AN INTEGRATED LEAN ENERGY FRAMEWORK

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ABSTRACT

AN INTEGRATED LEAN ENERGY FRAMEWORK

Energy expenses are one of the major cost items in a manufacturing facility. Furthermore, in order to satisfy the continuously increasing demand of energy, decision makers focus on the supply-side in general rather than demand-side improvements. In this thesis, the aim is to develop a methodology for energy demand-side management. The proposed approach is implemented in a footwear company. What is unique in this study is the methodology combines lean manufacturing principles with energy economics analysis and optimization. As a first step, an initial assessment of the current energy consumption profile is made identifying the major energy consuming units to point out improvement opportunities for the reduction of the energy used. These retrofitting opportunities and lean methods to reduce energy consumption are evaluated. They are economically analyzed using energy price forecasting and Monte Carlo Simulation and then optimized according to their investment costs and potential savings with a simple model which is later solved with GAMS software. The total energy consumption per product is compared before and after the application of the suggested improvements. The results showed that with short payback periods and small budgets, the energy use of the company can be optimized.

ÖZET

BÜTÜNLEŞİK BİR YALIN ENERJİ SİSTEMİ

Enerji maliyetleri bir üretim tesisindeki en önemli maliyet kalemlerinden biridir. Ayrıca, artan enerji talebini karşılamak için genellikle talep kısmı yerine arz kısmı dikkate alınmaktadır. Bu tezin amacı enerji talep yönetimi için bir metodoloji geliştirmek ve bir ayakkabı fabrikasında uygulamaktır. Önceki çalışmalardan farklı olarak, metodoloji enerji tasarrufu için yalın üretim prensiplerini mühendislik ekonomisi ve eniyileme yöntemleriyle birleştirmektedir. İlk olarak, kullanılan enerjiyi azaltacak çözümler bulmak amacıyla işletmenin mevcut enerji tüketim profili ve enerji tüketicileri analiz edilmektedir. Daha sonra ilgili yayınlardaki enerji verimliliği fırsatları incelenmektedir. Söz konusu gelişim fırsatları, öncelikle gelecekteki enerji fiyatı tahminleri ve Monte Carlo benzetim yaklaşımıyla ekonomik olarak analiz edilmekte ve ardından yatırım maliyeti ve potansiyel tasarruf açısından basit bir model oluşturulup GAMS yazılımı ile çözülmektedir. Sonuçlar kısa geri dönüş süresi ve küçük bütçeler ile işletmenin enerji kullanımının eniyilenebileceğini göstermiştir.

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LIST OF SYMBOLS

B_T	Budget constraint for the whole improvement opportunities
d	Integrative part of ARIMA
EI_p	Energy intensity for process p
EI_w	Energy intensity of the whole value stream
f	Index for energy efficiency improvement opportunities
g	Growth rate of energy price in percentage
H	Information entropy
i	index for factors
$i*$	index for factors eliminated in FA stage
j	index for equipments
k	Index for scorecards
K_f	Investment for improvement opportunity f in TL
p	Autoregressive part of ARIMA
P_e	Power input for different energy types
PI_f	Profitability index of improvement opportunity f
PP_f	Payback period of the investment on improvement opportunity f in years
PP_{max}	Pre-defined maximum payback period
q	Moving average part of ARIMA
r	discount rate
R_f	Rating change of improvement opportunity f
r_{xy}	Correlation coefficient
S_f	Saving as a result of improvement opportunity f
t	time
w_{kij}	Relative importance weight for scorecard k, factor i, equipment j
X_f	Investment decision on improvement opportunity f
τ	Kendall's tau coefficient

LIST OF ACRONYMS/ABBREVIATIONS

AC	Alternating Current
ACF	Autocorrelation Function
ARIMA	Autoregressive Integrated Moving Average
ASD	Adjustable Speed Drive
ASME	American Society of Mechanical Engineers
BEP	Best Efficiency Point
BIS	Bureau of Indian Standards
CANMOST	Canadian Motor Selection Tool
CCT	Correlated Color Temperature
CFL	Compact-Fluorescent Lamp
CRI	Color Rendering Index
C/O	Changeover Time
C/T	Cycle Time
DC	Direct Current
DE	Degree of Efficiency
DEA	Data Envelopment Analysis
DOE	U.S. Department of Energy
DSM	Demand-Side Management
EASA	Electrical Apparatus Service Association
EI	Energy Intensity
EMT	Energy Manager Training
EPA	U.S. Environmental Protection Agency
FA	Factor Analysis
FD	Factory Working Days
FL	Fluorescent Lamp
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GLS	General Lighting Service
GWP	Global Warming Potential
HEM	High Efficient Motor

HID	High-Intensity Discharge Lamp
HPMV	High Pressure Mercury Vapor Lamp
HPSV	High Pressure Sodium Vapor Lamp
HVAC	Heating Ventilation and Air Conditioning
IDA	Index Decomposition Analysis
IEA	International Energy Agency
IMSSA	International Motor Selection and Savings Analysis
IRR	Internal Rate of Return
KWH	Kilo-Watt Hour
MRP	Materials Resource Planning
LED	Light Emitting Diode
LPSV	Low Pressure Sodium Vapor Lamp
MWH	Mega-Watt Hour
NEIS	Non-Energy Intensive Sector
NPV	Net Present Value
OECD	Organization for Economic Co-operation and Development
OR	Operations Research
PACF	Partial Autocorrelation Function
PI	Profitability Index
PT	Processing Time
TAL	Task Ambient Lighting
TEDAS	Turkish Electricity Distribution Corporation
TPM	Total Productive Maintenance
TT	Takt Time
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
UNIDO	United Nations Industrial Development Organization
VFD	Variable Frequency Drive
VSD	Variable Speed Drive
VSM	Value Stream Mapping
WIP	Work-in Process
WM	Working Minutes

1. INTRODUCTION

1.1. Motivation for the Thesis

Energy is a crucial resource for daily life activities since it is used in services such as lighting, heating, cooling, cooking, food conservation and makes possible the use of various technological devices from washing machines and dishwashers to computers and televisions. With the developments in science and technology, energy consumption increased indispensably which is seen as the reason for global warming as a result of depletion of natural resources and the emission of greenhouse gases (GHG). Based on the conclusions derived from Climate Change Convention agreed upon in Rio de Janeiro in 1992 at the Earth Summit, it is unavoidable that many governments need to address global warming [1].

Today, limiting GHG emissions by regulations or by investment in new technologies is the idea lying behind many territorial decisions being made. Increasing global temperatures is the scientific argument these decisions are driven by. It is expected that a substantial abatement of emissions could reduce the negative impacts. According to Intergovernmental Panel on Climate Change, an increase in global temperatures more than two degrees compared to pre-industrial years will have intense effects as flooding, water shortages, reduced crop yields. As a result of these effects major ecological and social troubles are expected [2]. It is essential that the consciousness and sensitivity regarding energy saving issues should increase and every precaution should be taken to prevent the world from the potential hazardous scenarios.

A thorough evaluation carried out for Turkey reveals that Turkish electricity demand per capita is already below the European average, but Turkey is expected to achieve the fastest medium to long term energy demand growth among IEA member countries with its young and urbanizing population. In addition, Turkey had an exceptional GDP growth in the last decade compared to the other OECD countries [3]. As in all expanding economies, services sector is the largest economic sector with 57.7% of GDP in 2013 whereas industry constitutes 23.6% and manufacturing is the major activity in industry [4]. To this energy demand growth ensuring sufficient energy supply has generally been the main solution and not much attention has been shown in the demand side. In addition, although being a partner to UNFCCC since 2004 and to the Kyoto Protocol since 2009, Turkey is the only IEA member that does not have a quantitative emissions reduction target. It is also the only OECD country that does not have a national emission target for 2020 [3].

Less than 3% of Turkish consumption is satisfied with Turkey's domestic oil and gas production. Thus, the country is a major importer with 90% of crude oil coming from Iraq, Iran, Saudi Arabia and Russia [5]. Clearly, Turkey is an energy dependent country. As a consequence, the energy security and sufficient energy supply are among the main concerns of policy makers rather than demand-side management or environmental issues. Primary energy resources of Turkey are shown in Figure 1.1.

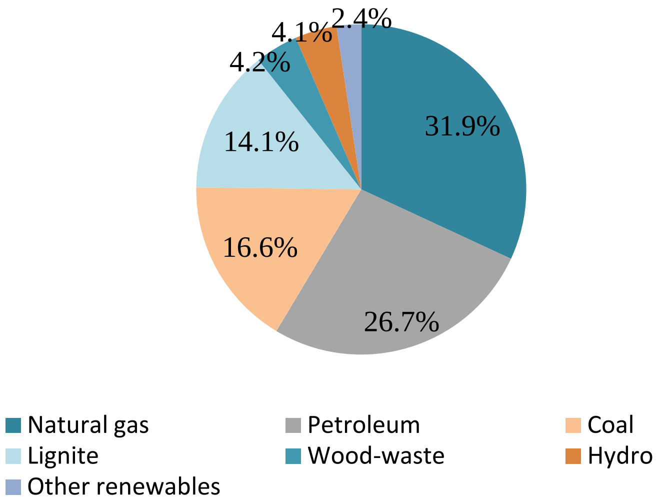


Figure 1.1. Resources used for energy generation.

Besides the electricity demand growth, another electricity consumption problem is the peak demand in particular hours of a day or a particular month of a year. In winter season, lighting and heating; and in summer season cooling is the main source of peak demand within a time period. Turkey has the summer peak in July and the winter peak in December or January. Because of peak loads, the lower pressure in the natural gas pumps and the unfulfillment of the demand cause blackouts or brownouts. Also the electricity prices increase because of the insufficient supply and excess demand. In Figure 1.2, energy demand and peak demand changes are given for a better understanding and it is obvious that peak demand increase sharply [6]. Thus, being an energy dependent country and having an increasing and unsmooth energy consumption make some alterative decisions necessary such as the management of demand-side of energy.

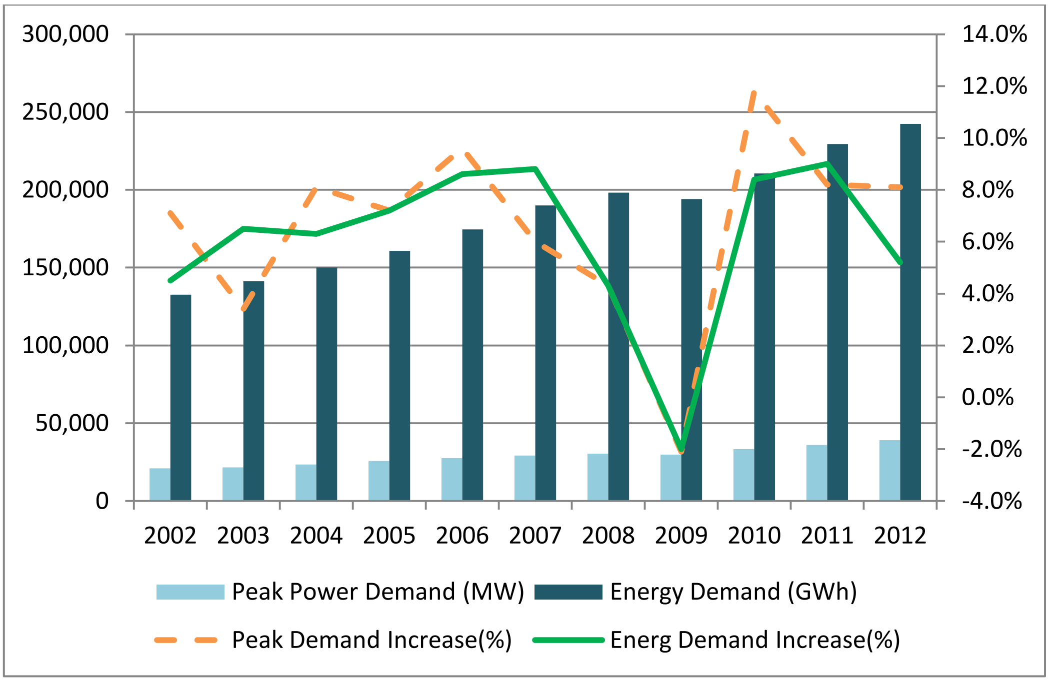


Figure 1.2. Turkish electricity and peak demand.

1.2. Thesis Subject and Scope

United Nations Environment and Development Commission has defined sustainable development as meeting the needs of the present without compromising the ability of future generations to meet their own needs [7]. This expression states that technological, social, environmental and economic factors should be managed by taking into account the future generations. Sustainability issues are critical for energy management programs since energy depletes the natural resources and causes global warming due to the emissions.

The demand-side of the energy aims to manage a sustainable environment, economy and society. Demand-side management (DSM) refers to actions, policies or programs in order to change electricity consumption habits of end users either with a reduction in electricity use or a change in the use. Energy efficiency which is a key component of DSM means the reduction of input energy for the same amount of output energy. This is generally realized with the use of other appliances or technological changes implemented [8].

The purpose of this thesis is to create a methodology for the reduction of energy use in industrial facilities. Lean tools and assessment, electricity price forecasting, engineering economics analysis and optimization with a limited investment budget are the techniques resorted in the methodology. An existing shoe manufacturing plant is taken as a case and the proposed methodology is implemented to achieve a sustainable factory. All improvement opportunities are clearly investigated, evaluated and the most promising choices are identified. The manufacturing plant is in the non energy-intensive sector (NEIS).

1.3. Expected Contributions and Limitations

Energy efficiency literature is generally based on supply-side strategies and methods, although implementation of demand-side strategies are more affordable and effortless. This thesis attempts to bring out a demand-side energy efficiency methodology. Furthermore, the methodology will consider energy consuming units in NEIS factory. The most significant contribution of the thesis is the integration of lean philosophy with economical analysis and optimization.

For the case study, the machine infrastructure is considered at a macro level just for the sake of illustrating and certain details are neglected. Due to restrictions in the data access, certain assumptions are made. Furthermore, since energy consumption reduction is the key focus, other lean improvement opportunities which are not linked to energy are omitted.

1.4. Data Collection

Energy efficiency literature is so broad to identify improvement opportunities with emphasis on their economic and environmental impacts. Although the literature mainly focus on energy-intensive facilities, some papers on low intensive sectors are also available. U.S. Department of Energy (DOE), U.S. Environmental Protection Agency (EPA), U.S. Environmental Program (UNEP), serve as the main sources besides numerous published articles, reports and conference proceedings about energy efficiency topic. The relevant data for the case study are gathered from the company. There are some assumptions made and transformations carried out on the available data.

1.5. Structure of the Thesis

The three-step structure of the study is illustrated in Figure 1.3.

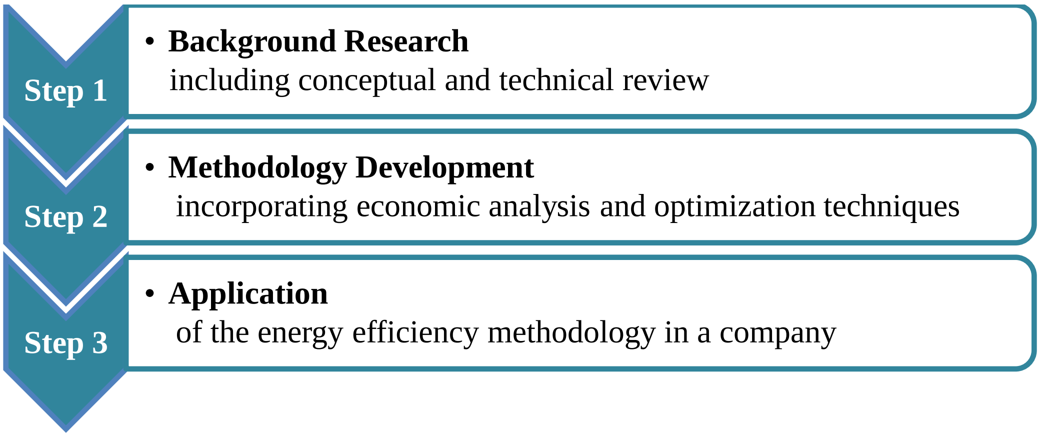


Figure 1.3. Structure of the study.

As a first step, the key notions of energy efficiency and energy intensity are reviewed. The barriers for energy efficiency are covered. Then, a descriptive and comprehensive overview of related research on energy efficiency methods are summarized from the available literature in Chapter 2. Furthermore, this chapter elaborates on how lean philosophy can be used for energy efficiency purposes and points out the previous experiences. This part takes part in Chapter 2.

The second step focuses on the development of the methodology and related concepts. In other words, the methodology is portrayed in detail in Chapter 3. This is the step where the integrated framework is proposed. This chapter constitutes the major contribution of the thesis.

Finally, a real life application takes place where a footwear company is assessed according to the methodology to provide an example for the proposed methodology. All the necessary information about the company and the processes are illustrated in Chapter 4 and Appendix A-B. Afterwards, the results are evaluated and a sensitivity analysis is carried out. Chapters 5 and 6 both examine the methodology in detail and embody it simultaneously with a case study whereas Chapter 7 summarizes the results.

2. LITERATURE REVIEW

Chapter 2 gives an overview on the terms and various approaches on energy efficiency. Firstly, in Section 2.1, the notions of energy efficiency and intensity are introduced, and energy efficiency measures are summarized. Barriers preventing energy efficiency to be achieved are listed in Section 2.2. Then, Section 2.3 points out the literature on the topic from a broader perspective. Afterwards, a specialized section on lean methodology is added which constitutes the studies on lean concept, energy value stream mapping methodology and combination of lean concept and energy efficiency.

2.1. The Notions of Energy Efficiency and Intensity

Demand-side management (DSM) refers to actions, policies or programs that aim to change the electricity consumption habits of end users either with a reduction in electricity use or an improvement in related processes. Energy efficiency, energy conservation and load management are three components of DSM. Energy efficiency means the reduction of input energy for the same amount of output energy which is generally realized with the use of other appliances or technology whereas conservation refers to changes in consumption and lifestyle. Load management is the program for shifting electricity consumption from peak hours to off-peak hours [8]. There is a high potential in reduction of energy consumption through energy efficiency studies. For example, in an analysis carried out by McKinsey & Company for Russian industrial sectors, it is seen that energy consumption is expected to have a 23% growth until 2030. However, 12% less energy consumption can be achieved through efficiency improvements [2].

According to Patterson, the term energy efficiency is not well understood in spite of its frequent use. He defines energy efficiency as the ratio of useful outputs to energy inputs for a system. The output may be considered as an energy conversion device, a building, a single industrial process, the whole firm, a sector or even an entire economy. Regardless of the problem scope, definition of usefulness and measurement of inputs and outputs will designate energy efficiency [9].

Energy efficiency can be measured as physical, thermodynamic or economic measures. For the physical measures, the outputs are defined in terms of physical terms, such as number of products or tones of steels produced or kilometers driven with an amount of energy. Thermodynamic terms are used to define the outputs for thermodynamic measures such as the amount of heat gained with a given amount of energy such as electricity or natural gas. Lastly, for economic measures, the outputs (and sometimes the inputs) are defined in economic terms, such as value added or GDP.

Physical and thermodynamic measures can also be called as mechanical measures. The term energy efficiency is mostly used for mechanical terms whereas for economic measures, it is more common to use the term energy productivity.

In industrial sectors, energy consumption is commonly classified as either process or generic. The former refers to energy directly used in the production process, whereas the latter refers to energy used in supporting tasks such as heating, ventilation, air conditioning (HVAC), lighting and information technology. However, the boundary between these two is not clear since generic applications are so minor compared to the process applications in terms of energy use. Process applications include compressed air, pumping, fan systems, steam systems and high-and-low temperature process heat [9].

Energy intensity is defined as the quantity of energy used per unit of output or activity. Thus, energy intensity is the inverse of energy efficiency [10,11].

Energy efficiency potential in German industrial sectors is investigated with an economic viewpoint. It is seen that the potential is higher in large-scale and energy-intensive processes that rely on a single source of demand. High-potential sectors are selected on two criteria which are total electricity demand and specific costs for energy. It is found that cement, inorganic materials and chemicals, aluminum, paper industry and hot metal industry are energy intensive sectors where the potential for demand-side management is high [12]. Thus, energy efficiency analyses in the industrial sector have generally focused on energy-intensive sectors. Thus, non-energy-intensive sector (NEIS) is generally ignored. Since their individual contribution to the total energy demand is lower, their products, processes and technologies are not homogenous, and reliable data about these sectors are missing, NEIS companies could not attract any attention. In other words, there are limited studies in this sector. One such study is due to Martinez where the German and Colombian NEIS companies are investigated in terms of energy efficiency. In this paper, the key factors affecting energy efficiency performance and the differences for a developed and a developing country are analyzed [13].

2.2. A Taxonomy of Barriers to Energy Efficiency

There is significant technical potential for improving industrial energy efficiency, sometimes even without any cost incurred and some other cases with the adoption of newly proven more effective technologies. However, it is observed that there are numerous barriers in adoption of such technologies as in Table 2.1 [9].

2.3. Measurement Approaches for Energy Efficiency

Researchers from different disciplines such as engineering, economics, industrial ecology and operations research used various approaches for the measurement of industrial energy efficiency. Greening classifies these approaches in four subtitles as trend decomposition methods, econometric models, top-down or bottom-up models and industry-specific micro-economic analyses [14].

Energy trend decomposition methods analyze the impacts of structural changes and energy efficiency (or other factors) on a country's aggregate energy or emissions trends [13]. Tol and Weyant state that 8 out of 10 most cited energy economics papers are on decomposition methods and its applications [15]. Ang and Zhang assesses new methods, classifies decomposition methods and present several tests to identify these desirable properties [16]. Alcantara and Duarte compares energy intensities of European Union countries while Unander decomposes manufacturing energy use in IEA countries [13]. It has been found that IDA-based energy efficiency studies mainly concern about the measurement of energy efficiency changes over time in a specific entity. This may be a country or a specific energy-consuming sector. Only a few deal with the benchmarking of energy efficiency performance across different entities [17].

Table 2.1. Barriers in adoption of energy efficiency.

