy and decision making. Wiley, New York.

79. Page´s, A. and M. Gondran. (1986) System reliability evaluation and prediction in engineering. Springer, New York.

80. Pickup, G. (1983) Innovation in home heating. Gas Engineering & Management 23(5):171–8.

81. Prasad, V. R. and W. Kuo. (2000) Reliability optimization of coherent systems. IEEE Transactions on Reliability 49:323–330.

82. Ronald, A. Z. (1997) Energy Efficiency Handbook, Council of Industrial Boiler Owners (CIBO).

83. Rosenquist, G., P. Chan, A. Lekov, J. McMahon and B. R. Van. (2002) Consumer life-cycle cost impacts of energy-efficiency standards for residential-type central air conditioners and heat pumps. ASHRAE Transactions 108(Part 1):619–30.

84. Schabe Hendrik. (1994) Constructing lifetime distributions with bathtub shaped

failure rate from DFR distributions. Microelectronics and Reliability. 34(9):1501-8.

85. Sciubba E. (1999) Exergy as a direct measure of environmental impact. Proceedings of International Mechanical Engineering Conference and Exposition - ASME Winter Annual Meeting Nashville, USA. p. 231–38.

86. Searle, M. and A. R. Shiret. (1986) The opportunities for a new generation of high efficiency gas boiler. Gas Engineering & Management 26(7–8):200–14.

87. Shook, J. R. (1991) Recover heat from flue gas. Chemical Engineering Progress 87(6):49–54.

88. Shooman, M. I. (1968) Probabilistic reliability: an engineering approach. McGraw Hill, New York.

89. Siddhartha Bhatt. (2000) Energy audit case studies I- steam systems. Applied Thermal Engineering 20:285-296.

90. Smith, R. M. and Bain I. J. (1975) An exponential power life-testing distribution. Communications In Statistics 4(5): 469-81.

91. Srinath, L. S. (1991) Reliability engineering. Affiliated East-West Press, New Delhi.

92. Streatfield, L. (1984) Are condensing boilers the correct choice for domestic heating systems. Heat Ventilat Engr 58(673):5–6.

93. Szargut, J. (1999) Depletion of unrestorable natural exergy resources as a measure of the ecological cost. Proceedings of ECOS '99, Tokyo, Japan p. 42–5.

94. Taniguchi, H., K. Kasahara, K. Kudo, J. Ohta, I. Park and S. Kitajima. (1984)

Performance characteristics of heat pump–boiler system. Transactions of Heat, Air-conditioning and Sanitary Engineering in Japan 25:51–60.

95. Thangamani, G., T. T. Narendran and R. Subramanian. (1995) Assessment of availability of a fluid catalytic cracking unit through simulation. Reliability Engineering & System Safety 47:207–20.

96. Thomas, W. C. (1973) Modeling the bathtub curve. Proceedings of the Annual Reliability and Maintainability Symposium.

97. Thompson, R. E. (1983) Condensing flue gas water vapor: another way to cut your fuel bill. Power 27(5):79–82.

98. Thorn, W. F. (1987) Waste heat recovery from stacks using direct-contact condensing heat exchanger. In: Paper Presented at the 9th World Energy Engineering Congress, p. 483–95.

99. Todinov, M. T. (2004) Setting reliability requirements based on minimum failure-free operating periods,Quality and Reliability Engineering International. 20:273–287.

100. Tonon, S., M. T. Brown, F. Luchi, A. Mirandola, A. Stoppato and S. Ulgiati. (2006) An integrated assessment of energy conversion processes by means of thermodynamic, economic and environmental parameters. Energy 31: 149–163

101. Tsatsaronis, G. and M. Winhold. (1985) Exergoeconomic analysis and evaluation of energy conversion plants; part I: a new general methodology; part II: analysis of a coal-fired steam power plant. Energy 10(1):81–94.

102. US Department of Energy (DOE). (2004) Improving steam system Performance: A sourcebook for industry, United States.

103. Valero, A. (1998) Thermoeconomics as a conceptual basis for energy-ecological analysis. International Conference on Advances in Energy Studies, Porto Venere, Italy: MUSIS. p. 415–44.

104. Varde, P. V., S. Sankar S and A. K. Verma. (1998) An operator support system for research reactor operations and fault diagnosis through a connectionist framework and PSA based knowledge based systems. Reliability Engineering and System Safety, 60(1):53–69.

105. Vassiliadis, C. G. and E. N. Pistikopoulos. (1999) Chemical-process design and maintenance optimization under uncertainty: a simultaneous approach. Proceedings of the annual International Reliability and Maintainability Symposium. p. 78–83.