Barrier	**Claim**
Risk	Energy efficiency investments represent a higher technical risk if the technology is unreliable. The risk of breakdown and disruptions are high which outweighs any potential benefits of the reduced energy costs. In conclusion, they also represent financial risk because of payback periods, liquidity, return of investment and opportunity costs.
Imperfect information	Lack of information on energy efficiency may result in the failure of cost-effective opportunities. In some cases, imperfect information may lead inefficient products to drive efficient products out of the market.
Hidden costs	Engineering economic analyses may fail to account for either the reduction in utility associated with energy efficient technologies, or the additional costs associated with them. Thus, the studies may overestimate energy efficiency potential. Examples of hidden costs include overhead costs for management, auditing, disruptions to production, staff replacement and training, formal procedures, and the costs associated with gathering, analyzing and applying information.
Access to capital	If an organization has insufficient capital through internal funds, and has difficulty finding additional funds through borrowing or share issues, investments may not go ahead. Investment could also be inhibited by internal capital budgeting procedures, investment appraisal rules and the short-term incentives of energy management staff whereas external financing may be risky.
Split incentives	Energy efficiency opportunities are likely to be inevitable if actors cannot appropriate the benefits of the investment such as when management is outsourced, and individual departments do not care for energy bills and environmental impacts. In such a case, they will have no incentive to improve energy efficiency.
Bounded rationality	Due to constraints on time, attention, and the ability to process information, individuals do not make decisions in the manner assumed in economic models, and they may neglect the small cost savings from energy efficiency improvements.

Econometric methods are used to find the aggregate demand for an industrial fuel. One other research area for these methods is the impacts of price or tax changes on industrial energy demand or type of energy used. The interaction between asymmetric price response and energy-saving technical change are also in the scope of econometric methods [14]. Single equation models [18], simultaneous equation models [19] and time series [20] are classified econometric analysis methods.

Top-down or bottom-up models are engineering based approaches. Top-down models are used to measure and evaluate industrial technology policies and the impacts of technological change, whereas bottom-up models are used in complex or simple settings respectively for world scope or in individual countries. Furthermore, these approaches analyze the relationship between technology and energy consumption using hybrid models [21], input-output modeling frameworks [22], optimization [23] and simulation [24].

Industry-specific micro-economic analyses which are applied to certain industries or their specific processes encompass a broad area and cover various models [14]. From simple simulation models to complex and detailed statistical or optimization techniques are employed [25-27].

Recently, energy efficiency is analyzed with an input-output framework using DEA methodology where energy is also taken into account as an input for the productive process so as to find the relation between energy intensity and the level of productivity [28]. Energy use results in the generation of byproducts alongside of desirable products [17]. Zhou & Ang measure energy efficiency performances of 21 OECD countries. Sarica and Or analyzed and compared performances of 65 thermal, hydro and wind power plants owned by private and public sectors in Turkey using DEA [29]. Mukherjee presented several models to measure energy efficiency from a production theoretic framework using DEA in Indian and U.S. manufacturing sectors [10,11].

Currently, aside from the classification proposed by Greening, lean philosophy has also been a fundamental approach since energy is a significant factor for competitive advantage and environmental protection in industrial level. Lean & Energy Toolkit published by the U.S. EPA in 2007 [30] was the first study that combined energy consumption with VSM which is popular tool of lean manufacturing. Later, energy value stream mapping was extended and named as Environmental Value Stream Mapping regarding environmental factors such as water consumption instead of solely energy use [31]. Simons and Mason introduced a method called Sustainable Value Stream Mapping linking GHG and CO_2 emissions to production with the prediction that social benefits will be the outcome of economic and environmental benefits. Joining UK environmental key performance indicators, Notron and Fearne applied sustainable value stream mapping to the food industry [32]. For the cooperation of lean philosophy and energy efficiency a simulation-based assessment with improvement cycles was proposed by Baysan et al [33]. Schmidtke *et al.* also used discrete-event simulation to overcome the limitations of paper and pencil methodology of VSM [34]. Another energy value stream mapping approach that aimed to improve efficiency in small and medium sized companies gave an application of future oriented method using Bayesian networks [35]. A techno-economic evaluation method for energy retrofitting was also introduced by Kumbaroğlu and Madlener using Monte Carlo Simulation, expected NPV with real options approach [36].

2.4. Enhanced Lean Methodology

Substantial amount of energy savings can be achieved with lean activities since eliminating non-value added activities is the main focus. Nevertheless, not considering energy as a waste may cause an overlook in the way to improve performance and reduce costs. There are several reasons to integrate lean and energy efficiency as in Figure 2.1 [30,37].

- Economic objectives: Reducing costs that are hidden in the energy waste has meaningful impact on enhancement of the business economy.
- Environmental objectives: Forward-looking for environmental and climate impacts of energy use is inevitably important both to industry and society whereas missing that point is a potential business risk.
- Acceptance and competitive advantage: Reduced operating costs, improved staff morale, and responding to customer expectations for environmental performance and energy efficiency increases competitive advantage. These also bring social and economical acceptance.

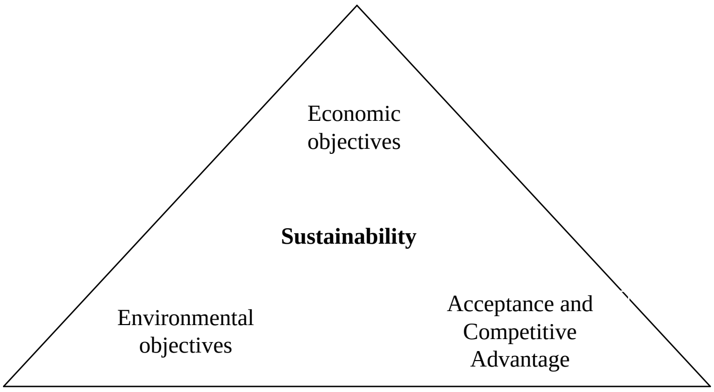


Figure 2.1. The reasons to integrate lean and energy efficiency.

2.4.1. Lean Production

Lean thinking concept entered into our lives in 1990 with the book "The Machine Changed the World: The Story of Lean Production" written by Womack, Jones and Roos. Western traditional mass production methods were compared to Japanese production methods and the most striking difference between two were declared to be the aim of the method. The western manufacturing system is viewed as being sufficiently good, having an acceptable amount of defects and inventories with a narrow range of products whereas lean methods aim perfection in which zero defects, zero inventory, endless range of products and low cost are targeted. Value stream mapping is one of the tools to reach those targets [38].

Lean thinking can be traced back to the years of the Second World War. Toyoda Kiichiro, manager of Toyota Motor Company, stated that unless American automobile industry is overtaken, the Japanese industry would no longer survive. Later on, investigations showed that the production in U.S. was based on mass production with long preparation times. Since Japanese low demand market could not afford such a system, Taichi Ohno started working on the elimination of waste and non-value added activities with several tools and adopting continuous improvement as the culture of the company [38]. Womack and Jones define five pillars of lean production as follows [39].

(i) Value: The process starts with the customer since the customer is the definer of the value. Something can be defined as value if and only if the customer is willing to pay for that. Frankly, value creation is product or service creation for which customer is willing to pay for and that created item satisfies customers' specific needs in certain times [40].

(ii) Value Stream: Analyzing and defining value stream is the second step of lean thinking. It is composed of the value-added and non-value-added activities that are available for all products or services. Non-value-added activities here can also be named as waste.

(iii) Flow: After the value is defined in customer's point of view and all activities are analyzed in a value stream, the next step is providing the flow between those value-added activities.

(iv) Pull: After eliminating waste and providing the flow in the value stream, the next step is to let customers pull products which will adjust the production rate to answer their demand.

(v) Perfection: Since all prior steps are applied and feedbacks are seen, using kaizen and other methods, wastes should be eliminated and a continuous improvement level should be achieved.

According to Taichi Ohno, the wastes can be divided into seven groups as given below and will be revised from the energy saving perspective for the purpose of this thesis.

- Overproduction
- Waiting
- Transportation
- Inventory
- Defects
- Motion
- Overprocessing

2.4.2. Value Stream Mapping

Value increases the worth of the product or service in customer's point of view [41]. From this perspective, activities are split into two classes as value adding and non-value adding. All those activities included in 7 wastes such as transportation and delay times are in the second group. Value stream is the combination of value-added and non-value-added activities required in all steps of a product flow. This flow is in two ways as material and information flow [42]. Value stream mapping (VSM) is the process of planning, systematic data collection, and analysis where lean initiatives are applied to the system [43].

VSM aims to define and eliminate non-value-added activities in these value streams. In order to define value stream, products should be grouped in product families, and then one of the products or a product family should be analyzed and investigated from raw material to the customer [41]. After products are grouped in families, the one with the largest volume, the one with the highest defect, the one that brings the highest profit, the one with the greatest number of processes or the one which has the highest return from the customer can easily be chosen for investigation. Pareto analysis is another method to assist the decision maker for this selection. Having a 80-20 shares can easily show which product to consider but if the ratio is about 40-60, then product matrix should be used for decision making [43]. It is important to select just one product family since all products may have different processes or goals. The product matrix is a tool which displays products in one axis while the processes are placed in the other axis. Later, if a specific product has some process in its production cycle, then it is checked. Eventually, products with the similar processes can be grouped as a family [44].

Current state map should be used as a depiction of the current situation to define energy efficiency potentials and future state should be the desired situation to conclude which will make improvement opportunities visible. The potential improvement opportunities should be evaluated with design guidelines of lean philosophy to achieve the future state. The outputs that people are willing to see in a future state map generally are flexibility, shorter delivery time, combined processes, easier information flows and awareness about the needs of the customer.

Value stream mapping process can be divided into three phases as analysis, design and implementation. In the analysis stage where current state map is drawn, system elements are measured, visualized and analyzed. In the design stage, future state map is created. Lastly, in implementation stage, the improvements are applied to the system [44].

2.4.3. Lean Energy Efficiency and Value Stream Mapping

Keskin *et al.* combined lean energy efficiency factors as shown in Table 2.2 based on the concepts and tools of lean manufacturing and industrial energy efficiency mentioned in various studies in the literature [35]. Not only the concepts and tools for energy efficiency but also the goals differentiate the methodology. As energy efficiency in production systems have economic and ecological goals in all kinds of sectors, not only in energy-intensive sectors, new requirements arise in the design of processes to achieve energy efficiency. Although being vital for sustainability of the production line, environmental and social metrics are not considered in traditional VSM methodology [32]. In particular, energy value stream provides a method to see overall energy consumption with a comprehensive and transparent representation. Energy consumption and energy need can thus be achieved and compared where energy flows of the production site are analyzed with energy value stream mapping. Key energy consumers and the areas of greatest energy waste are identified and total energy efficiency is aimed to be improved [37].

Table 2.2. Concepts and tools of lean manufacturing and energy efficiency.

Lean Manufacturing

Value
Value Maps
Takt Time
Kanban
Visualization
5S
Standard Work
Pull
One Piece Flow
Continuous Improvements
Process Kaizen
Changeover Reduction
Shorter Maintenance Time
Cellular Manufacturing

+

Energy Efficiency

Determining energy intensive processes
Energy bill analysis
Theoretical minimum energy usage
Key performance indicators
Energy efficient technology investments
Energy efficiency improvements

=

Lean Energy Efficiency

Non Value Added Energy UsagE
Energy of Work-In-Process
Overproduction
Faulty Production
Cellular Energy Usage (Fewer carriage, fewer field)
Energy Efficiency Kaizens (EEK)
Total Productive Maintenance (TPM)

The energy value stream map should reach the following goals [37]:

(i) Rough analysis of energy consumptions with regard to production preconditions
(ii) Identifying all relevant kinds of energy such as electricity and compressed air
(iii) Identifying all relevant energy consumers
(iv) Creating transparency of process-related energy consumptions
(v) Avoiding energy waste
(vi) Providing the basis for optimization of energy consumption

(vii) Key figures to estimate the energy efficiency
(viii) Estimating potential energy efficiency
(ix) Systematic process to increase energy efficiency
(x) Providing design guidelines for a systematic search for improvement
(xi) Visualizing an ideal future state as a target

The analogy of energy value stream mapping which is derived by classical VSM is drawn in Figure 2.2 below [45].

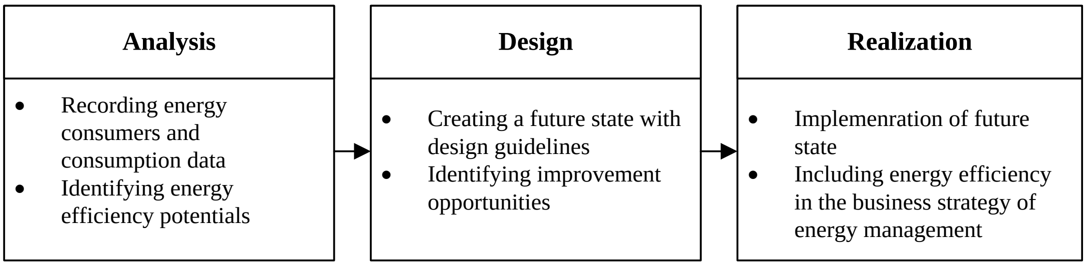


Figure 2.2. The analogy of energy value stream mapping.

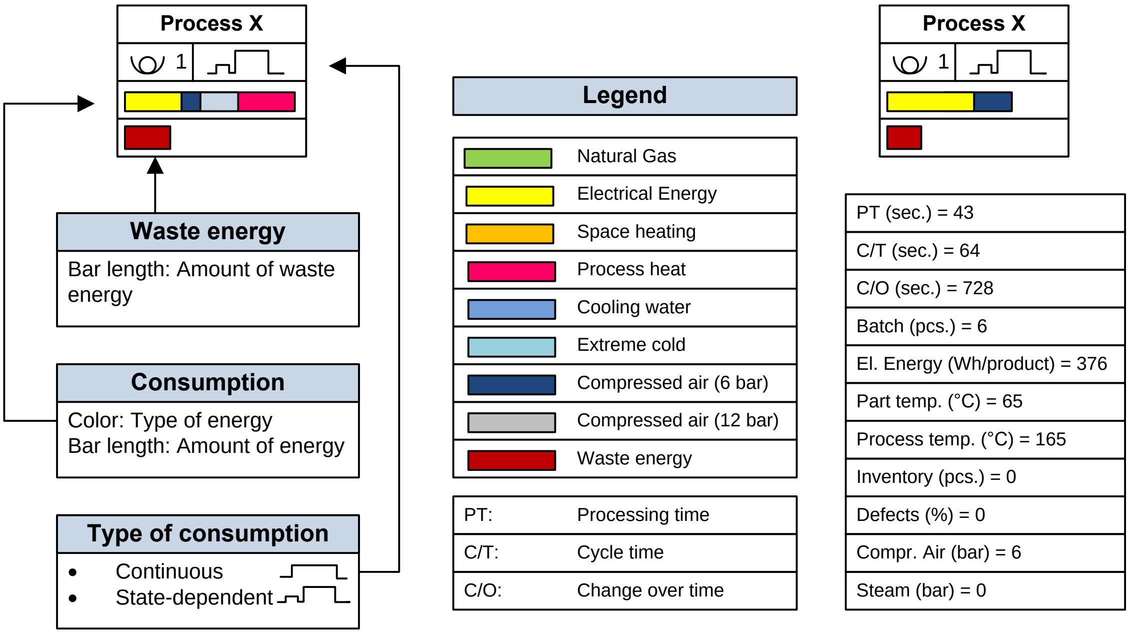
For value stream analysis stage, system elements are technology, organization & management, and human & behavior. Complete consideration of all these 3 system elements is vital for sustainable improvement of energy efficiency.

Lean energy wastes which lean are aimed to eliminate are of critical importance. The eight typical classes of wastes are illustrated from energy viewpoint [30,46]:

- Overproduction: Use of surplus energy by an inefficient manufacturing system to make unnecessary products
- Waiting: Energy used while production is down such as heating, cooling, lighting during production downtime
- Transportation: More energy used for transport such as the inefficient transportation of compressed air
- Inventory: More energy used for heating, cooling, and lighting of inventory storage and warehousing space

- Defects: Energy consumed to manufacture a defective product or more space required for rework and repair, increasing energy use for reprocessing, as well as heating, cooling and lighting
- Motion: Inefficient transportation of goods such as more space required for work in process (WIP) movement which increase lighting, heating and cooling demand and energy consumption
- Overprocessing: More energy consumed in operating equipment related to unnecessary processing. Use of improper-sized equipment which results in high energy use per unit of production
- Unused Human Talent: Failure to integrate employees when defining energy efficient processes

After system elements and types of energy waste are defined, data from the manufacturing plant are gathered such as process parameters, power, temperature and compressed air. When all the data is collected, then current state map can be drawn. The classical maps are enhanced embedding energy measures as in Figure 2.3. Energy value stream map consists of different modules representing the different manufacturing processes, transportation processes and supply units [46].



PT (sec.) = 43
C/T (sec.) = 64
C/O (sec.) = 728
Batch (pcs.) = 6
El. Energy (Wh/product) = 376
Part temp. (°C) = 65
Process temp. (°C) = 165
Inventory (pcs.) = 0
Defects (%) = 0
Compr. Air (bar) = 6
Steam (bar) = 0

Figure 2.3. A data box for energy value stream mapping.

After current state map is drawn and energy efficiency potentials are analyzed, the next step is the visualization of future state map and design of improvement opportunities.

Finally, completing all prior steps, the proposed changes can be implemented to the real system and continuously improved.

3. RESEARCH METHODOLOGY

This chapter presents the construction of the research methodology. The similarity of problem solving processes in different disciplines are highlighted and an integrated framework based on classical value stream mapping approach is provided. This framework not only combines energy efficiency and lean but also embeds quantitative assessment, economic analysis and optimization steps to the classical approach.

Problem solving and decision making processes use identical approaches in different disciplines. The similarity in their problem solving methodologies of operations research, systems engineering and multi-criteria decision making is apparent. All these methodologies start with problem structuring and continue with model development including identification of selection criteria and solution alternatives, consequently evaluation and final decisions are taken based on the evaluation.

Multi-criteria decision making framework for problem solving is given as [47]:

- Problem structuring (Stakeholders, alternatives, uncertainties, key issues, external environment, constraints, goals, values)
- Model building (Elicitation of values, definition of criteria, specification of alternatives)
- Use of the model to inform and challenge thinking (Sensitivity analysis, robustness analysis, creating new alternatives, challenging intuition, synthesis of information)
- Development of an action plan

In texts on Operations Research, Churchman, Ackoff and Arnoff present a six-step OR process in 1960 as [48]:

- Formulation of the problem
- Construction of a mathematical model
- Derivation of a solution
- Testing of the model and the solution

- Establishment of controls over the solution
- Implementation

In systems thinking, the steps of the modeling process can be summarized as [49]:

- Problem articulation (Boundary selection)
- Formulation of dynamic hypothesis
- Formulation of a simulation model
- Testing
- Policy design and evaluation

Since all methodologies are more or less identical, this thesis develops its methodology taking into account the same steps. Research methodology is depicted in Figure 3.1.

Firstly, as the basic principles of lean philosophy, the value by a product family or a set of product families is specified from the view of the customer. For the selected product family, all the steps of the value stream are identified. In this step where the boundary and the environment are defined, the product to refer in the analysis is determined through product family matrices or production procedure and family likeness. However, it was obligatory to choose a specific product family, namely boots, due to seasonality of the footwear industry and the investigation period in the manufacturing plant.

Having considered which product family to work on, the next step is the definition of production processes, material flow and information flow and illustrating them as a value stream map to provide a clear understanding. Rather than typical value stream maps where all production related issues are covered, this methodology will mainly focus on energy-related viewpoints which will result in a remarkably selective inspection.

Following the preparation and execution steps, potential areas for energy efficiency improvement are identified. Current system is mapped with value stream mapping and motors, pumps, compressors and fans are investigated in detail. Taking these resources as a reference point, scorecards are designed for a quantitative assessment of energy efficiency.

The factors included in each scorecard are chosen delicately with factor analysis and their weights are determined as a result of weight optimization.

Input energy consumption is aimed to be decreased with the use of lean techniques which are shown as potential solutions for waste categories with which the activities are matched. Applying various lean techniques and improvements result in diverse future states. Illustration of these future state maps makes it apparent to notice the major change in energy consumption. Nonetheless, there is hardly any company to invest the whole amount needed for such a project and thus, economic analysis is added to the ordinary value stream mapping application.

Engineering economics techniques are used to calculate present value of investments and Monte Carlo Simulation is applied for this particular purpose. On the other hand, although investment decision may be advantageous, increasing energy prices may dominate the potential improvement. Therefore, energy prices are also forecasted for the following years and its effect is also considered in economic analysis.

After all improvement opportunities are defined and their economic impacts for the company are achieved, an optimization procedure is performed under different budget constraints. The test hypothesis here is that lower budgets assure higher rates of saving/investment than huge amounts of investments.

Eventually, the optimal set of improvements are applied within a plan in the company and controls are performed occasionally if there are any further and economic improvement opportunities. Furthermore, to attain sustainability, this energy efficiency management system can be embedded to the company's management procedures.

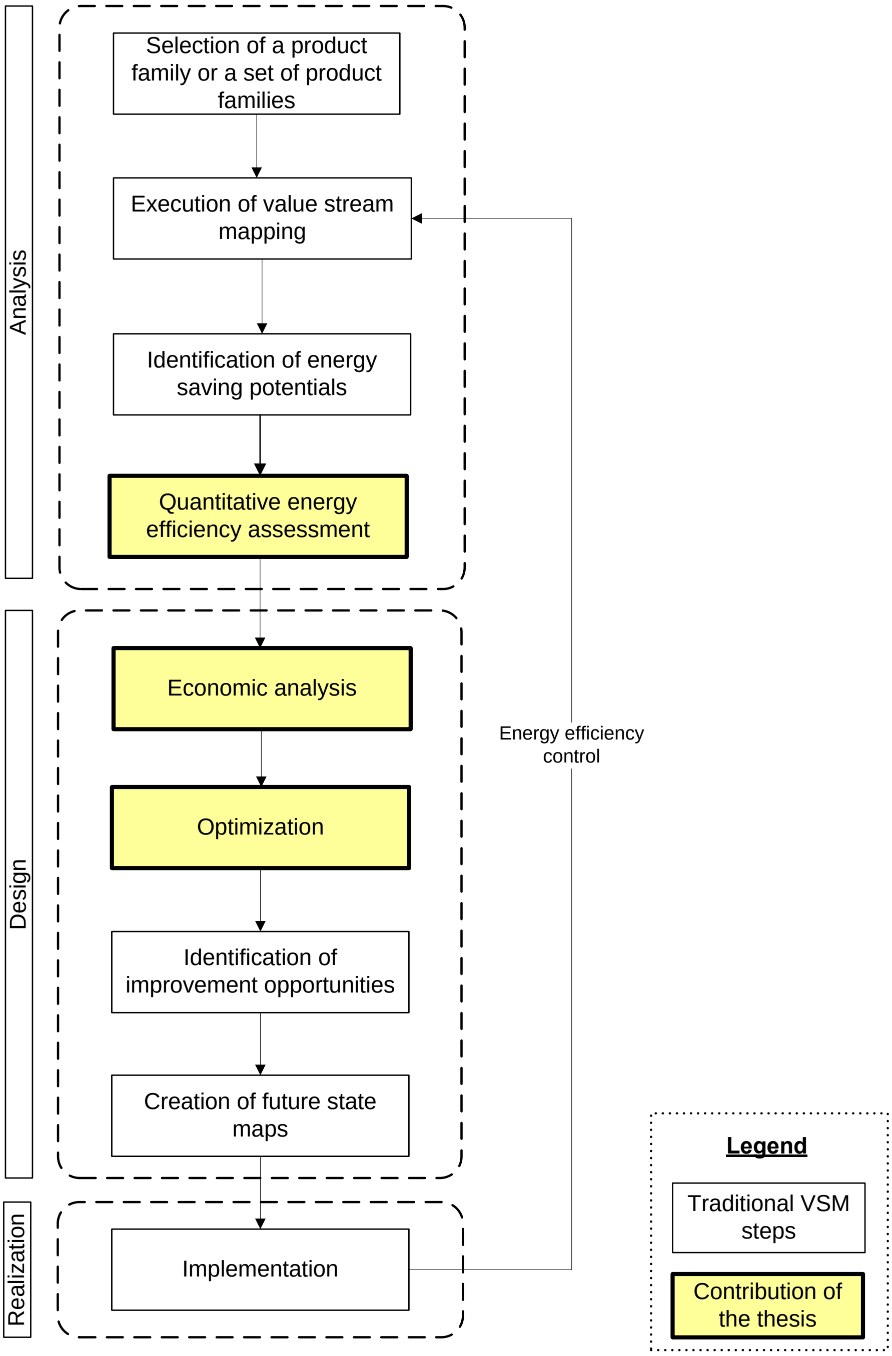


Figure 3.1. Energy value stream mapping research methodology.

4. APPLICATION IN FOOTWEAR INDUSTRY

This chapter serves as the step prior to the conceptualization of energy efficiency assessment scorecards. It gives a descriptive background on the sector, summaries the workflow and eventually elaborates on how motors, pumps, compressors and fans may be more efficient in term of energy. In section 4.1, a broad information is given from the company and the sector. Due to data availability, textile industry is considered as a whole rather than solely footwear. Afterwards, in sections 4.2 to 4.6 technical equipments are detailed in order to base factor explanations of the assessment on them.

4.1. General Background

4.1.1. Leather and Textile Sectors

Almost 25 billion shoes were produced and purchased in the world, in 2010. Nearly all of them (90%) were manufactured in developing and transitional economies [50]. This shows a significant reason to focus on the footwear sector.

Textile and footwear sectors are almost similar in terms of manufacturing and energy use since same machinery and raw materials are used for identical operations. Thus, both of them are considered as non-energy intensive. However, a significant amount of energy is consumed as a result of comprising a large number of plants together. The share of total manufacturing energy consumed by the textile industry is different for various countries. For instance, the textile industry accounts for about 4% of the final energy use in manufacturing in China [51] whereas it is less than 2% in the U.S. [52]. Statistics show that textile, leather and clothing industry accounts for about 8% of the total energy consumption and 17% of total manufacturing energy consumption in Turkey [53].

The shares of total product expenses also vary from one country to another. The general shares of cost factors of combed cotton yarn production among the chosen countries are given in Table 4.1. Total manufacturing cost includes raw material, labor, energy, capital cost of machinery, auxiliary material cost and waste classes. Energy cost is the third important cost factor after raw material and capital costs [54].

Table 4.1. Manufacturing costs for textile sector in various countries.

Countries	**Manufacturing Cost Factors for the Chosen Countries (%)**						
	Brazil	**China**	**India**	**Italy**	**Korea**	**Turkey**	**USA**
Raw material	50	61	51	40	53	49	44
Waste	7	11	7	6	8	8	6
Labor	2	2	2	24	8	4	19
Energy	4	8	12	10	6	9	6
Auxilliary Material	4	4	5	3	4	4	4
Capital	32	14	23	17	21	6	21
Total	99	100	100	100	100	80	100

U.S. DOE (2004) gives the breakdown of final energy use by end use in the U.S. textile industry in Figure 4.1. However, the percentages are not the same for all countries. For example, the U.S. textile industry contains less labor-intensive processes than developing countries like China and India [55].

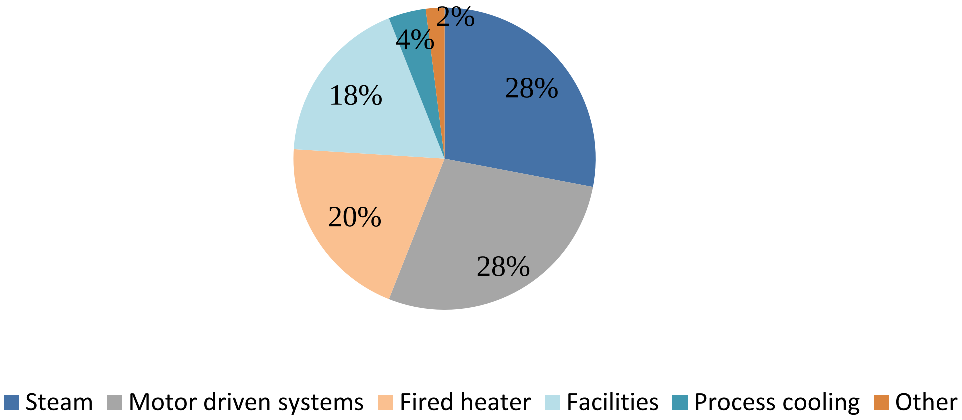


Figure 4.1. Final energy end-use in the U.S. textile industry.

U.S. DOE works also to reduce losses that occur all along the energy supply and distribution system. Energy is lost both in power generation and steam systems, both off-site at the utility and on-site within the plant boundary due to equipment inefficiency and mechanical and thermal limits. Furthermore, energy conversion systems such as heat exchangers, process heaters and pump motors also have losses [56]. The breakdown of reasons lying behind losses are also given in Figure 4.2 [55].

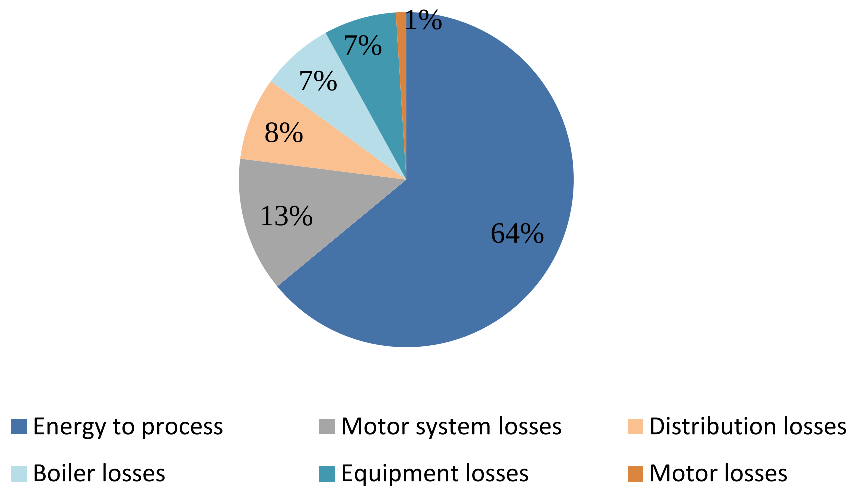


Figure 4.2. Onsite energy loss profile for the U.S. textile industry.

4.1.2. Work Flow of Shoe Production

Work flow of shoe production consists of several processes which will be mentioned in the following sections. Figure 4.3 summarizes the whole processes whereas all individual processes are further explained in Appendix B with process and machinery photos taken in the facility.

4.1.3. Production Profile

The company produces boots in summer for the forthcoming winter season, and sandals and shoes in winter for the forthcoming summer season. The production planning is prepared according to demand forecasts based on previous years' sales data. When the number of shoes manufactured in the company are examined, it is realized that there is a dramatic fluctuation. As seen from the production volume of the plant in Table 4.2 and Figure 4.4, there is not a trend in the production.

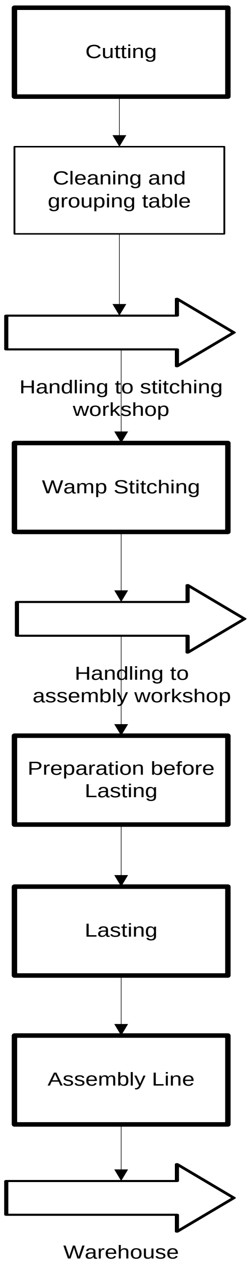


Figure 4.3. Workflow of the whole system.

Table 4.2. Shoe production in the last four years.

	Shoe Production (Pairs)				
	2010	**2011**	**2012**	**2013**	**2014**
January		133,053	110,716	126,425	130,137
February		109,691	112,757	92,749	110,224
March		70,192	11,738	78,580	92,133
April		84,921	95,655	76,014	88,658
May	55,307	115,476	109,631	102,713	99,475
June	112,573	123,925	104,165	100,862	107,694
July	119,078	113,391	102,084	110,008	
August	108,401	97,671	74,785	82,564	
September	97,780	81,296	105,173	95,331	
October	116,033	60,983	105,274	96,236	
November	82,314	85,593	81,628	88,739	
December	143,720	127,931	103,267	105,571	

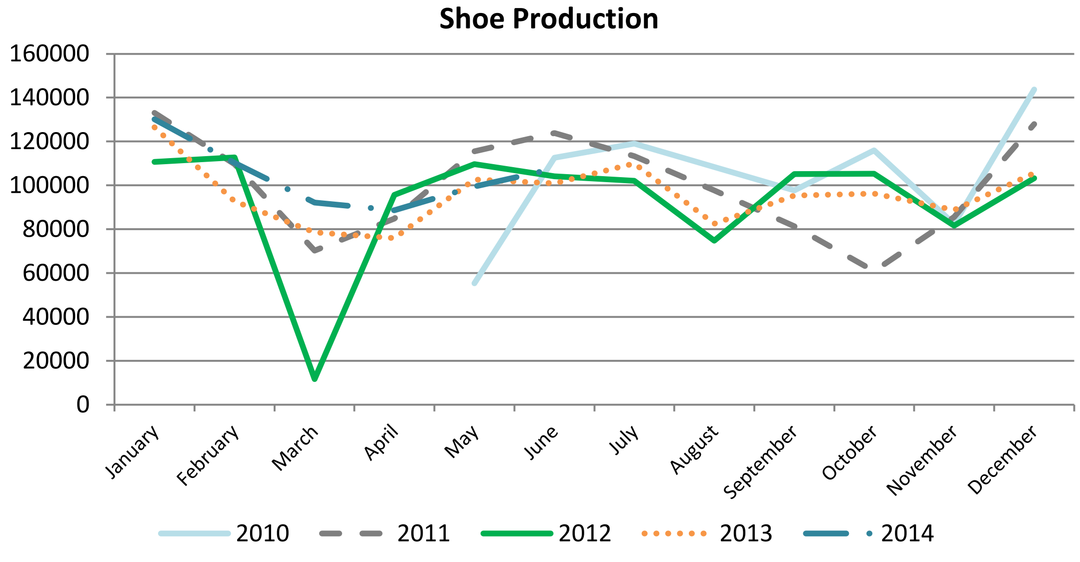


Figure 4.4. Graphical representation of shoe production.

4.2. Lighting

Lighting has always been an indispensable part of our daily life. In addition, mankind has exploited a variety of artificial lighting sources over the centuries to use when the sunlight is not available [57]. Since lighting system is vital to ensure the comfort, productivity and safety of the occupants in a building, it should be designed in a way that the desired illumination level can be achieved with the minimum amount of electricity use, emissions, and operation and maintenance costs.

Lighting constitutes 20-45% of commercial and 3-10% of industrial total energy consumption [58]. DOE states that the percentage of lighting is 7% of the US total energy use and 18% of total US electricity use in 2010 [59] while the same number is 13.7% for Japan [57].

Different types of lamps are introduced in Appendix C. In addition, properties of those lighting systems are summarized Table 4.3 [60]. Furthermore, Table 4.4 shows the advantages and disadvantages of each lighting family [57].

Table 4.3. Properties of different lighting systems.

Type of lighting	**Power (W)**	**Life (h)**	**Efficiency (lm/W)**	**Color rendering index (Ra)**
Incandescent lamp	15-1000	1000	4-25	Excellent (100)
Halogen lamps	20-2000	2000-3000	20-25	Excellent (100)
FL	6-65	4000-7000	46-60	Good (67-77)
CFL	9-25	8000-10000	50-83	Very good (85)
HPMV	50-1000	7000	44-57	Fair (45)
HPSV	50-1000	6000-12000	67-121	Fair (22)
LPSV	8-180	6000-12000	101-175	Poor (10)
Metal halide	400-2000	8000	75-125	Good (70)
LED	5-60	40000-100000	30-50	Good (>75)

Table 4.4. Characteristics of different lighting systems.

Type of lighting	**Characteristics**	
	Advantages	**Disadvantages**
Incandescent lighting	Cheapest and convenient Can be directed freely Enhanced color Gives us comfort	Short lifespan Low efficiency Causes large amount of heat
Fluorescent lighting	Long lifespan High efficiency Can produce many different colors of light	Low tolerance for low temperatures Low tolerance for repeated on and off
HID	Long lifespan High efficiency Small and bright	Expensive Takes about 10 min. to glow
LED	Long lifespan High efficiency No warm-up Directional	Expensive More precise current needed

The use of different lighting systems varies according to the aim and attitude of the users. In the study of DOE, distribution of lamps by the end-use sector of U.S. in 2010 is given as in Table 4.5 [59].

Table 4.5. Distribution of lighting by end-use sector in 2010.

	Residential	**Commercial**	**Industrial**	**Outdoor**	**All Sectors**
Incandescent	66.4%	6.0%	0.3%	12.3%	48.9%
Fluorescent	32.7%	90.4%	89.5%	23.1%	48.0%
HID	0.0%	1.7%	9.8%	52.2%	1.7%
LED	0.2%	1.8%	0.4%	10.8%	0.8%

4.2.1. Important Factors for the Efficiency of Lighting

Energy efficiency opportunities alters from one plant to another. But general energy saving opportunities by means of lighting can be written as follows [60]:

- Using natural day light

The utility of using natural daylight instead of electric lighting is well known and some industrial plants benefits from it. North lighting, innovative design of the building and atriums are well-known methods for natural daylight.

- De-lamping to reduce excess lamping

De-lamping is an effective way to reduce energy consumption. In some industries reducing mounting height of lamps or eliminating unneeded lamps significantly increase lighting energy efficiency.

- Task Ambient Lighting (TAL)

Task ambient lighting is the lighting operation of the small working area in a required level whereas other areas are kept at a lower level such as machine mounted lamps or table lamps. If properly implemented, task lighting provides less number of lighting fixtures, less wattages of lamps, a more energy efficient workplace and a nicer ambience [60]. TAL also reduces power consumption by 30% and an additional 15% decrease is achieved by air conditioning as a result of reduced radiation of heat caused by lighting [57].

- Selection of high efficiency lamps and luminaries

According to the work requirements, the lighting system can be replaced with a more efficient one as mentioned in previous sections. In Japan, replacing lamps with more efficient ones was stated to provide 9.2% reduction in energy use compared to 2010. It is also added that if these replacements are done with LED lamps, the saving would have been 56% in year 2050 [57].

- Reduction of lighting feeder voltage

Reduction in lighting feeder voltage can save energy provided the drop of light output is acceptable. Since in many areas, night time grid voltages are higher, reduction in voltage is a way to save energy. 10% voltage reduction decreases light output by 9% and power input by 15% for fluorescent lamps while the same numbers are 20%-16% and 24%-20% for HPMV and mercury blended lamps.

- Electronic ballasts

Conventional electromagnetic ballasts provide higher voltage for the lighting of the tube and limit the current during normal operation. The main functions of them are to ignite the lamp, to provide a stable gas discharge and to supply the power to the lamp. Compared to 10-15 Watt losses in standard electromagnetic ballasts, losses in electronic ballasts are only around 1 Watt.

- Lighting controllers

Automatic controls to switch the unnecessary lights off can lead to high energy savings. Occupancy or time-based sensors, daylight linked control and localized switching are some controllers that may be used.

- Lighting maintenance

Maintenance is significant for efficiency since lighting levels can decrease because of lamp aging and dirt on fixtures and lamps. These reasons decrease illumination by 50% although the light works fully.

The necessary formulations that will be used to measure the cost savings are given as below:

$$\begin{aligned}&\mathit{Energy\ Consumption} = \\ &(\mathit{Total\ Power}) \cdot (\mathit{Ballast\ Factor}) \cdot (\mathit{Operating\ hours})\end{aligned} \tag{4.1}$$

$$\mathit{Energy\ Cost} \equiv (\mathit{Energy\ consumption}) \cdot (\mathit{Unit\ electricity\ cost}) \tag{4.2}$$

$$\begin{aligned}&\mathit{Energy\ Consumption\ Savings} \equiv \\ &\quad (\mathit{Total\ Power\ Reduction}) \cdot (\mathit{Ballast\ Factor}) \cdot (\mathit{Operating\ hours})\end{aligned} \tag{4.3}$$

$$\begin{aligned}&\mathit{Annual\ Energy\ Cost\ Savings} \equiv \\ &\quad (\mathit{Energy Consumption\ Savings}) \cdot (\mathit{Unit\ Electricity\ Cost})\end{aligned} \tag{4.4}$$

$$\mathit{Implementation\ Cost} \equiv (\mathit{Cost\ difference\ of\ lamps}) \cdot (\mathit{Number\ of\ lamps}) \tag{4.5}$$

$$\mathit{Payback\ Period} \equiv \frac{\mathit{Implementation\ Cost}}{\mathit{Annual\ Cost\ Saving}} \tag{4.6}$$

4.3. High Efficient Motor Systems

Electric motor systems are responsible of 60% of industrial electricity consumption and 15% of final industrial energy use worldwide. Additionally, in Turkey, motors account for 65% of total industrial energy use [61]. There is a high potential of improvement in energy efficiency of motors which is not fully realized. Although the individual efficiency of motors is high such as 85-96%, the overall efficiency of the system is quite low. Motor systems lose on average 55% of their input energy before they reach the end-use processes [62]. In favor of alternative investments and also because of different barriers or market failures, energy efficiency improvement decisions of electric motors are often delayed or rejected. Attention of the plant manager, higher initial cost or access to capital for the developing countries are some of the barriers [63].

Electric motors are used in most industrial systems such as ovens, refrigeration and material processing & handling. The shares of application areas of motors in U.S. industry are given in Figure 4.5 [62].

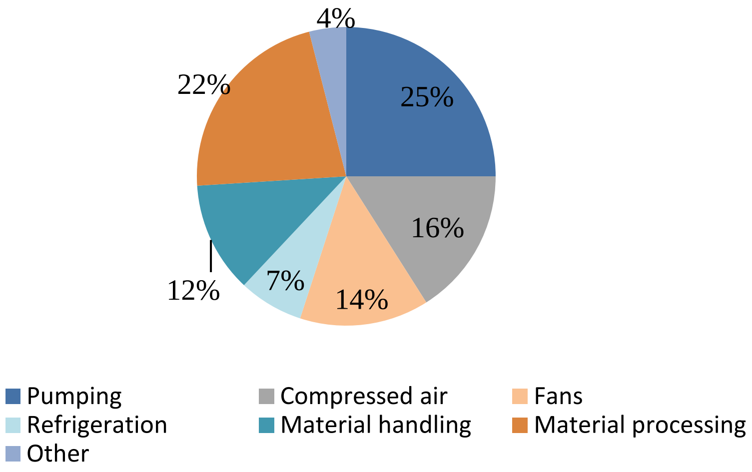


Figure 4.5. Share of electricity use of different motor systems.

4.3.1. Basic Electrical Characteristics of Motors

A deep knowledge of the motor's technical and operational parameters is needed to assess the impact of motors on the energy bill. Motor performance, maintenance and age are the factors that affect motor efficiency.

The information about a motor's performance which is buried in the characteristics of the electrical signals at the motor's terminals is huge. With the nameplate of the motor and electrical characteristics, it is possible to find many energy saving opportunities for a motor. Some of the basic electrical characteristics that can be used to maximize energy savings are voltage, current and frequency [64].

- Voltage variations
- Voltage unbalance
- Motor load (based on current)
- Total harmonic distortion
- Power factor

Voltage variations: Motor performance is affected by the quality of input power which is the actual volts and frequency available at motor terminals. In India, motors must comply with the standards set by the Bureau of Indian Standards (BIS) for tolerance to variations. According to these standards a motor should be capable of delivering its rated output with +/- 6% voltage fluctuation and +/- 3% frequency fluctuation [60]. It is stated that a 10% voltage variation increases the motor load by 2.5 -3.5%, reduces efficiency by 1% and reduces power factor by 10% [64].