106. Vaurio, J. K. and P. Tammi. (1995) Modeling the loss and recovery of electric power. Nuclear Eng Des 157:281–93.

107. Vaurio, J. K. (1997) Reliability characteristics of components and systems with tolerable repair times. Reliability Engineering and System Safety 5643–52.

108. Von Spakovsky, M. R. and C. A. Frangopoulos. (1993) A global environomic approach for energy systems analysis and optimization; part I and part II. Proceedings of the International Conference on Energy Systems and Ecology, Cracow, Poland. ASME, vol. 1 p. 123–44.

109. Wang, K. S., S. T. Chang and Y. C. Shen. (1996) Dynamic reliability models for fatigue crack growth problem. Engineering Fracture Mechanics 54(4): 543-56.

110. Wang K. S., F. S. Hsu and P. P. Liu. (2002) Modeling the bathtub shape hazard

rate function in terms of reliability. Reliability Engineering and System Safety 75:397-406.

111. Wang, K. S., E. H. Wan and W. C. Yang. (1993) A preliminary investigation of new mechanical product development based on reliability theory. Reliability Engineering and System Safety 40:187-94.

112. Wang, Y., R. C. M. Yam, M. J. Zuo and P. Tse. (2001) A comprehensive reliability allocation method for design of CNC lathes. Reliability Engineering and System Safety; 72247–252.

113. Warburton, D., J. E. Strutt and K. Allsop. (1998) Reliability-prediction procedures for mechanical components at design stage. Proceedings of Institution of Mechanical Engineers 212(Part E):213–24.

114. West, T. (2002) From mechanical to electronic control in industrial burners, Technical Bulletin, Energy Technology and Control Ltd.

115. Xie, M. and C. D. Lai. (1996) Reliability analysis using an additive Weibull model with bathtub shaped failure rate function. Reliability Engineering and System Safety 52: 87-93.

116. Yalaoui, C. C. and E. Chatelet. (2005) Reliability allocation problem in a series-parallel system. Reliability Engineering and System Safety 9055–61.

117. You, P. S. and T. C. Chen. (2005) An efficient heuristic for series-parallel redundant reliability problems. Computers and Operations Research, 322117–2127.

118. Zheng, D., Y. Uchiyama and M. Ishida. (1986) Energy-utilization diagrams for two types of LNG power-generation systems. Energy 11(6):631–9.

119. Zheng, D., R. Yao and H. Jin. (2004) Thermodynamic methodology of energy-flow framework diagram for technical energy systems. Energy 29: 2473–2486.

PUBLICATIONS RELATED WITH THE RESEARCH

1. Presentations in conferences

1. Shouri P. V. and Sreejith P. S. Algorithm for breakeven reliability allocation in system modification. Proceedings of the First International & 22nd AIMTDR Conference, 21-23 December 2006, IIT Roorkee, India. pp 752.
2. Shouri P. V. and Sreejith P. S. Application of system valuation model in reliability allocation of modified steam system. Proceedings of the International Conference on Global Manufacturing and Innovation, 27-29 July, 2006, Coimbatore, India. pp 147.
3. Shouri P. V. and Sreejith P. S. Importance of pumping reliability in system valuation. Proceedings of the International Conference & Exhibition on Fluid Power Technology- EMCHAFT 2005, 25-27 November 2005, Chennai, India. pp 265.
4. Shouri P. V. and Sreejith P. S. Process valuation model incorporating reliability. National conference on manufacturing and management, 26-27 August 2005, M.A. College of Engineering, Kothamangalam, Kerala, India. pp 56.
5. Shouri P. V. and Sreejith P. S. Effect of improving Energy Efficiency on Process Reliability. All India Seminar on Emerging trends in Maintenance Management, 23- 24 July 2005 , National Aluminium Company Limited, NALCO Nagar, Orissa, India. pp 281.

6. Shouri P. V. and Sreejith P. S. Reliability and Energy Efficiency. National Conference on Recent Trends in Design and Manufacturing Technologies, 17-18 March 2005, Coimbatore. India. pp 47.

2. International Journals

1. Shouri P. V. and Sreejith P. S. Algorithm for breakeven availability allocation in process system modification using a deterministic valuation model incorporating reliability. International Journal of Energy Conversion and Management (Communicated).
2. Shouri P. V. and Sreejith P. S. Application of System Valuation Model in Reliability Allocation of Modified Steam System. Special Edition of the International Journal of Operations Research in Connection with the International Conference on Global Manufacturing and Innovation, GMI 2006 (Communicated).
3. Shouri P. V. and Sreejith P. S. Importance of the Relative Magnitude of the Change in Energy Efficiency and Reliability in System Modification. Applied Energy (Communicated).