Voltage Unbalance: Voltage unbalance, the condition where the voltages in the phases are not equal, can be hazardous to motor performance and motor life. This is both a leading cause of motor failures and a major contributor to energy losses in motors. The effect of unbalanced voltages on polyphase induction motors is equivalent to the introduction of a "negative sequence voltage". This rotates opposite to the balanced voltages and produces a flux in the air gap rotating against the direction of the rotor, tending to produce higher currents. The voltage unbalance is formulated as [64]:

$$\text{Voltage unbalance (\%)} \equiv \frac{\text{maximum voltage deviation from average voltage}}{\text{Average voltage}} \tag{4.7}$$

Voltage unbalance is recommended to be less than 1% since anything above this will cause to the failure of the motor [60]. The impacts of voltage unbalance are as follows [64]:

- Increase in winding temperatures. The increase in temperature causes additional power losses and a significant drop in motor efficiency.
- Increase in vibrations and noise

Motor load: Motor loads increase with stresses stemming from bearing and unusual mechanical load. 50% of machinery problems of the motor are caused by excessive load due to unbalance, misalignment and belt tension. Heat, power supply anomalies, humidity and contamination are other stresses that degrade components with time. Lifetimes of motors can be several hundred thousand hours when these stresses are minimized with the use of technologies to maintain the motor and its drive systems [64]. Estimating motor loading helps to indicate the percentage of loading and unbalance, power factor, pressure, flow, temperature, machine side losses, idle operations etc. [60].

Total Harmonic Distortion: Harmonic distortion is the change in the waveform of the supply voltage from the sinusoidal waveform which is the ideal form. Intercommunication of altering customer loads and impedance of the supply network causes this distortion. It leads to heated transformers, capacitors, induction motors, and overloading of neutral conductors that are not classified to carry large currents. Thus, total harmonic distortion should be monitored [64].

Power Factor: Power factor is the ratio of the real operator current to the total current drawn. When the motor load decreases, the magnitude of the active current also decreases. However the magnetizing current which is proportional to supply voltage does not change and as a result the power factor of the motor decreases. Especially, the induction motors working below their capacity are the reasons for low power factors [60].

Motor losses considerably increase with insufficient maintenance and unreliable operation. For instance, friction may increase with inappropriate lubrication both in motor and associated drive transmission equipment. Another increase would be in resistance losses which are the causes of temperature rises. Sufficiently ventilated and clean motor cooling ducts eradicate heat and reduce extra losses. The life of the motor may also be longer according to the working temperature of the motor [60].

Although motor cores are generally produced from silicon steel or de-carbonized cold-rolled steel, poor maintenance such as inadequate lubrication, insufficient cleaning etc. can cause a decline in motor efficiency [60].

4.3.2. Important Factors for the Efficiency of Motors

The factors that improve the efficiency of a motor can be classified as:

- Reduced motor losses,
- Energy audit,
- Standards,
- Repair or replacement of motors,
- Preventive and predictive maintenance,

- Proper motor sizing,
- Speed control,
- Computer tools to analyze motor energy use,
- High efficiency belt drive systems

4.3.2.1. Reduced Motor Losses. The efficiency of a motor is determined by intrinsic losses which can only be reduced by changes in motor design. These motor losses can be classified as fixed and variable losses which are explained as follows [61] and visualized in Figure 4.6 [65].

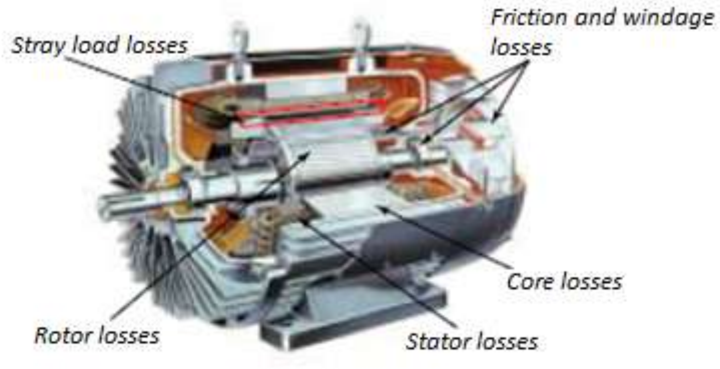


Figure 4.6. Losses in the various parts of a motor.

Electrical energy is converted to mechanical energy with a motor for the performance a useful work. Although standard motors operate with 83-92% efficiency, energy efficient motors have greater results. Just an efficiency increase from 92 to 94% needs a 25% loss reduction. In addition, heat rejected to the atmosphere and cooling loads are reduced.

Magnetic core losses and friction and windage losses are fixed losses which are independent of the motor load. Magnetic core losses (iron losses) include eddy current and hysteresis losses in the stator. On the other hand, friction in the bearings of the motor and losses in the aerodynamic system associated with the ventilation fan and other rotating parts cause friction and windage losses.

Variable losses which change with respect to the load comprise of resistance losses in the stator, rotor and various stray losses. With the resistance to current flow and rotor, heat is generated which is proportional to the resistance of the material and square of the current (I^2R). Stray losses are caused by several sources and they are hard to measure and calculate, but proportional to the square of the rotor current.

With the existing design and manufacturing, motor efficiency can be improved with the improvement opportunities given in Table 4.6 [60].

Table 4.6. Power loss area and related efficiency improvement.

Power Loss Area	Efficiency Improvement
Core	Use of thinner gauge, lower loss core steel reduces eddy current losses. Longer core adds more steel to the design, and due to operating flux densities losses decrease.
Friction & Windage	Use of low loss fan design reduces losses due to air movement.
Stator	Use of more copper and larger conductors increases cross sectional area of stator windings. Resistance of the windings is reduced and losses due to current flow are reduced.
Rotor	Use of larger conductor bars increases size of cross sectional area, lowering resistance and current.
Stray load	Use of optimized design and strict quality control procedures reduce stray load losses.

4.3.2.2. Energy Audit. Energy audit is a systematic approach to visualize industrial energy consumption and identify sources of waste. The profit of the company is directly affected by the savings achieved through auditing [61]. Energy auditing procedure is outlined as a flow chart in Hong *et al.*'s article and also the objectives of energy auditing are given [66]:

- assisting energy users to establish energy audit systems
- assisting energy users to implement energy management
- providing on-site energy audit and guidance, technology and information services related to energy saving

In China, an energy auditing study was applied in the paper industry as it consumes one of the highest shares of industrial energy. The energy use and CO_2 emissions of the mill and each machine were presented. The energy saving potential was found to be 8-37% for paper machines and 14.4% for mills. In addition, CO_2 reduction potential was reported as 14.7% of total CO_2 emissions from the mill during the auditing period [67]. In another study, as in our case, energy auditing was applied to the shoe manufacturing facility and for three companies the energy saving opportunities was found to be between 3.78 – 9.32% [68].

4.3.2.3. Standards. The standards used for the performance assessment of motor and its drive systems are as follows [64]:

- Minimum Energy Performance Standards
- NEMA Standard - Effects of Variations of Voltage and Frequency on the Performance of Motor
- ISO 10816-3 Vibration Severity Chart
- Alignment Tolerance

4.3.2.4. Repair or replacement of motors. The decision whether to replace a motor with high efficiency motor (HEM) or repairing it contains many factors to consider. In an HEM, the AC induction motor has been improved continuously with optimized stator and rotor design (size), electrical material properties and quantity (steel, aluminum and copper). New motors reduce losses with the use of copper rather than aluminum for the conductor bars. Copper rotor motors can be found easily from 0.1 to 100 kW. But, the design efforts and advanced technology of production add significant costs to the product. Although it is costly, there are some advantages which must be taken into consideration with the use of copper instead of aluminum [64]:

- Lower coefficient of expansion: Aluminum will move approximately 33% more than copper.
- Tensile strength: Copper is 300% stronger than aluminum and thus able to withstand high centrifugal force and the repeated hammering from current-induced forces during each start.

- Higher melting point: Copper can withstand better thermal cycling over the life of the motor.

It is common practice to rewind burn-out motors and in some industries the share of rewound motors is about 50% of total. Sometimes careful operation can conserve the motor efficiency to the previous levels, but mostly losses occur. Winding and slot design, the material, insulation quality and operating temperature which are the contributors of a motor efficiency are affected by this action. However if appropriately worked on, energy efficiency may also increase such as changing the winding design, using wires of greater cross section, slot size permitting, etc. [60]. Additionally, buying HEM is a capital investment whereas rewinding is maintenance expenditure. It is also stated that a rewound motor for less than 100 HP lasts for 2 years at most as a common experience and motor efficiency reduces from 5 to 7.6% [64]. EASA explains the advantages and disadvantages of rewinding operation as well as the methods and procedures and asserts that there is no disadvantage when the conversion is done properly [65].

4.3.2.5. Preventive and Predictive Maintenance. In order to figure out and get rid of motor failures, both preventive and predictive measures should be incorporated in a maintenance program implemented as part of a motor management plan. Preventive maintenance is used to keep motors in a good operating condition and reducing the risk of unexpected motor failures and predictive maintenance is used to determine and repair/replace the motor related components may cause to downfalls [69].

The five factors that are responsible for motor failure are: heat, dirt, moisture, vibrations and voltage irregularities. Thus preventive maintenance takes action to reduce the effects of these factors.

Heat: Motors may be overheated due to undersizing, incorrect starting torque characteristics, high ambient temperature and poorly ventilation. For the prevention of overheating, motors should be correctly selected and properly placed.

Dirt: Ruins in a plant or outdoor working area, such as a construction project can increase the heat of the motor as a result of a damage in mechanical and electrical components. Many motors are designed to keep dirt and harmful materials outside of the motors for a better operating lifetime.

Moisture: Moisture causes corrosion in the motor's mechanical and electrical components and especially adverse to motors that are not used regularly. In damp motor running environments, in order to reduce these effects forced ventilation or mechanical dehumidification is used. In addition, to protect idle motors internal space or winding heaters are useful.

Vibration: The reason for vibration may be various defective components of motor or its load. Vibration degrades motor's bearings bit by bit and if there is a serious result, mechanical components may cause cracks or fractures.

Voltage irregularities: Variations beyond the motor's specifications such as underbalanced voltage, undervoltage, overvoltage, voltage transients, and other equipment's harmonics may cause overheating of windings. Thus, voltage should be checked frequently and corrected.

Lubrication: Sealed bearings of many small or integral horsepower motors do not require re-lubrication, but all others need it. Re-lubrication with different grease can cause the bearing to fail because of the mix of inappropriate mix. In addition, excess amount of grease or greasing frequently can cause greases to past the bearing shield or seal into the motor and as a result winding damage. Thus, lubrication is also a factor to be checked [61].

For the assessment of the above mentioned factors on motor health, there are various ways to predict failure including monitoring systems. Infrared thermal imaging is a technique to pinpoint overheated bearings and wiring, vibration sensors to diagnose vibration and bearing problems, and electrical analyzers to identify power supply problems. A regular measurement of motor characteristics can give a baseline to detect any problems and schedule maintenance program. These efforts are preemptive against motor failure and help problems to be solved with lower cost before occurrence.

4.3.2.6. Proper Motor Sizing. Improperly sized machines are disadvantageous by means of efficiency. Electric motors work with the highest efficiency at 75-100% load depending on motor size. If the load is under 50%, then the motor efficiency decreases dramatically. Proper sizing is not only an issue of motors but also for other system components such as pump and fan systems in which flow velocities and friction losses are minimized with correct sized pipe or duct.

Sizing with the measurement of the typical load profiles of the machine, obtaining a necessary peak load and starting torque condition starts the motor replacement process. No matter what, an HEM is able to stand 10-20% overload and run cooler, thus it can be sized with less safety margin. Proper sizing offers several advantages: smoother operation, lower cost, longer life and fewer losses [70].

4.3.2.7. Speed Control. When speed capability was the aim, DC motors have been used traditionally. A broad range of output speeds can be obtained in DC motors with controlling rotor voltage and field current. Due to mechanical communication problems at large sizes, the use of DC motors are restricted to a low-speed, low-to-medium power applications. They are also restricted for use in clean, non-hazardous areas because of the risk of sparking in brushes. DC motors are also more expensive than AC. The limitations of DC motors make AC motors popular for variable speed applications. [60]. Multi speed motors and adjustable speed drives are examples of speed control techniques.

Multi-speed motors: Motors can be wound with two speeds with the ratio of 2:1. Furthermore, two windings can be applied to the same motor where four speeds can be achieved from the it. Multi-speed motors can be designed for applications involving constant torque, variable torque, or constant output power. They can be used for operations where limited speed options are needed and are less efficient than single-speed motors.

Adjustable Speed Drives: Many motors work for long hours but with variable loads and the possible gains that may be achieved by adapting motor speed and torque to the required load is large [70].

The technology used to adjust the motor, voltage and frequency in order to achieve the required torque and speed is an electronic controller called as "VFD (variable-frequency drive)". VFD is the most common type of ASDs. VFD includes an AC/DC converter, a DC link and filter, and a DC/AC converter. It is placed between the grid and the motor. With the demand in both standby and several variable operational modes, any loss of VFD have to be over-compensated as a result of reducing losses in partial load [70]. Today, variable speed is used in most of the new technologies and their advantages are as below [61]:

- Energy cost savings
- Reliability improvements
- Simplified pipe systems (elimination of previous methods control valves and bypass lines)
- Soft start and stop
- Reduced maintenance
- As a result lower life cycle costs

4.3.2.8. Computer Tools to Analyze Motor Energy Use. Computer tools also have a vital role for the analysis of motor use. MotorMaster+, EuroDEEM, ProMot Europe, CanMOST, IMSSA are the most popular tools among all.

The free online motor selection and management tool MotorMaster+ was developed by the Washington State Energy Office to support facility managers, industrial energy coordinators, plant electricians for the selection of energy efficient motors and funded by the U.S. Department of Energy. Over 10.000 available motor information is included in the database of MotorMaster in which the efficiencies and specifications of standard and high efficient motors can be compared by means of first cost, operating cost, technical data, payback period. Operating cost is calculated taking energy cost, operating hours, load factor and efficiency of the motor into account [71].

To reduce electricity consumption in motor-driven systems, European Commission started a voluntary initiative called EuroDEEM. Motors systems are desired to be improved with the selection of most cost effective motors or with the right decision of repair or replacement with EuroDEEM which is served for free online. The current version of the software contains manufacturer's databases for over 25,000 NEMA motors and over 7200 IEC motors [72].

With 18.000 motor models from more than 25 manufacturers, a 2003 database ProMot Europe is a web environment and a standalone software consisting of 5 different databases. New installation, refurbishment, replacement, and energy and economic analysis can be accomplished with this tool [61].

CanMOST is a motor selection software which has been launched in 2004 and consisting of 43.000 motors in its regularly updated motors. Energy and demand savings due to the purchase of new energy efficient motor, predictions of energy and cost savings of replacement decisions, selection of the best-available motor, identification of inefficient or oversized motors, comparison of operating costs of various motor types and calculation of rate of return are the basic operations that CanMOST presents. CanMOST was developed Natural Resources Canada by the Washington State University Extension Energy Program and modeled on MotorMaster+ software [73].

IMSSA software was built on experiences of MotorMaster+ and EuroDEEM softwares to achieve a universal, flexible software and was sponsored by the organizations: Corporacion Nacional del Cobre de Chile (Codelco), the UK Action Energy (Carbon Trust), the European Community – JRC, Natural Resources Canada, the U.S. Department of Energy; and the International Copper Association. There are multiple analyses in the software such as motor analysis, new motor purchasing or repair/replacement decisions, life cycle costing, and best available motor identification [74].

4.3.2.9. High Efficiency Belt Drive Systems. Power transmission devices generally include belts, gears and roller chains and the overall system efficiency is affected by the selection of these system components. One less unit of energy saved in the belt drive operation leads to the use of one less unit of energy for the motor to deliver, reducing motor output. Power belt drives and especially V-belt drives are used in about one-third of electric motors in industry and if correctly installed, they work with 95-98% efficiencies.

However, the efficiency of V-belts decreases with time as much as 10%, when they are improperly maintained.

For the transmission of power between belt and pulley, V-belts rely on friction as a result of which heat (energy) is lost. Slippage and creeping are also usual when torque loads are high. Speed is lost and efficiency is reduced due to slippage and more energy is consumed for bending around pulleys since V-belts have thicker cross sections than synchronous belts. Tooth-grip principle is the way synchronous belts work n which to transmit power, belt teeth matches with corresponding grooves. There are numerous factors why synchronous belt drives are more efficient than V-belt drives:

- Torque loss is lower since less energy is required to bend the belt around the sheave
- The friction between belt and teeth is lower and so less heat is lost
- As synchronous belts do not slip or creep as V-belts, less speed is lost

Synchronous belt drives are about 5% more efficient than V-belt drives and their efficiency is about 98% through their lifetime. In addition, synchronous belt drives do not need re-tensioning as V-belts and lubrication as chain and gear drives. Finally, less time is required for maintenance, so maintenance cost is lower [75].

4.4. Compressed Air Systems

Compressed air is used when the direct use of electrical energy for tools and equipment is dangerous or not practical in most production industries. Approximately 7 volumes of air at atmospheric conditions are taken by the air compressor and squeezed into 1 volume at elevated pressure and the generated high pressure air is distributed for the operation of tools and equipment. This process is illustrated in Figure 4.7 [76].

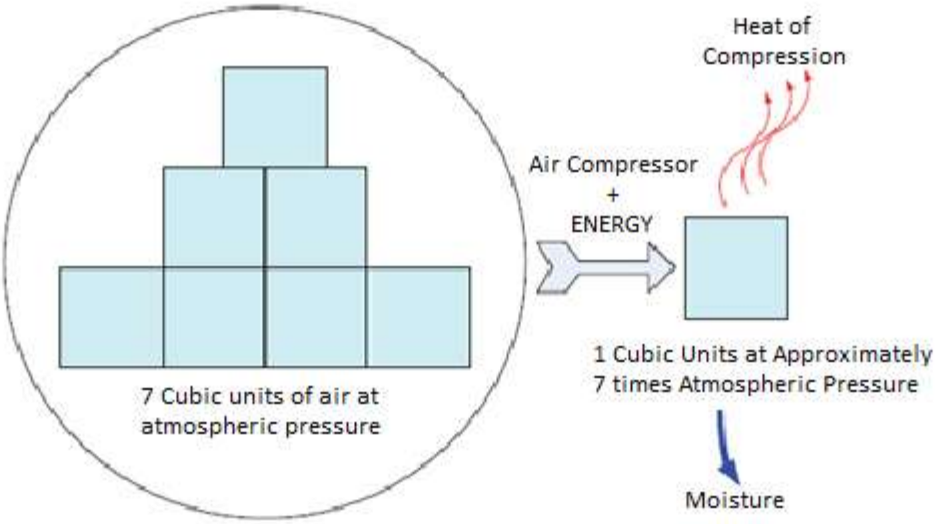


Figure 4.7. Conversion of atmospheric air into compressed air.

Energy that reaches to the point of end-use accounts for just 10-30% and balances 70-90% of the power whereby the remaining is converted to unusable heat energy or lost in forms of friction, misuse and noise [60].

There are many types of compressors used in industry. Two basic types of compressors are positive displacement and dynamic. In the positive displacement type, a specified quantity of air is squeezed in a compression chamber and the pressure prior to discharge is increased with the reduced volume. The three widely used types of air positive displacement compressors in small and medium sized industries are rotary screw, vane and reciprocating air compressors. On the other hand, dynamic compressors are widely used in large industries and include centrifugal and axial machines [76]. The types of compressors can be classified as in Figure 4.8 [77].

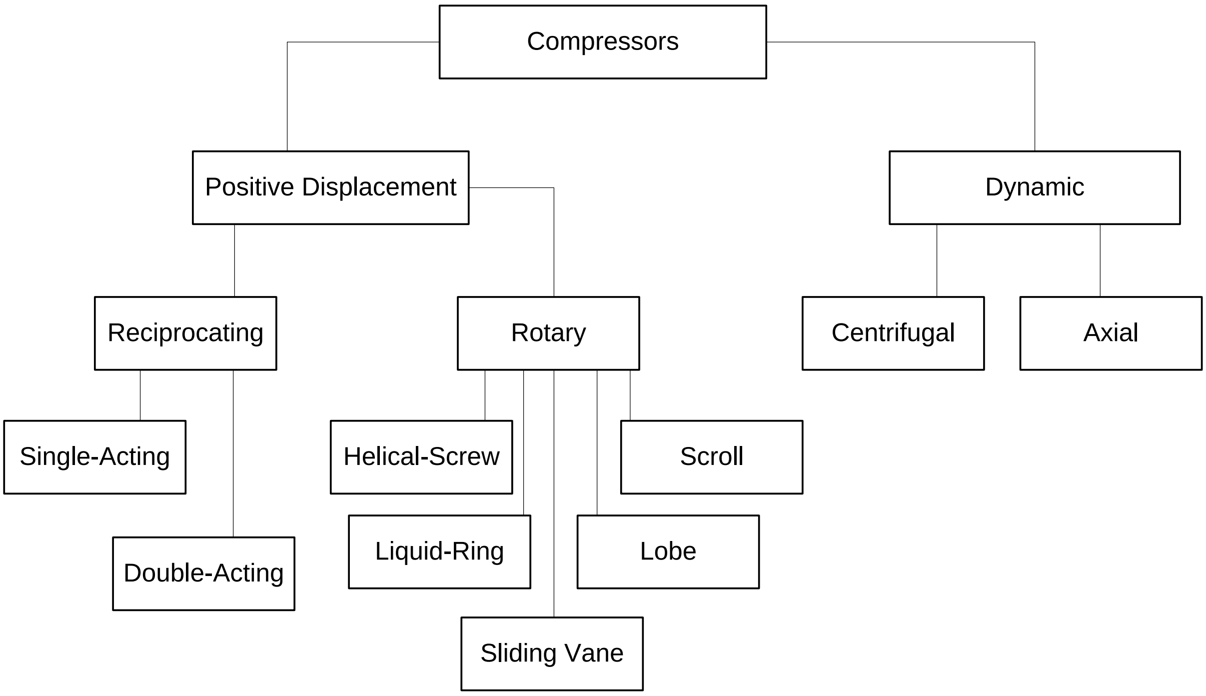


Figure 4.8. Compressed air family.

In a plant, compressed air is one of the most expensive sources of energy. Figure 4.9 shows the lifetime costs of a compressor in which it is seen that the electricity has the greatest share [78].

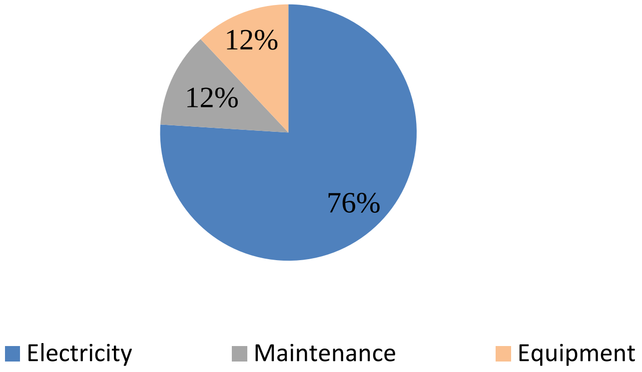


Figure 4.9. Typical lifetime ownership cost of compressed air systems.

There are several major sub-systems and sub-components in a modern industrial compressed air although the first industrial compressors were simple, reciprocating piston-driven machines powered by a water wheel. Some components of a major sub-system are compressor, prime mover, controls, distribution system, treatment equipment and accessories. The duty of the prime mover is to power the compressor while regulation of compressed air is accomplished by the controls. In addition, the contaminants from the compressed air are removed by the treatment equipment and the proper operation of the system is maintained by accessories. Finally, distribution systems take the compressed air wherever needed. A representation of an industrial compressed air system and its components is given in Figure 4.10 [77].

Compressed air systems can be divided into supply and demand side where compressors, air treatment and primary storage are included in supply side and distribution, storage and end-use equipment are included in demand side. A properly managed supply side results in delivery of clean, dry and stable air in a dependable and cost-effective manner. Major supply sub-components are air intake, compressor, after-cooler, motor, controls, treatment equipments and accessories. A properly managed demand side results in minimized pressure differentials, reduced wasted air leakage and drainage and utilized compressed air for suitable applications. A simplified diagram in Figure 4.11 illustrates how some of the major components are connected [76].

4.4.1. Important Factors for the Efficiency of Compressed Air

Compressed air is an inefficient source of energy and the energy used can be changed to other sources if possible. Many motor systems run in an efficiency range of only 5-10% as shown in the figure [79]. Some areas for compressed air use are air brakes, air piston powering, cleaning, controls, conveying, cooling, dehydration, fertilizing, forming, injection molding, mixing, mold press powering, packing, pressure treatment, spraying coatings, stamping, tool powering and vacuum melting. Inappropriate uses and potential solutions are given as examples in Table 4.7 and Table 4.8 [76].

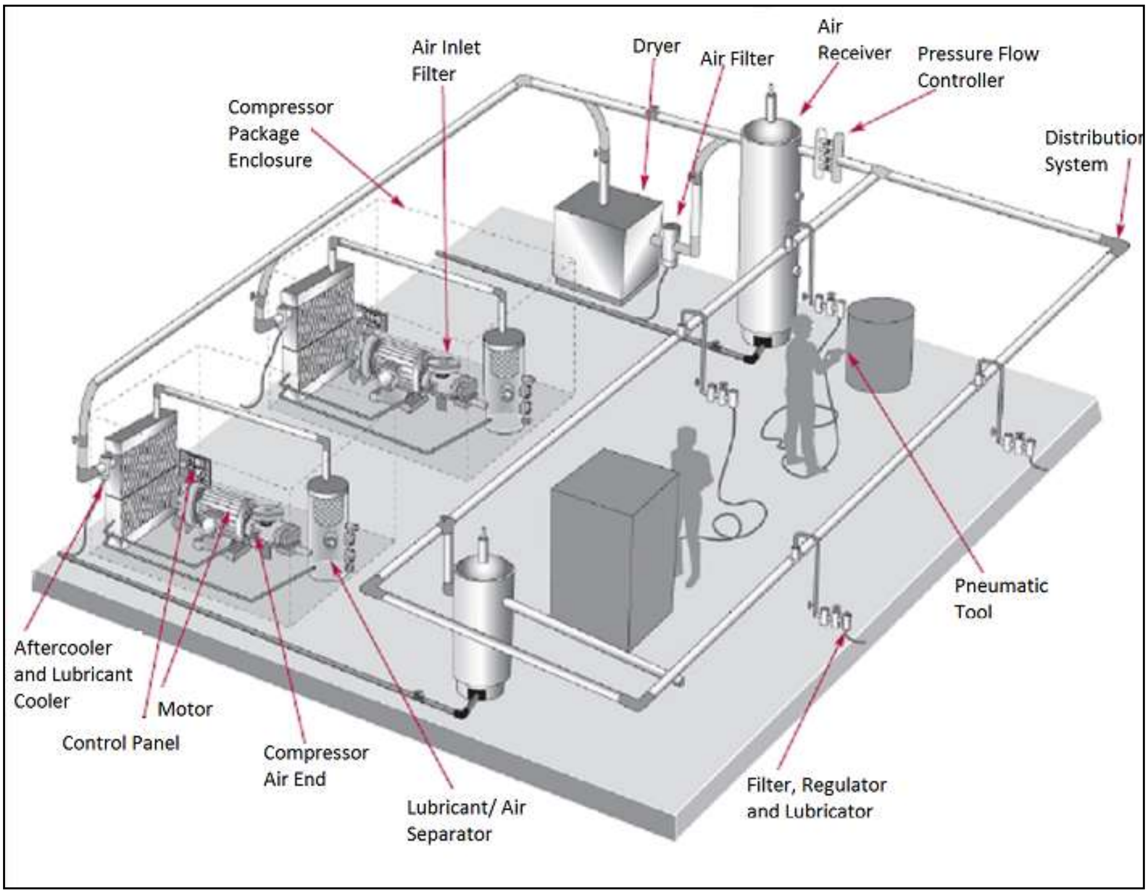


Figure 4.10. Components of a typical industrial compressed air system.

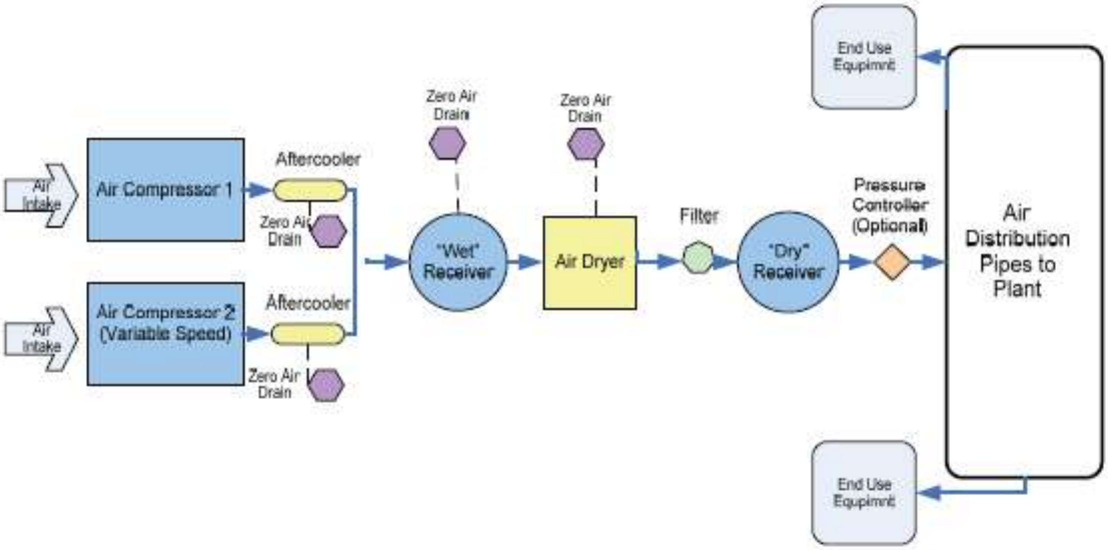


Figure 4.11. Compressed air block diagram.

4.4.1.1. Compressed Air System Leaks. Air leaks constitute an important part of wasted energy in a compressed air system and lead to productivity losses. It is so usual to have 20-30% waste of a compressor's output caused by air leaks in industry. Proactive leak management programs can reduce these wastes below 10% and with a payback period of less than 6 months.

Air leaks cause other operating losses beyond primary losses since the overall compressed air system pressure is affected by the number and magnitude of them. For instance, air tools and equipment can be affected by lower air pressure as a result of reduced mechanical output and decreased productivity [76]. In addition, excess compressor capacity results in higher costs and unnecessary cycling. Increased run time decrease service life and increase maintenance of the equipment [80].

Air leaks are not easy to notice in an environment where there is high background noise. The hissing can be heard when the plant is shut down and if the noise is present, ultrasonic leak detector should be used to recognize by their ultrasonic sound patterns. According to the experiences in industrial plants, joints and connections are the areas that leaks mostly occur. These are used to tighten a connection or replace a root cause in the areas such as couplings, fittings, pipe sections, hoses, joints, drain traps and valve stems [76].

Table 4.7. Examples of losses in a compressed air system.

Source of power loss	**Transferred useful power (kW)**	**Power loss (kW)**
Electrical power input	100	
Air from compressor	10	90 (heat)
Treatment	9	1 (e.g. filter pressure drop)
Leakage	6	3 (leakage)
Distribution system	5.5	0.5 (e.g. excess pressure drop)
Over-pressure	5.0	0.5 (heat)

Table 4.8. Potential inappropriate uses of compressed air.

Inappropriate Compressed Air Use	Description and Examples	Potential Solutions
Abandoned Equipment	Although the equipment does not operate, compressed air is still supplied	Install shut-off valves Remove redundant equipment
Aspiration	Aspirating uses compressed air to induce the flow of another gas with compressed air such as flue gas	Low-pressure blower
Atomizing	Compressed air is used for dispersion of liquid to a process as an aerosol	Low-pressure blower
Equipment or personnel cooling	Using compressed air for personnel cooling may be dangerous (fine particles or unsecured hoses)	Fans
Unregulated Equipment	End-use equipment operation without a regulator at full system pressure	Install pressure regulator
Vacuum generation	Negative pressure vacuum is generated with a venture	Vacuum pump

Some tips for preventing air leaks before they occur are:

- Installing fittings properly with appropriate sealants where applicable
- Isolating non-operating equipment with a valve in the distribution system
- Lowering the air pressure of the system where possible
- Selecting high quality fittings from reputable suppliers including air hoses, tubing, disconnects

4.4.1.2. Minimizing Pressure Drops. Pressure drop is the term used to describe the reduction in air pressure to the actual point-of-use from the compressor discharge and it occurs with the movement of compressed air through the treatment and distribution system. Pressure drop is measured from the receiver tank to the point-of-use and should be less than 10% of the compressor's discharge pressure. Excessive energy consumption and poor system performance are the causes of excessive pressure drop. For any type of flow, energy consumption is higher when the operating pressures are higher for every part and minimizing these differentials is an important way of increasing efficiency. For pressure drop upstream of the compressor, higher compression pressures are needed for which the most typical areas of problem are after-cooler, lubricant separators and check valves. Energy consumption increases approximately 1% for every 2 psi increase in discharge pressure. One another cause of high pressure is that raising the compressor discharge pressure and increasing the demand of every unregulated usage which is generally as high as 30-50% and varies plant by plant. With 30-50% unregulated usage, energy consumption increases by about 0.6 to 1% for 2 psi increase in header pressure as a result of consuming extra unregulated air. Thus, the overall effect is about 1.6 to 2% for the same conditions [77].

The following are some of the ways to minimize pressure drop in compressed air systems [76].

- The equipment components for air treatment including after-coolers, moisture separators, dryers and filters should be selected taking into account the lowest practical pressure drop at specified maximum operating conditions. Maintenance should be tracked and documented after installation step.
- Air filtering and drying equipment should be maintained to eradicate the moisture impact such as pipe corrosion.
- Appropriate pipe diameter size and looped system configurations should be chosen for the design of the distribution system.
- The travelling distance of the air through the distribution system should be minimized.
- End-use applications should be checked in terms of their pressure level requirements. To match the point-of-use requirements the compressed air system should be minimized.

- Air pressure at the inlet to the air tools should be checked if sufficient pressure is being supplied. Generally caused by undersized air lines, quick couplers, filters, regulators and lubrications, 30 to 40 psi pressure drop is usual between header drop and the point-of-use.
- Each end-use point should be checked and the one with the highest pressure requirements should be found. Then, this amount should be reduced to maintain functionality, and to have a lower overall system pressure.
- Lowest pressure differentials and the best performance characteristics for regulators, lubricators, hoses and connections should be found specifically; and the actual flow rates should be used rather than average.
- Larger size couplings should be preferred for reduced pressure differential. For instance, a 3/8 inch quick coupler has one-sixth the pressure differential of a 1/4 inch connector at the same flow.

4.4.1.3. Minimizing End-Use Energy Requirements. End use energy requirements of the compressed air system can be minimized with the accomplishment of the below tips [76].

- Unsuitable end-use applications (such as open blowing) should be replaced by efficient models (vortex nozzles, atomizers).
- A flow controller should be installed for the reduction of plant pressure and artificial demand caused by higher than required pressures.
- Air consuming equipment can be turned off with the use of electric solenoids or manual shutoff valves.
- Operation of air loads with no load should be avoided as more air is consumed than a tool under load.
- Worn tools should be replaced as a result of the requirement for higher pressure and excess consumption of compressed air compared to the tools that are in good shape.
- Air tools should be lubricated as recommended by the manufacturer. So as to maximize tool life and effectiveness, the air used by all end-uses should be kept free of condensate.
- End use air equipment should be grouped where possible and practical taking the similarity of pressure and air quality requirements.

4.4.1.4. Heat Recovery. Industrial air compressor converts as much as 80-93% electrical energy into heat. 50 to 90% of this thermal energy can be recovered anywhere in a properly designed heat recovery unit and put to a useful work in heating air or water. Supplemental space heating, industrial process heating, water heating, makeup air heating and boiler makeup water preheating are typical uses for recovered heat [78,79].

4.4.1.5. Compressed Air System Control. One of the most important determinants of overall system energy efficiency is compressed air system control to match the supply and demand of compressed air. Both individual and overall system compressor control are vital for efficient operation and high performance. Any control strategy aims also to shut down unneeded compressors and delay purchasing additional compressors until needed and all operating units should be run at full-load. Since just a few air systems work with full-load all the time, part-load performance is important and is affected by compressor specifications and facility's demand profile. In each case, both compressor and system control selection should be considered as the most important factors affecting system performance and efficiency [77].

The following additional points should also be considered with compressor control [76]:

- Multiple compressor systems require more advanced controls or control strategies for the coordination of compressor operation and air delivery to the system.
- The time needed to start up the compressor and the time that the compressor brought to speed should be considered for the design or tuning of a compressor control system.
- Adjustments should be applied to cascaded, single pressure bands from time to time.

Demand events in a compressed air system can be controlled with storage by reduction of both the amount of pressure drop and the rate of decay. Critical pressure applications can be protected from other events in the system. Another goal of storage is to control the rate of pressure drop to end uses [77].

4.4.1.6. Compressed Air Storage. Compressed air storage allows a compressed air system to meet its peak demand needs and eliminates the need for additional compressors. Air demand patterns, required air quantity and quality determine the appropriate type and quantity of air storage. The feature of an optimal air storage strategy is to provide enough air for satisfaction of temporary air demand events while minimizing compressor use and pressure. Air receivers is effective especially for systems with variable air demand patterns where enough stored air is provided by a large receiver and both the system can be served by a small compressor and the capacity control system operates more effectively [78].

4.4.1.7. Using Outside Air Intake. Compressors are located generally inside the industrial plant or outside in adjacent shelters. Normally the intake air is drawn from inside the building or shelter. But the air temperature of the building is higher than the outside air temperature in many locations as a result of space heaters in winter and the heat caused by mechanical and electrical equipments throughout the year. The reason of the increase in the temperature is the dissipation of the heat from the compressor and its motor. Even in hot summer days, the air in the outside is cooler and thus denser than in the compressor room. Thus, to ensure the air to be supplied directly from the outside of the building rather than inside, installing an intake duck to the inlet is advised. Compressing a specified amount of cool air with less energy than compressing the same amount of warm air will reduce the energy consumption [81].

4.4.1.8. Optimized Air-Dryers. Air-dryers are responsible of significant compressed air and electrical power consumption and often have limited turndown capabilities. Upgrading or replacing the present air-dryer can produce effective results. The following should also be considered [76].

- Energy savings cycling stage should be considered for new purchases of refrigerated air-dryers
- Drying the air to a dew point level that is lower than needed should be avoided
- Energy saving dew point controllers should be used for all types of regenerative desiccant dryers.

4.5. Pumps

Pumps are broadly used in industry to support cooling and lubrication services, to move fluids for processing and to maintain the motive force in hydraulic systems. To accomplish their daily operations, most industrial plants and commercial buildings depend on pumping systems. Pumping systems account for nearly 20% of the world's energy used by electric motors whereas the same ratio is 25 to 50% of the total electricity used in certain industrial facilities. In the commercial sector, heating, ventilation and air-conditioning (HVAC) systems are the areas where pumps are used in for heat transfer. Since the aims of use are various, it is common to see pumps in different sizes from fractions of a horsepower to several thousand horsepower. For the reduction of pumping system energy consumption, there are important opportunities with means of smart design, retrofitting, and operational practices. Above all, there occurs huge potential for savings in many pumping applications with different duties. Improvements are not only encountered in energy but also in performance, reliability and life cycle costs [82,83].

A typical pumping system is illustrated in Figure 4.12 and it contains the following basic components [82,84].

- Pumps (positive displacement or centrifugal where these categories relate to the manner in which energy is given to the fluid)
- Prime movers (electric motors, diesel engines or air system)
- Piping (to contain and carry out the fluid from pump to the point-of-use)
- Valves (to control the flow in the system)
- Other fittings, controls and instrumentation
- End-use equipment with various requirements (e.g. pressure, flow) which determines the components and configuration of the pumping system such as heat exchangers, tanks and hydraulic machines.

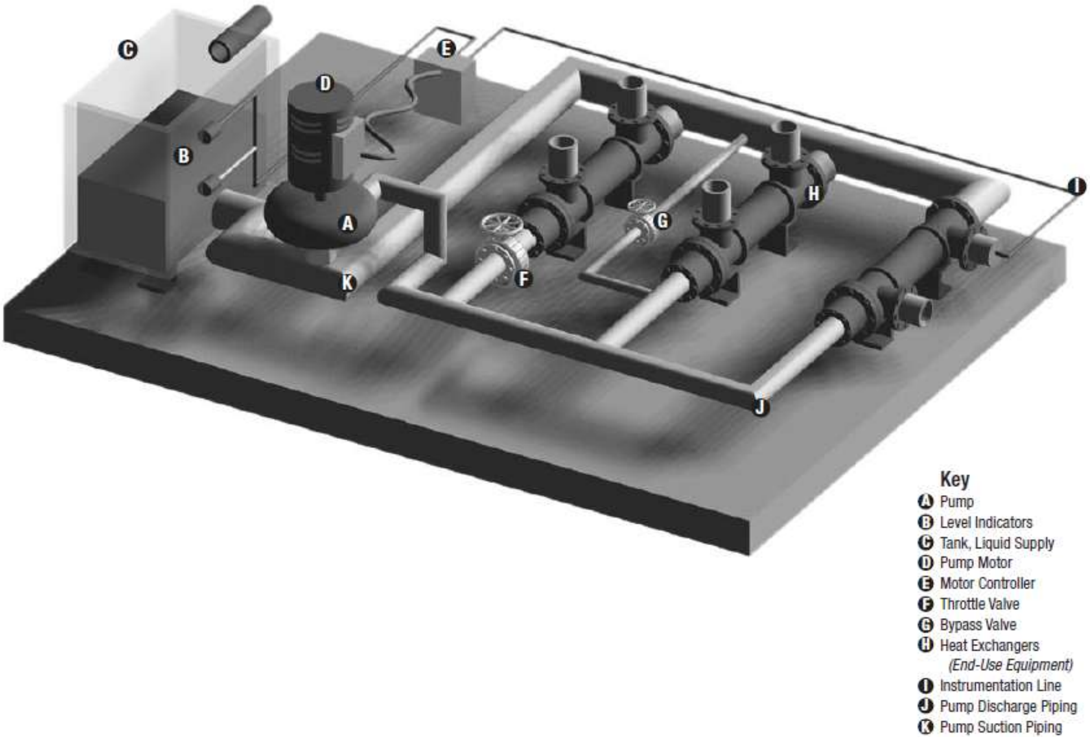


Figure 4.12. Typical pumping system components.

Studies show that in industrial plants, pumping efficiency can be less than 40% in average and 10% of pumps operate less than 10% efficiency. The two most important causes of this inefficiency are told to be oversized pumps and the use of throttled valves. With the changes in equipment or control system, as much as 30-50% energy saving could be realized. Another cause of inefficiency is the wear during normal operation which reduces efficiency by 10 to 25%. Thus, 50 to 60% overall efficiencies in pumps are commonplace and sometimes the improvement opportunities are prominent [85].

4.5.1. Important Factors for the Efficiency of Pumps

Energy efficiency opportunities for pumps can be grouped in the following subtitles [84,86]:

- Analysis of the system requirements
- Selection of the right pump
- Controlling the flow rate by speed variation
- Multiple pumps to meet varying demand
- Eliminating by-pass control

- Start/stop control of pump
- Impeller trimming

4.5.1.1. Analysis of System Requirements. Understanding every aspect of system requirements such as peak demand, average demand and the variability in daily and annual basis is vital for the improvement in system performance and reliability. Relatively smaller demand variation increases the reliability of the system and it is easier to design and operate such systems.

The very first step of pump selection to obtain the most active and effective system is learning operating conditions of the system such as fluid properties, pressures, temperatures and system layout. The flow rate-time intervals and pump head of the system throughout the year should also be well known. The type of the pump chosen should meet the needs of the system. Basically there are two types of pumps as positive displacement and centrifugal pumps where axial-flow pumps are also classified as centrifugal as they have the same operating principals. Positive displacement pumps squeeze a fluid in a collapsing volume to provide pressure, such as a piston in a cylinder. On the other hand, centrifugal and axial-flow pumps load kinetic energy to a fluid and increase pressure while conversion of it to potential energy. The areas of use are also different for two type of pumps since positive displacement pumps are used in low-flow, high-head applications with high-viscosity fluid whereas, centrifugal pumps are used in high-flow, low-head applications with not-so-high-viscosity [82,86].

4.5.1.2. Selection of the Right Pump. The pumping system is designed for peak loads while normal operating loads are much smaller, so there is often a problem with oversized pumps. On the other hand, forcing excess energy to the system not only increases operating costs but also results in unnecessary wear on components such as valves, piping and piping supports.

Generally, the pump installed in a system is most effective in terms of cost while being oversized and not technically the most efficient. The most efficient pump based on the operation profile of the system should be chosen and ensuring that it benefits the life cycle cost since energy consumption usually has the greatest share for life cycle cost [87].

On the other hand, the initial purchasing costs are in 3-5% levels of life cycle cost which is low compared to energy costs [86]. Thus, rather than short-term perspective, future results of the pump selection should be taken into account.

4.5.1.3. Controlling the Flow Rate by Speed Variation. One another point to consider which is often underestimated is the impact of running a system with higher-than-needed levels of flow and pressure. That is, pumps and valve lineups are adjusted to meet the worst-case demand. For instance, cooling system is not readjusted to lower demand after it is used to handle the largest heat load. Improvements in the operating cost and reliability can be achieved with the recognition of the variability of system demand and matching flow and pressure requirements [82].

Performance of a centrifugal pump is impacted by the varying rotational speed, as the peripheral velocity of the centrifugal pumps’ rotating impeller is dependent on the shaft rotational speed. Understanding the relationship between flow rate, head and power will help to take control of the pump which has a varying performance with different rotating speeds.

There are different methods to get a pump system with variable flow rates such as operating the pump when it is needed (part load operation) or operating pump continuously by sending some of the liquid back to the tank (by-pass system). In these methods the system is fed from a tank for part load operation considering the level of the tank, and with the help of a control valve adjusting the flow rate to adjust the rotational speed taking the need s of the operation into account [86].

The need for variation of flow or pressure forces the single installed pump to be oversized to meet the greatest output demand which results in inefficiency for other duties. Therefore, variable speed drives is one of the control methods to save energy cost in which the driving power of the pump is reduced when demand is low. Like other methods, VSDs have some benefits and drawbacks for pumps too. Benefits of VSDs are as follows [82,83].

- Energy Savings: Savings in rotodynamic pumps has been between 30-50% whereas in positive displacement pumps energy consumption is directly proportional to the volume pumped and savings are quantified.
- Cost Savings: Since control valves, by-pass lines and conventional starters are not needed any more, capital and maintenance costs are reduced.
- Improved Process Control: Process performance is increased since VSD can answer more rapidly than any other control tools to variations in process requirements.
- Improved System Reliability: Pump wear especially in bearings and seals are reduced with the use of VSD. The time interval between maintenance or breakdowns can also be estimated.
- Soft Starter Capability: Lower starter current is enough for the start of the motor.

4.5.1.4. Multiple Pumps to Meet Varying Demand. Rather than using one pump for the system requirements, another option is the use of several smaller pumps in parallel. A single pump is not able to operate near to its best efficiency point (BEP) and thus it results in higher operating and maintenance costs. Performance and service life of the pumps are optimized around a capacity described as BEP and every centrifugal pump has a BEP where its operating efficiency is highest and radial bearing loads are lowest. BEP is a function of inlet configuration, impeller design, casing design and pump speed.

Both efficiency of each pump and overall efficiency increase with energizing and de-energizing multiple pumps to meet the changes in demand particularly in those with high static head requirements. However this efficiency increase relies on the characteristics of the pumps and the demand changes. Some benefits of multiple pump use are flexibility, redundancy, and efficiently satisfying the changes in flows which are summarized as follows:

- Flexibility: Using several pumps in parallel expands the range of flow delivered to the system. Furthermore, a closer operating point to BEP is achieved with energizing and de-energizing pumps. One issue to be careful about for operators is that minimum flow requirement is achieved for each pump or not.

- Redundancy: Since there are multiple pumps, one of the pumps can be repaired while others go on operating which results in the continuity of the system although one unit fails.
- Maintenance: In multiple pump use, each pump operates close to its BEP and thus bearing wear is reduced as well as pumps run smoother. In addition, dependence on by-pass lines and throttle valves is eradicated. Variable speed drives also benefit for the same purpose.
- Efficiency: Operating closer to BEP, increases overall efficiency since all pumps work around a smaller region with smaller variations not like single pumps which operate over a larger range and far away from its BEP.

In multiple pump arrangement, pumps are generally identical for a balanced load-sharing in a parallel operation simultaneously. When pumps are of different sizes, largest pump may dominate the system and as a result, other pumps operate below their minimum flow ratings. All pumps should be adjusted in a way that no pump works below its minimum flow rating in such a different-size multiple pump arrangement [82].

4.5.1.5. Eliminating By-pass Control. By-pass lines control accurate flow as well as preventing a pump from the danger of "deadheading" which is the situation in which the flow is usually choked off by closed downstream valves. In by-pass lines the discharge of the pump is divided into two flows which go into two different pipelines. While one of the pipelines delivers the fluid to the delivery point, the other one returns the fluid to the source. That is, part of the fluid is pumped around meaninglessly, therefore by-passing flow is the least energy-efficient flow control option generally and should be avoided [82,84].

4.5.1.6. Start/Stop Control of Pump. Starting and stopping the pump is a simple, meaningful and energy-efficient way to reduce the flow rate unless it is too often. This method can be applied for a pump which fills storage at a steady rate. In such a system, installing the minimum and maximum levels to start and stop the pump is enough and used by some companies to get rid of lowered maximum demand [84].

4.5.1.7. Impeller Trimming. Impeller trimming is the process that the diameter of an impeller is processed to reduce the energy added to the system fluid. For pumps which are oversized for their applications, impeller trimming is a useful process. Trimming an impeller brings a less effective result than buying a new small impeller from the manufacturer. Generally, the next smaller size of an impeller is too small and those are not suitable for the pump, therefore it is the alternative of replacing whole pump/motor assembly. The following are the times to consider impeller trimming:

- When many bypass valves are open, which means there is excess flow to system equipment
- When excessive throttling is necessary to control flow through system and process
- When high levels of noise and vibration results excessive flow
- When the pump is beyond its design point

The flow and pressure generated by the pump is reduced as a result of reducing speed with impeller trimming. Another benefit of reducing the size of impeller is decreased operating and maintenance costs. Less fluid energy is wasted in the by-pass lines and through throttle valves, or wasted as noise or vibration.

The wear on piping, valves and piping supports are also reduced as well as energy savings. Pipe welds and mechanical joints are fatigued with flow-induced piping. With time, welds crack and joints loosen resulting in leaks and downtime for repairs [82].

4.6. Fans

Fans have a wide area of use in industrial and commercial sectors from shop ventilation to material handling to boiler applications. In industrial sector 15% of energy consumed by motors is due to fans. Figure 4.13 depicts general components of a fan.

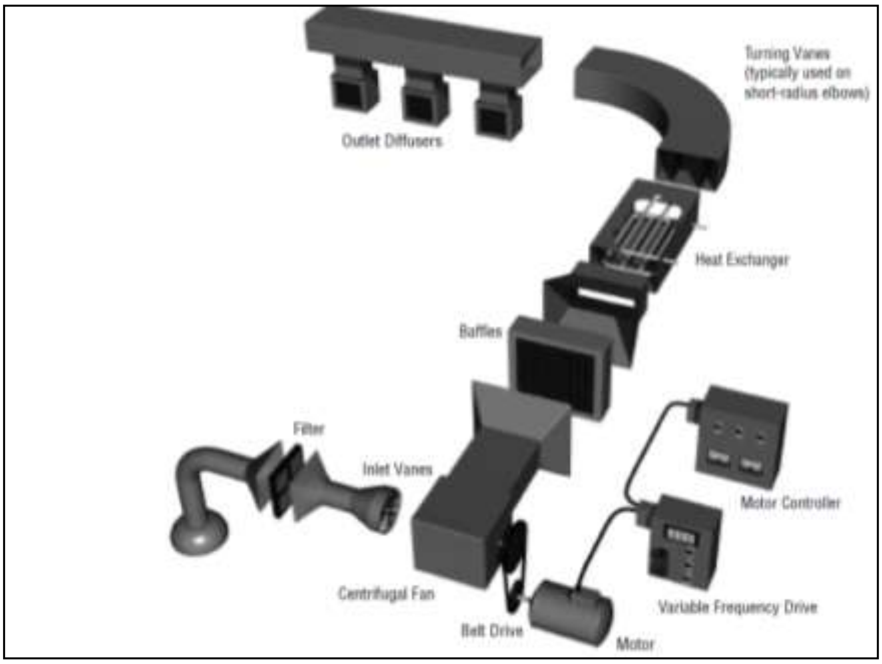


Figure 4.13. Fan system components.

Fan reliability is vital for plant operation. For instance, there will be a sudden stoppage in the process when fans used for material handling operations fail. In industrial ventilation, fans again may cause a process to be shut down. Even in heating and cooling, for a productive work environment, fans are inevitably important. As mentioned, failure of fans may cause to reductions in worker productivity and product quality. In order not to be responsible of under-performing systems, fan systems are often designed over-capacitated. Thus, oversized fans decrease reliability and increase costs.

Fans, blowers and compressors are individualized by the method used to move the air and the system pressure they operate against. ASME, The American Society of Mechanical Engineers, uses the ratios given in Table 4.9 to show the difference between each.

Since the operating conditions and system requirements are not extremely different, fans and blowers also have the same energy efficiency opportunities as told in compressor section.

Table 4.9. Difference between fans blowers and compressors.

Equipment	Specific Ratio	Pressure Rise (mmWg)
Fans	Up to 1.11	1136
Blowers	1.11 to 1.20	1136 - 2066
Compressors	More than 1.20	-

Briefly, in fan selection, noise, rotational speed, air stream characteristics, temperature range, variations in operating conditions, space constraints, system layout and costs for purchasing, maintenance with operating lifetime are the criteria for the initial choice of fans. Reduction in system resistance, closer operation to BEP, regular maintenance and control of the fan air flow are other improvement opportunities. Variable loads, reducing system leaks and using multiple fans can also be applied for a more energy efficient system [88].

4.6.1. Important Factors for the Efficiency of Fans

In a market study to improve energy efficiency of fans the improvements are grouped under five categories [89]:

- Control and motor drive system
  - (i) Control system (including demand control and operation schedule)
  - (ii) Operation schedule (to optimize timely consumption-the energy saving range: 10 to 50%)
  - (iii) Demand control (adjustable speed drives, adjusting the pitch of blades, CO_2 level monitoring-the energy saving range: -5 to 50%)
- Motor
  - (i) High efficiency motors (the energy saving range: 2 to 10%)
  - (ii) Right type and size of motor (the energy saving range: 5 to 20%)
- Transmission
  - (i) Changing from direct drive to V-belt drive (the energy saving range: 5 to 15%)
  - (ii) Changing from V-belt drive to flat drive (the energy saving range: 5 to 10%)

- Ducting
  - (i) Design including many bends and diameter changes
  - (ii) Balanced ventilation system (the energy saving range: about 15%)
- Additional savings
  - (i) Proper selection of fan and components, maintenance, etc. (the energy saving range: 5 to 20%)

5. ENERGY VALUE STREAM ANALYSIS

The chapter focuses on the first step of energy value stream mapping. The product family selection, visualization of the current value stream map and quantitative assessment of technical equipments are placed here. Chapter 4 is used as an input feeding the subjective factor explanations of the energy efficiency maturity index. Steps for the construction of the assessment are further explained, and related calculations are attached to this thesis as excel files.

A facility cannot go beyond the ordinary if solely technological improvements are considered as retrofits and not all production processes are coordinated and appropriately linked. To this respect, to enhance overall performance, a holistic approach based on value stream mapping is adopted rather than focusing on isolated improvements.

The value stream moves from suppliers to customers where material and information flows are also included. The primary emphasis in value stream mapping is customer's point of view since it is the customer who defines the value. Accordingly, overall production process is specified including all related activities [44].

An energy value stream analysis starts with the choice of the product family to be investigated. Two methods are developed for product family selection. The first method is based on the use of production family matrix whereas the second one emphasizes the similarities among the production processes.

The next step after the product family selection is the analysis of customer order placement reflecting the demand size and the required lead time. If all process times of the corresponding work stations are balanced with the calculated takt time, the process is in agreement with the customer request. Customer takt time (TT) can be computed as follows in terms of factory working days (FD) and working minutes per day (WM) [37].

$$TT=\frac{(Available\ operating\ time\ per\ year)}{(Customer\ order\ per\ year)}=\frac{FD*WM}{units} \tag{5.1}$$

For the company under investigation in this thesis, there is a high customer demand volatility. Winter footwear items are produced to stock during the summer season with high demand expectations. Similarly, this process is repeated for the summer footwear. Since seasonal working pattern governs footwear industry, accurate demand forecasts play a critical role in the decision process of how much to produce.

Cycle time (C/T) is the total elapsed time throughout the process. Basically, it includes all the operation times in the value stream. A shorter cycle time can be achieved by placing more resources concurrently.

Changeover time (C/O) is the time required to switch from one product type to another at a workstation in the related production process [90]. Set-up, warm-up, trial run and adjustment times are included in changeover time.

Availability is the percentage of time when machines are available to perform the requested tasks. Machines may not be accessible in certain situations such as scheduled service and maintenance activities or unexpected technical problems [90].

The production system includes several processes and those processes are visualized as rectangular data boxes in which the top row includes the name of the process, number of workers, cycle time, changeover time, availability and uptime. The value stream map is enhanced to incorporate energy related data such as energy type, energy consumption and energy intensity. An illustration of a data box can be seen in Figure 5.1. Energy intensity (EI) is the production process-related energy consumption for unit process p and is calculated as the product of customer takt time, TT and the power input, P_e summation for different energy sources e such as electricity, gas and compressed air [37]:

$$EI_p = TT * \sum_e P_e \tag{5.2}$$

Energy intensity of the whole value stream is also defined by Erlach and Westkämper as:

$$EI_w = \sum_p EI_p \tag{5.3}$$

The degree of efficiency is the comparison of energy consumed in a manufacturing process to a reference value and is used to quantify the process quality. For example, specific energy consumption is 2.97 kWh/kg for a 220 g. product that consumed 654 Wh energy (654Wh/220g=2.97 kWh/kg). Degree of efficiency is calculated as 0.54 when reference for energy consumption is 1.6 kWh/kg (1.6/2.97=0.54).

$$\text{Degree of efficiency (DE)} = \frac{\text{Reference for energy consumption}}{\text{Specific energy consumption as measured}} \tag{5.4}$$

where

$$\text{Specific energy consumption} = \frac{\text{Energy Intensity}}{\text{Reference Value}} \tag{5.5}$$

When it comes to material and information flow, there are three types of material flows such as outside the factory conducted with trucks, internal transport with forklifts and process-related conveyance with roller conveyors. These flows are visualized with the symbols of their means of transportation.

Every storage location needs to be included in a value stream map. Data related to storage location and stored material are specified the volumes of raw material and products. Value stream analyst's counting and entering storage values makes possible to reveal hidden storage whereas writing down the given values may continue concealing problematic conditions. Storage information is added to the data box depicting storage functions [44].

Shipping is the next stage in a value stream map. The subjects to be covered in this stage are added to the supplier box as follows: supplier, respective means of transport, required mode of dispatch and packaging and delivery frequency [43,89].

Both formal and informal communication can be added to a value stream map. Insufficient and inconsistent information flow may lead into confusion or even chaotic situations. Order entry, production planning and material procurement are example business processes mapped represented as information flows. Material flow in the facility can be understood with the help of the symbols whether consumption-driven or demand-controlled dispatch is applied.

Once value stream map is completed, 7 deadly wastes eliminated through lean manufacturing can be reviewed for energy efficiency potentials. Types of wastes are reviewed from the energy perspective and improvements to achieve lean energy approaches are classified as below [30,46]:

- Overproduction: Use of surplus energy by an ineffective production system to make excessive products
- Waiting: Energy used while heating, cooling and lighting during production idle time
- Transportation: Loss of energy due to inefficient energy transportation such as in using compressed air or gas
- Inventory: Energy used for heating, cooling, and lighting of inventory storage and warehousing space
- Defects: Energy consumed to manufacture a defective product or additional space required for rework and repair, increasing energy use for reprocessing
- Motion: Inefficient transportation of goods
- Overprocessing: More energy consumed in operating equipment related to unnecessary processing
- Unused Human Talent: Failure to integrate employees when defining energy efficient processes

5.1. Description of the Current System

The current state energy value stream map of the system is visualized in Figure 5.1. Energy consumption of each department is written in the data box related to that department.

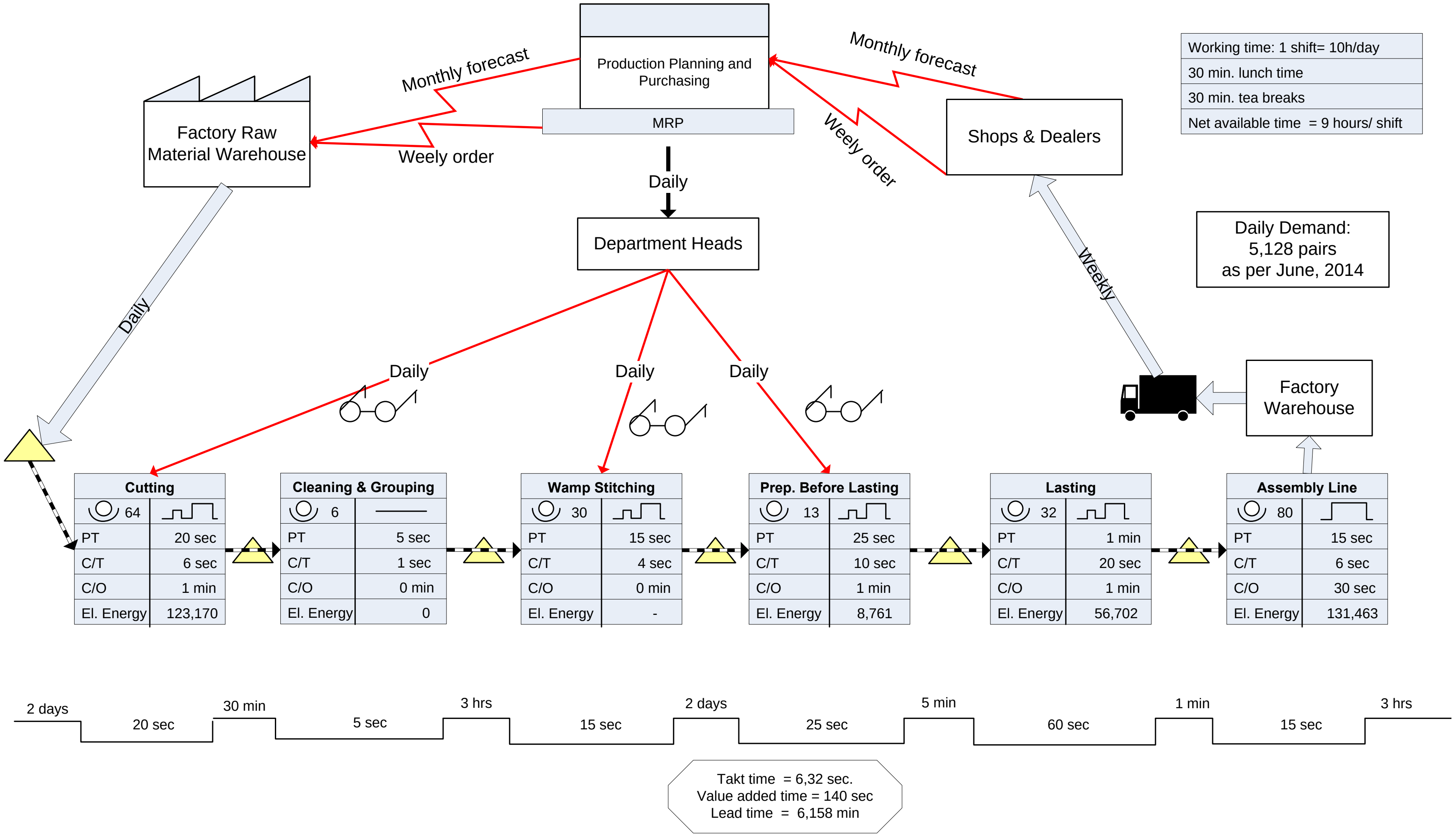
The footwear company works Monday through Friday between 8.00 a.m. and 6.00 p.m. Excluding two 15-min. breaks where all processes stop automatically and 30-min.

lunch, net available time in the value stream can be calculated as 9 hours per day. To find customer demand during the same period, data from the last available month (June) can be used which is 107,694 pairs of shoes. Since there are 21 working days in June, daily demand is 5,128 pairs. Thus, takt time is calculated as 32,400 seconds / 5,128 pieces=6.32 seconds. Based on this takt time, one piece must be completed and be ready for shipping on the average of 6.32 seconds.

Cycle times and changeover times have also been measured and written in process boxes of the value stream map. It is obvious that lead time is extremely high compared to processing times. Furthermore, all process steps' cycle times are above takt time and processes are unbalanced. Line balancing which has the goal of balancing and pacing the flow of the value stream may be applied in this facility so as to arrange process cycle times less than the takt time and as close to the same as possible [90].

Production is done in batches where lots are placed in containers and transported to the next department using forklifts which results to some waiting between processes. Since there are delays in the production line, different units of the factory may work on different type or model of shoes. The greatest amount of inventory time in the company is due to leather raw material which is followed by the time interval between wamp stitching and preparation before lasting.

Although the primary objective of this study is to reduce energy consumption for the same amount of output, other lean initiatives should also be applied to improve the current process. Apart from the improvement opportunities related to material flow and processing times summarized above, there are also energy losses referred as deadly wastes of lean philosophy.



Working time: 1 shift= 10h/day
30 min. lunch time
30 min. tea breaks
Net available time = 9 hours/ shift

	Cutting	Cleaning & Grouping	Wamp Stitching	Prep. Before Lasting	Lasting	Assembly Line
	64	6	30	13	32	80
PT	20 sec	5 sec	15 sec	25 sec	1 min	15 sec
C/T	6 sec	1 sec	4 sec	10 sec	20 sec	6 sec
C/O	1 min	0 min	0 min	1 min	1 min	30 sec
El. Energy	123,170	0	-	8,761	56,702	131,463

Takt time = 6,32 sec.
Value added time = 140 sec
Lead time = 6,158 min

Figure 5.1. Current state energy value stream map.

Figure 5.2 illustrates eight types of energy wastes in the energy flow model that can be mapped and reduced by the energy value stream map [91]. These waste types can be mapped with 7 deadly wastes of lean manufacturing to increase their visibility in Figure 5.3. The potential solutions for each waste are also summarized in Figure 5.4.

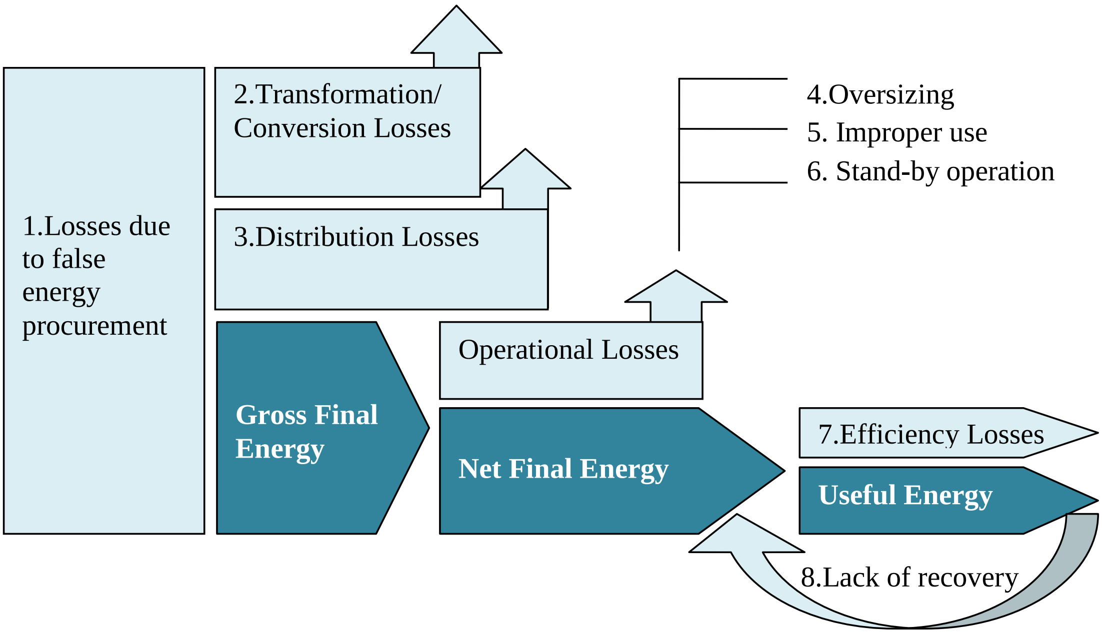


Figure 5.2. Depiction of energy wastes in energy flow model [91].

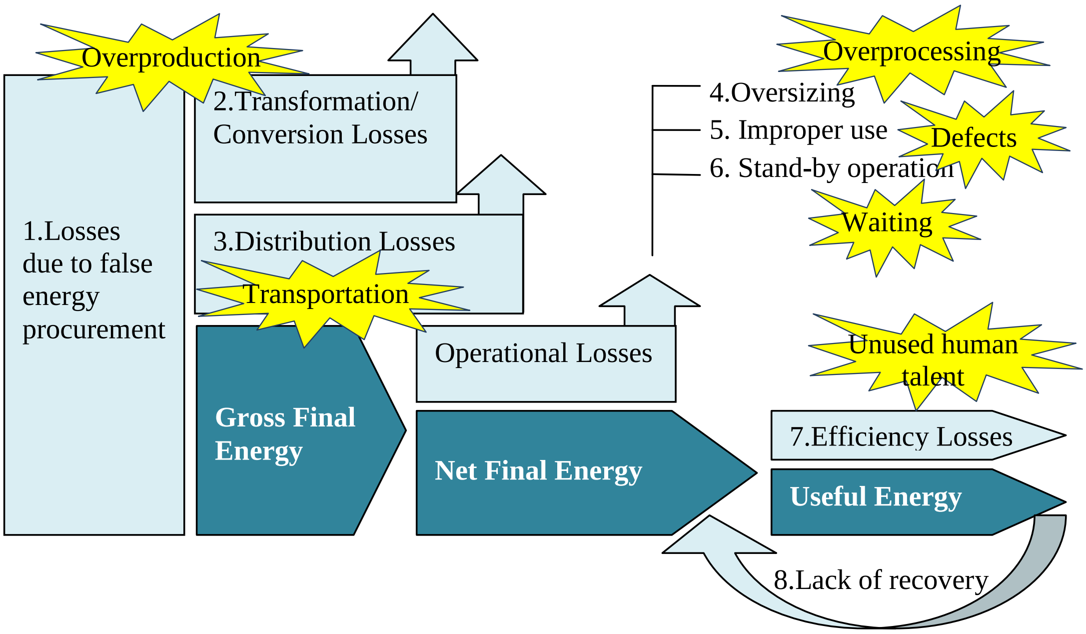


Figure 5.3. Mapping energy wastes with lean manufacturing wastes [91].

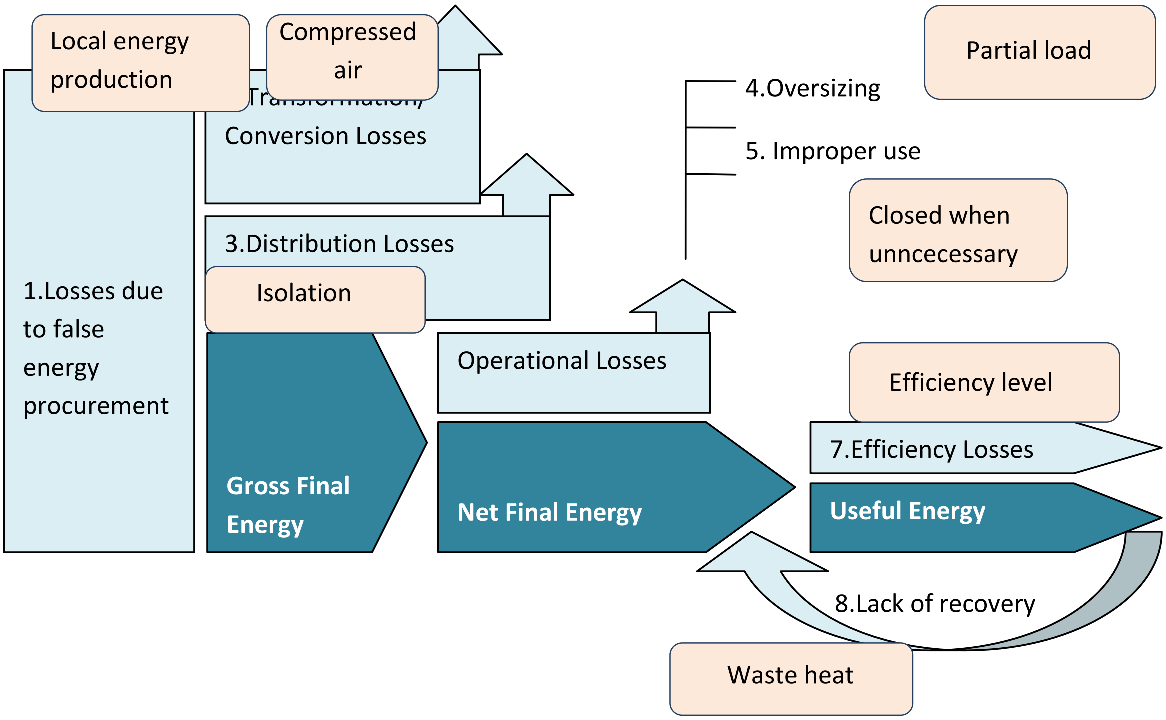


Figure 5.4. Potential improvement opportunities for energy wastes [91].

The wastes are summarized and concrete examples are given in the following eight paragraphs:

Overproduction is one of the major wastes in the company such as the use of excess energy by an ineffective manufacturing system to make unnecessary products. As the factory does not adopt just-in-time manufacturing as explained in Appendix B, a safety stock is maintained which means consuming energy to stock excess products.

Waiting is another waste widely seen in any facility. In production downtime such as lunch time and two 15-minute breaks, all the lights and machines are closed down and no energy is consumed. A button occurs with which the foreman opens or closes all the operating units' electricity according to the needs. In addition using one pump for all operations of the same machine causes waiting while the operator changes settings of the pump for the related operation. Using multiple pumps with varying loads helps to overcome this problem.

Inefficient transportation of energy causes transportation wastes. In the company, these wastes are tried to be eliminated with regular controls of the system. In addition, design of the facility also necessitates long pipes and tubes to transport energy where waste is inevitable.

Warehouse of the company consumes a great amount of energy in the means of lighting and cooling which results in inventory wastes. In addition, faster assembly lines force employees to store all shoes not worked on yet in the shelves beside them or on the storage line above their assembly line which then starts working and consume extra energy. Containers, shelves and unused machinery are temporarily stored in front of the windows. Consequently, they form a barrier for the daylight to enter the workplace causing excess use of lighting.

Not following the maintenance rules of machinery and tools, use of wrong components for machinery and leaks in the compressor may lead to defects in the company. In addition, failure in the first quality check may be asserted as the most deadly waste for the company since the most expensive material, leather is processed according to the result of the quality control. If the controller approves the quality of leather inadvertently, all processes until the last control are waste of time whereas the materials used through these processes are wasted materials. Thus, quality control is of great importance to eradicate both defects and also overprocessing with excluding faulty products in the first stage and eliminating processing these items.

As emphasized in Appendix B, wamp stitching process is outsourced to a subcontractor located in the adjacent building. This causes substantial motion wastes to transfer semi-finished products to wamp stitching workstations and bringing them back for other operations such as lasting and assembly. Furthermore, unbalanced assembly lines also force workers to carry shoes to shelves when they cannot adjust their tempo to the line. When there is a high amount of buffer storage, the line is stopped and shoes are carried back to the working area as a rework.

Improper type of machinery such as motors, pumps and fans with a greater power than needed result in higher energy consumption which brings forth overprocessing. In addition, not insulating the equipment may also cause overprocessing because of the longer time needed to achieve to the same temperature. Using constant speed or heat for different purposes is another issue encountered in facility visits like the steam ovens always operating at the same pace. The temperature of the oven should be adjusted for different kind of shoe materials, but employees do not decrease the temperature, indeed they open the cover to cool it to a lower degree. Rather than waiting for the oven to cool, the way employees work not only consumes a higher amount of energy but also and most importantly worsen their working conditions.

Employees in the factory are not aware of productivity, lean concept and energy consumption which is the cause of waste of unused human talent. Organization of 5S or Kaizen events with the employees both increase their motivation because of participation in management decisions and also produce better improvement ideas since they are the final user of the machines for years.

5.2. Assessment of the Current System: Energy Efficiency Maturity Index

The aim of this section is to create a quantitative and generic scorecard for the evaluation of energy efficiency maturity. Since the value stream is composed of direct energy-consuming processes, 4 distinct scorecards, namely for motors, pumps, compressors and fans will be appropriate. The three steps for the construction of energy efficiency maturity index is outlined in Figure 5.5. In addition, single factor analysis step is also extended in Figure 5.6.

Firstly, having decided the scorecards, the content and the potential factors to be included in scorecards should be determined as an initial model design step. This stage is further explained in Section 5.2.1.

The second step in building a maturity index is factor analysis (FA) where each factor is examined independently employing the methods outlined below to develop a better understanding of the factor and its potential in assessing a facility's energy efficiency. Each potential factor is evaluated to determine its impact on the clarity and usability of the maturity index. Model factors are tested respectively to reveal biases, concentrations, and skewness of their distributions; to recognize factors with little or no effect; to test the ability of ranking and to pinpoint repetitions and unsatisfactory factor correlations. Desired factors for such an index should ensure intuitiveness of factors, consistency with expectations, and high degree of discriminatory power. Elaborative information can be found in Section 5.2.2.

The third and last step is the weight optimization which includes the determination of weights of the selected factors through several analysis. Weights are specified with a heuristic approach for which details are given in Section 5.2.3.

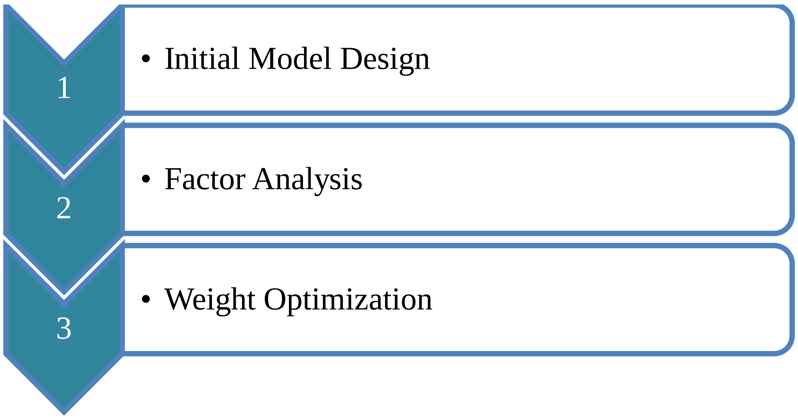


Figure 5.5. Steps for the construction of maturity index.

Figure 5.6. Factor analysis methodology.

5.2.1. Initial Model Design

The preliminary step for the construction of a maturity index is determination of boundaries, sections and factors. The objectives of initial design include the following:

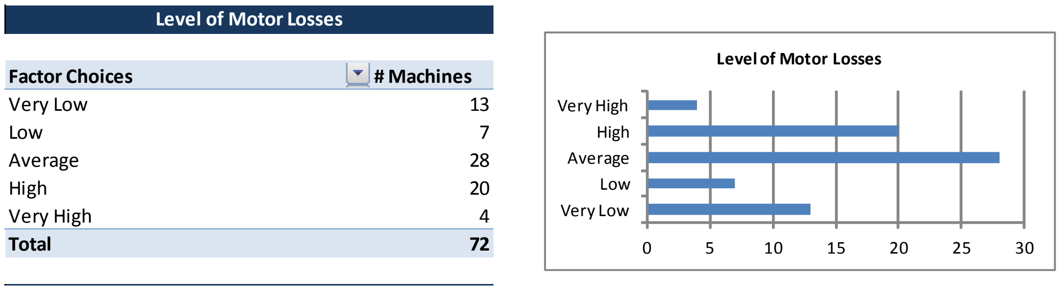
- Define the model boundaries

- Identify factors to be included in the model with brainstorming and literature review
- Classify factors with respect to equipments
- Design the initial model composed of proposed scorecards

5.2.2. Factor Analysis

The aim of Factor Analysis (FA) is to cut down the candidate list of factors generated in Initial Model Design stage to a shorter, more efficient list of factors. Each factor is examined independently with the methods outlined to understand its overall effect after data analysis process.

5.2.2.1. Step 1: Factor Distribution. The first step of FA is the evaluation of responses for every factor to identify biases or undesired skewness that may be related to the sample or appropriateness of the factors. Important differences between the observed and the expected or intuitive distribution infer that a modification in the factors or scoring is compulsory. A distribution concentrated mainly in the highest or lowest scores is a clear evidence of bias which may be the result of an inefficient wording for qualitative factors. In addition, position analysis should also be carried out to ensure data availability where high frequency of missing or zero values for answers are not desirable. Histograms are widely used to visualize frequencies of factor distribution and the results are compared to expert intuition for that specific question. An factor response distribution example is given in Figure 5.7 for level of motor losses from motor assessment.



Level of Motor Losses

Factor Choices	# Machines
Very Low	13
Low	7
Average	28
High	20
Very High	4
Total	**72**

Figure 5.7. An illustration of factor distribution.

5.2.2.2. Step 2: Information Entropy. Information entropy is used to measure the information inherent in a given variable, i.e., the diversity of responses for a subjective factor. This step aims to identify factors with little or no information contributed to the model due to highly concentrated responses within a limited number of answers.

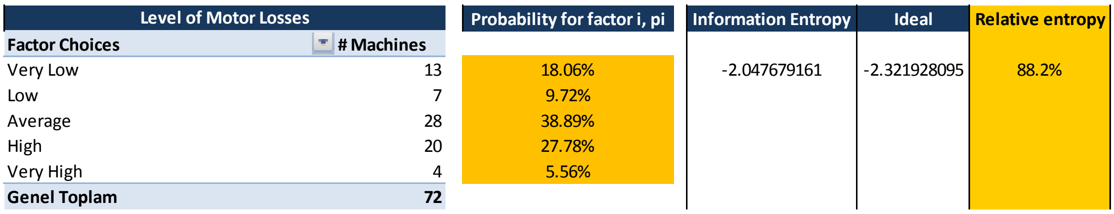
To summarize, in information theory, entropy is used as a measure of uncertainty associated with a random variable and can be defined as the minimum number of bits (i.e. switches that are either true or false) to quantify the expected value of the information contained within a question. For example, three bits are required for a question with 8 possible answers which are equally likely to occur. However, if the answers are not evenly distributed then same amount of information can be stored with fewer bits. Given a subjective question with n possible answers information entropy is defined as below (H) where probability is p_i for answer i [92]:

$$H= -\sum_{i=1}^{n}\left(p_i * \log_2 p_i\right) \tag{5.6}$$

When the probability for each answer is equally likely to occur, information entropy is at its maximum value, i.e., $p_i = 1/n$. The entropy in case of two possibilities is with probabilities p and $q=1-p$ [92]. Relative information entropy calculation is used in the analysis where observed information entropy is divided by maximum information entropy.

For strong information entropy, a threshold of 0.70 is used to determine factors containing above average or high information content and identify factors that are the most diverse across the range of possible responses and therefore support the model with additional information. On the other hand, for weak information entropy a threshold of 0.50 is used to determine factors containing low or nonexistent informational content and identify subjective questions that are the most concentrated across the range of possible responses, thus, contributing little to the model.

An illustration of relative information entropy calculation is given in Figure 5.8. An illustration of information entropy calculation. for level of motor losses. Information entropy is calculated with the formula 5.6 and relative entropy is achieved as a comparison of the current and the ideal entropy.



Level of Motor Losses		Probability for factor i, pi	Information Entropy	Ideal	Relative entropy
Factor Choices	# Machines				
Very Low	13	18.06%	-2.047679161	-2.321928095	88.2%
Low	7	9.72%			
Average	28	38.89%			
High	20	27.78%			
Very High	4	5.56%			
Genel Toplam	72				

Figure 5.8. An illustration of information entropy calculation.

5.2.2.3. Step 3: Rank Ordering. Large number of variables is used in the model to assess energy efficiency maturity from different perspectives such as motor, pump, compressor and fan. These variables lead to an over fitted model as the model is designed with the data collected from current environment. Thus, in order to avoid poor performance, rank order correlation of potential factors is measured using Kendall's Tau coefficient. Rather than absolute level of correlation, this statistic measures the degree of correspondence between two random variables, x_{ij} and y_j, and assess the significance of this correspondence where x_{ij} stands for the ith factor score for jth machine whereas y_j is the overall score for the same machine . In other words, Kendall's Tau measures the strength of association in the distribution of factor score and the expert judgment for each machine.

Let $(x_1, x_2, \ldots, x_n)$ and $(y_1, y_2, \ldots, y_n)$ be two sets of observations of the joint random variables X and Y respectively such that all the values of (x_i) and $(y_{i'})$ are unique. Any pair of observations (x_i, y_i) and $(x_{i'}, y_{i'})$ are said to be concordant if the ranks for both elements agree that if both $x_i > x_{i'}$ and $y_i > y_{i'}$ or if both $x_i < x_{i'}$ and $y_i < y_{i'}$. On the other hand, they are said to be discordant, if $x_i > x_{i'}$ and $y_i < y_{i'}$ or if $x_i < x_{i'}$ and $y_i > y_{i'}$. If $x_i = x_{i'}$ or $y_i = y_{i'}$, the pair is neither concordant nor discordant. Kendall's tau coefficient can be calculated as follows [93]:

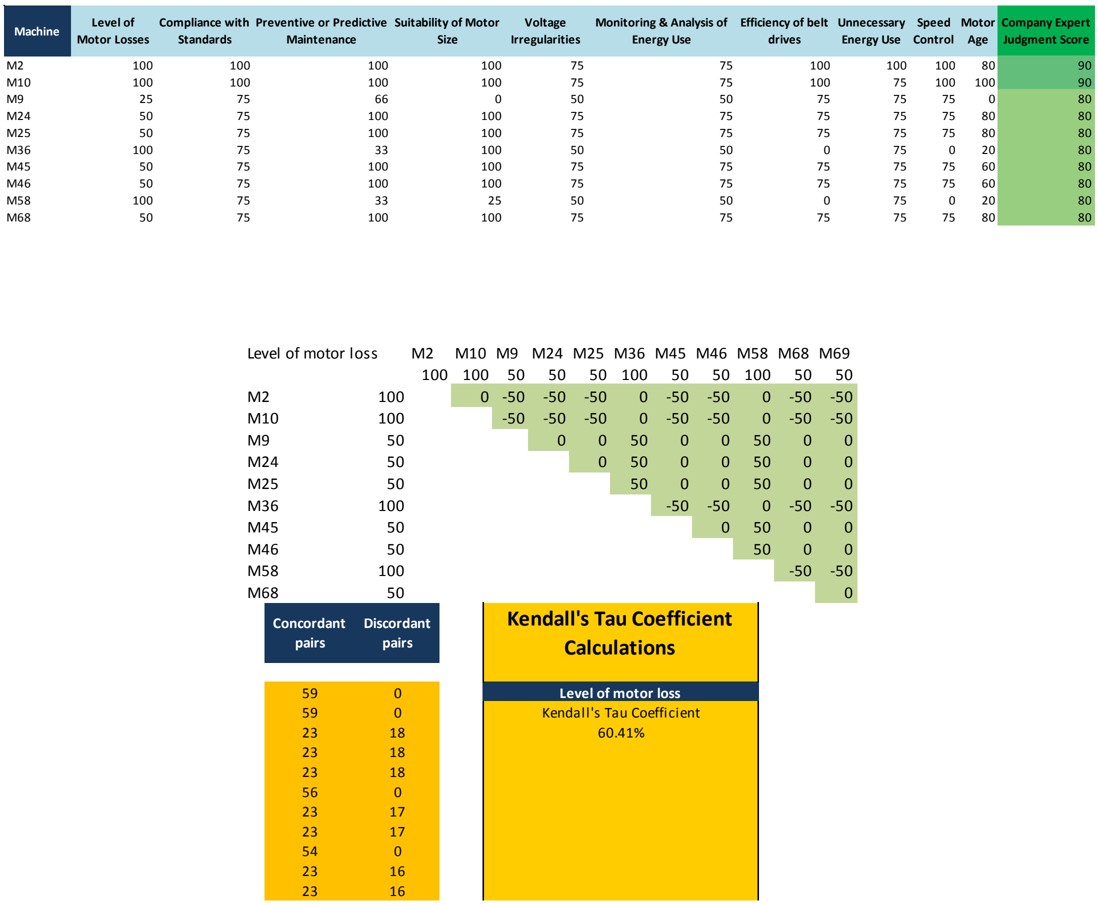
$$\tau = \frac{\textit{(number of concordant pairs)- (number of discordant pairs)}}{\frac{1}{2}n\ (n\text{-}1)} \tag{5.7}$$

The properties of Kendall's Tau coefficient (τ) are:

- The coefficient is 1 when the agreement between two rankings is perfect
- The coefficient is -1 when the disagreement between two rankings is perfect
- The coefficient lies between -1 and 1 for other arrangements

- The coefficient takes the value 0, if the rankings are completely independent

Thresholds are defined as 0.30 and 0.10 for strong and weak rank ordering powers. Tau coefficient greater than 0.30 means that the factors contribute more to the overall while coefficients lower than 0.10 fail at rank ordering contributing the least to the overall assessment. Kendall's tau coefficient for level of motor losses is calculated as in the excel sheet in Figure 5.9. Here, factor scores for related machine is compared with company expert judgment and concordant and discordant pairs are used to obtain Kendall's tau coefficient.



Machine	Level of Motor Losses	Compliance with Standards	Preventive or Predictive Maintenance	Suitability of Motor Size	Voltage Irregularities	Monitoring & Analysis of Energy Use	Efficiency of belt drives	Unnecessary Energy Use	Speed Control	Motor Age	Company Expert Judgment Score
M2	100	100	100	100	75	75	100	100	100	80	90
M10	100	100	100	100	75	75	100	75	100	100	90
M9	25	75	66	0	50	50	75	75	75	0	80
M24	50	75	100	100	75	75	75	75	75	80	80
M25	50	75	100	100	75	75	75	75	75	80	80
M36	100	75	33	100	50	50	0	75	0	20	80
M45	50	75	100	100	75	75	75	75	75	60	80
M46	50	75	100	100	75	75	75	75	75	60	80
M58	100	75	33	25	50	50	0	75	0	20	80
M68	50	75	100	100	75	75	75	75	75	80	80

Level of motor loss		M2	M10	M9	M24	M25	M36	M45	M46	M58	M68	M69
		100	100	50	50	50	100	50	50	100	50	50
M2	100		0	-50	-50	-50	0	-50	-50	0	-50	-50
M10	100			-50	-50	-50	0	-50	-50	0	-50	-50
M9	50				0	0	50	0	0	50	0	0
M24	50					0	50	0	0	50	0	0
M25	50						50	0	0	50	0	0
M36	100							-50	-50	0	-50	-50
M45	50								0	50	0	0
M46	50									50	0	0
M58	100										-50	-50
M68	50											0

Concordant pairs	Discordant pairs
59	0
59	0
23	18
23	18
23	18
56	0
23	17
23	17
54	0
23	16
23	16

Kendall's Tau Coefficient Calculations

Level of motor loss

Kendall's Tau Coefficient

60.41%

Figure 5.9. An illustration of rank ordering correlation calculation.

<u>5.2.2.4. Step 4: Factor Correlation.</u> As well as the rank ordering correlation, correlation between model factors should also be analyzed to prevent the use of highly correlated factors which capture similar information. If both correlated factors are included, a complex model with one over-weighted dimension is inevitable. Pearson's correlation is

used to see the measure of linear relationship. An example factor correlation matrix is provided in Table 5.1.

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2 \sum_{i=1}^{n}(y_i - \bar{y})^2}} \tag{5.8}$$

Table 5.1. An illustration of factor correlation matrix.

Factor Correlations	Level of Motor Losses	Compliance with Standards	Preventive or Predictive Maintenance	Suitability of Motor Size	Voltage Irregularities	Monitoring & Analysis of Energy Use	Efficiency of belt drives	Unnecessary Energy Use	Speed Control	Motor Age
Level of Motor Losses	100.0%	54.0%	-9.0%	53.5%	50.1%	-23.2%	-9.6%	54.1%	21.4%	51.0%
Compliance with Standards	54.0%	100.0%	17.5%	52.6%	25.0%	15.2%	23.7%	65.0%	42.0%	53.7%
Preventive or Predictive Maintenance	-9.0%	17.5%	100.0%	14.4%	9.1%	55.6%	68.5%	42.1%	41.5%	27.9%
Suitability of Motor Size	53.5%	52.6%	14.4%	100.0%	52.5%	-19.2%	28.6%	58.0%	58.8%	63.6%
Voltage Irregularities	50.1%	25.0%	9.1%	52.5%	100.0%	-10.2%	7.6%	30.1%	43.0%	59.7%
Monitoring & Analysis of Energy Use	-23.2%	15.2%	55.6%	-19.2%	-10.2%	100.0%	31.9%	5.9%	-10.6%	3.9%
Efficiency of belt drives	-9.6%	23.7%	68.5%	28.6%	7.6%	31.9%	100.0%	34.4%	60.9%	36.1%
Unnecessary Energy Use	54.1%	65.0%	42.1%	58.0%	30.1%	5.9%	34.4%	100.0%	55.5%	55.7%
Speed Control	21.4%	42.0%	41.5%	58.8%	43.0%	-10.6%	60.9%	55.5%	100.0%	60.6%
Motor Age	51.0%	53.7%	27.9%	63.6%	59.7%	3.9%	36.1%	55.7%	60.6%	100.0%

5.2.3. Weight Optimization

Weight optimization is performed with heuristic method which is an experience-based technique for problem solving and does not guarantee to find the optimal solution but a good enough solution is found for a given set of goals. The reason lying behind the use of heuristic method is to speed up the weight optimization process rather than spending time with the burdensome algorithms. What’s more, in order to prevent some critical factors to stay out of the scorecard with zero weights, this approach took advantage of expert judgment.

An initial weight combination is provided for maturity index before the search begins. The combinations are evaluated in terms of their objective functions which are defined to be Kendall’s tau in this problem with a constraint to have a total weight of 100 and the poor combinations are eliminated. The Kendall's tau distance utilizes pairs of elements from the union of two lists to find a super-list which would be as close as possible to all individual ordered function [94].

Mathematical formulation for weight optimization is as follows:

$$max \quad \text{Kendall's Tau coefficient } (\tau) \qquad \forall\, k,j \tag{5.9}$$

subject to

$$\sum_i w_{kij} = 1 \qquad \forall\ k,j \qquad (5.10)$$

$$w_{ki^*j} = 0 \qquad \forall\ k,j,\ i^* \qquad (5.11)$$

where k denotes the index for scorecard, i is the index for factors, $i*$ is the index for eliminated factors in factor analysis stage, and j stands for the index for equipment. w_{kij} is the relative importance weight for scorecard k, factor i, equipment j.

Taking into account one of the maturity indexes, motor assessment, all FA and weight optimization steps can be visualized.

In the first step of FA, histograms show that there is no skewness or bias in any factor. Information entropy step also indicates that relative entropy is much higher than the cut-off point for all factors. Rank ordering step reveals that one factor, monitoring & analysis of energy use, can be eliminated from the assessment since it has a Kendall’s tau coefficient below 10%. Factor correlation step also reinforces the previous factor elimination decision with presenting a negative correlation of the same factor with other factors. After all steps of FA are accomplished, it is obvious that all remaining factors will result in a stronger assessment of motors. As FA is complete, the paired list of factors undergoes an optimization process to move from an array of possible weight combinations to an optimized model with the highest explanatory power. Initial weight combination gave a Kendall’s tau coefficient of 24% whereas the final coefficient is 35% at the end of several runs which can be seen in Figure 5.10.

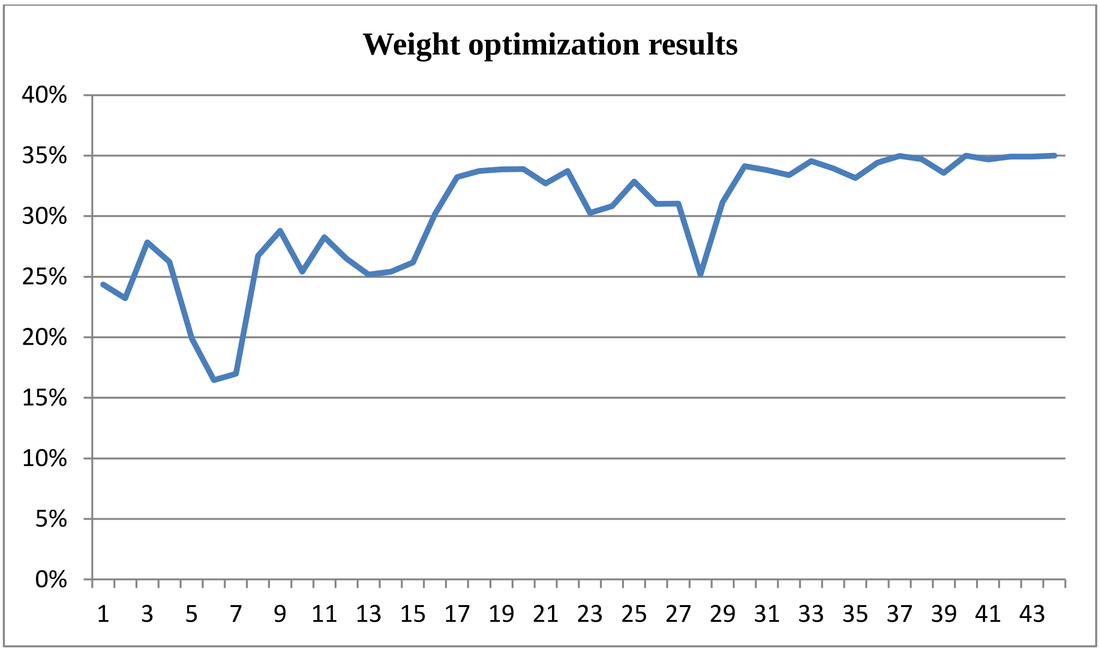


Figure 5.10. Weight optimization results for motor assessment.

5.3. Assessment-Integrated Energy Value Stream Map

At the end of initial model design, FA and weight optimization steps, final assessment factors for motors, pumps, compressors and fans are designated in Table 5.2-Table 5.5.

Table 5.2. Motor assessment weights.

Motor Assessment	
1.Level of Motor Losses	4%
2.Compliance with Standards	5%
3.Preventive or Predictive Maintenance	7%
4.Suitability of Motor Size	20%
5.Voltage Irregularities	24%
6.Monitoring & Analysis of Energy Use	0%
7.Efficiency of belt drives	5%
8.Unnecessary Energy Use	20%
9.Speed Control	10%
10.Motor Age	5%
Average Relative Entropy	*91%*
Average Kendall's Tau	*55%*

Table 5.3. Pump assessment weights.

Pump Assessment	
1.Analysis of system requirements	13%
2.Selection of the right pump	7%
3.Speed variation	8%
4.Multiple pumps for varying demands	8%
5.By-pass control	0%
6.Start/stop control of pump	24%
7.Impeller trimming need	40%
Average Relative Entropy	*83%*
Average Kendall's Tau	*55%*

Table 5.4. Compressor assessment weights.

Compressor Assessment	
1.Analysis of compressed air needs	8%
2.Appropriate use of compressed air	28%
3.Compressed air system leaks	11%
4.Controlled system pressure	17%
5.Compressed air system control	0%
6.Compressed air storage usability	25%
7.Maintenance	11%
Average Relative Entropy	*88%*
Average Kendall's Tau	*69%*

As a consequence, the assessment factors with the above-mentioned weights bring about the energy efficiency maturity scores provided in Table 5.6.

Having obtained the assessment results, current state map is enriched with the above results embedded to it as shown in Figure 5.11. After improvements are completed, future state map will show the magnitude of change considering electrical energy consumption and differences in respective and overall scores.

Table 5.5. Fan assessment weights.

Fan Assessment	
1.Selection of the right fan	5%
2.Operation schedule	5%
3.Demand control	30%
4.Right motor-fan combination	7%
5.Efficiency of transmission devices	15%
6.Closeness of operation to BEP	32%
7.Maintenance	6%
Average Relative Entropy	*83%*
Average Kendall's Tau	*48%*

Table 5.6. Weighted average scores.

Module	**Weighted Average Score**
Motor	47.67
Pump	50.15
Compressor	70.01
Fan	48.83
Overall Score	*53.51*

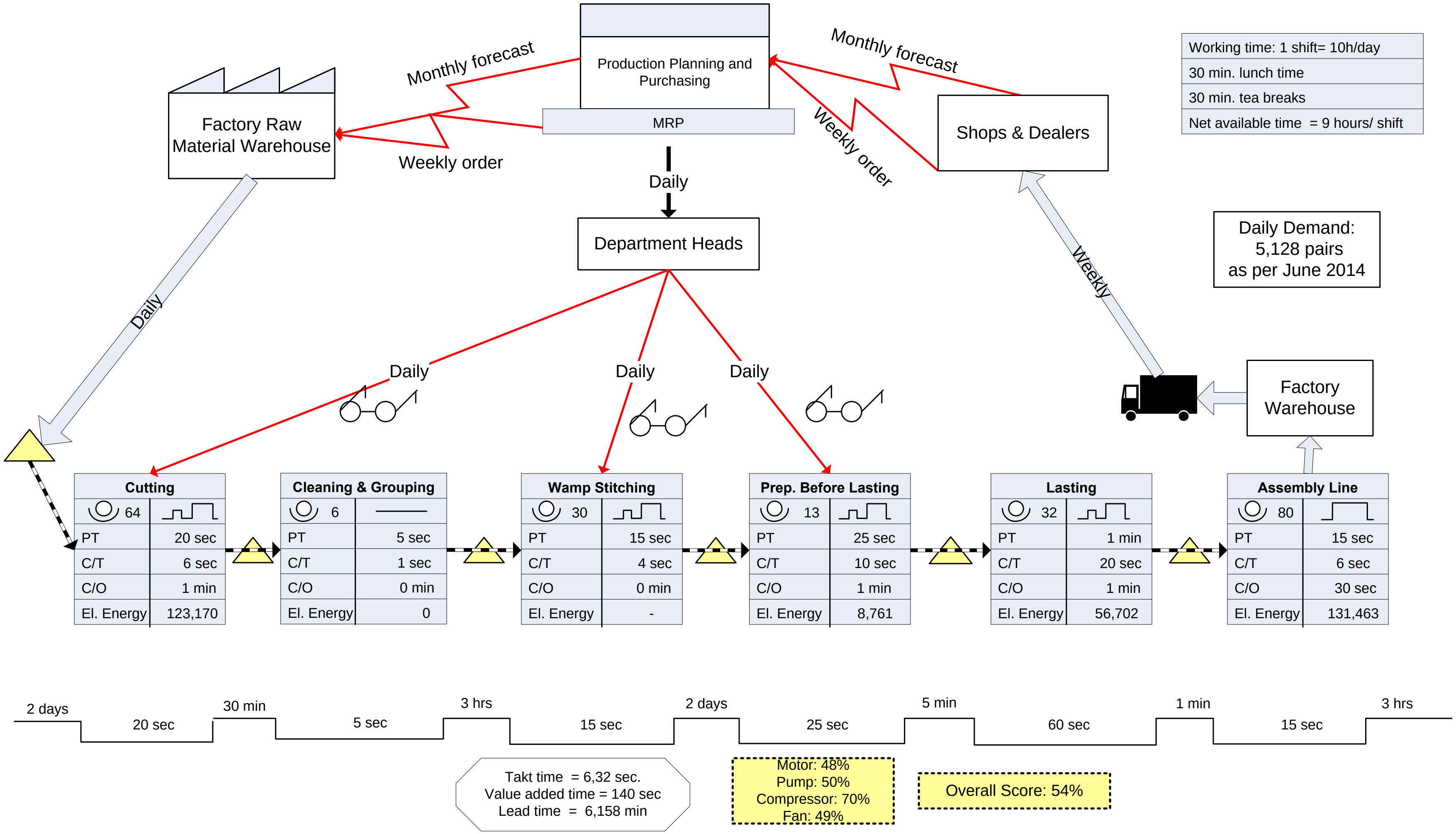


Figure 5.11. Assessment integrated current state energy value stream map.

6. ENERGY VALUE STREAM DESIGN

After completing the energy value stream analysis in Chapter 5, we focus on the improvement opportunities for energy efficiency in this chapter. The ultimate goal is to create a superior future state map from the current situation in the energy value stream analysis. The eight design guidelines proposed by Erlach are employed as a systematic procedure to create a future state map. After summarizing these guidelines, improvement opportunities are evaluated using economic analysis and optimization tools. Consequently, the future state map is constructed [45,95].

Guideline 1: Manufacturing at an optimum operating point: The resources should be set up so that the production can be met with minimal energy intensity and also in accordance with takt time. In this respect, production facilities should be adjusted to increase performance level as well as keeping track of operation in optimum performance. Oversizing and overprocessing should thus be eliminated. The main idea of this guideline is depicted in Figure 6.1 [95].

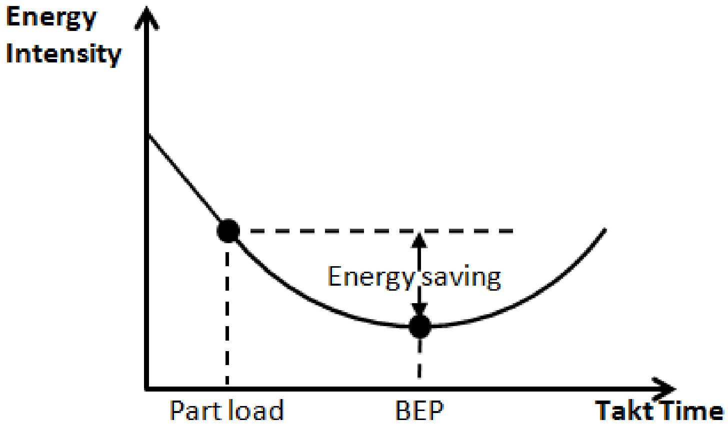


Figure 6.1. Manufacturing at an optimum operating point.

Guideline 2: Reducing energy demand of resources by technical improvements: The energy demand of resources in normal operation can be reduced by technical improvements as visualized in Figure 6.2. Utilization of machinery and equipments according to the current technology and exchange of technical components is useful for the accomplishment of this task. Employee training for the economical use of energy is also another way to reduce energy demand [95].

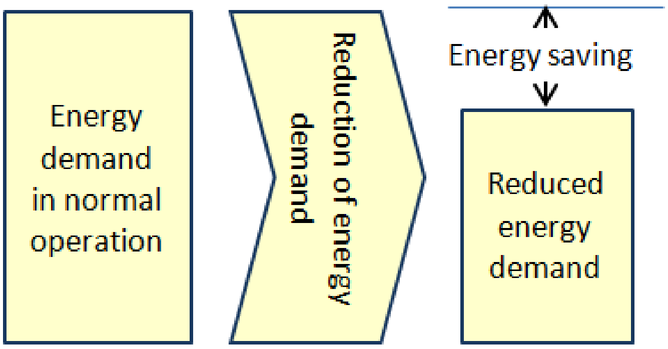


Figure 6.2. Reducing energy demand of resources by technical improvements.

Guideline 3: Minimizing energy consumption of resources during stand-by: Energy consumption of the resources in stand-by operation should be minimized as in Figure 6.3. Some options for this guideline are to stop machinery when they do not operate, to use energy saving devices for automatic shutdown, to reduce energy consumption in stand-by operation, to design production processes for frequent and short stand-by times and to train workers about when to shutdown the machinery [95].

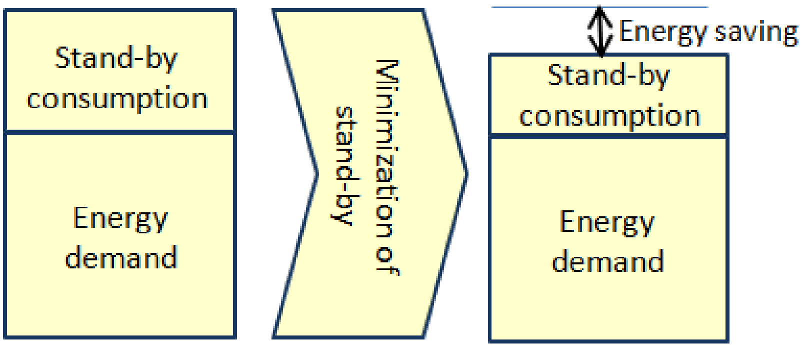


Figure 6.3. Minimizing energy consumption of resources during stand-by.

Guideline 4: Minimizing energy consumption during turn-on and turn-off: Energy consumption of the equipment due to turn on and off should be minimized by avoidance of peak demands. Figure 6.4 illustrates this guideline. Automatic start-up technologies, smoothing energy consumption during the entire process and eliminating peak demands are the major ways to successfully implement this guideline [95].

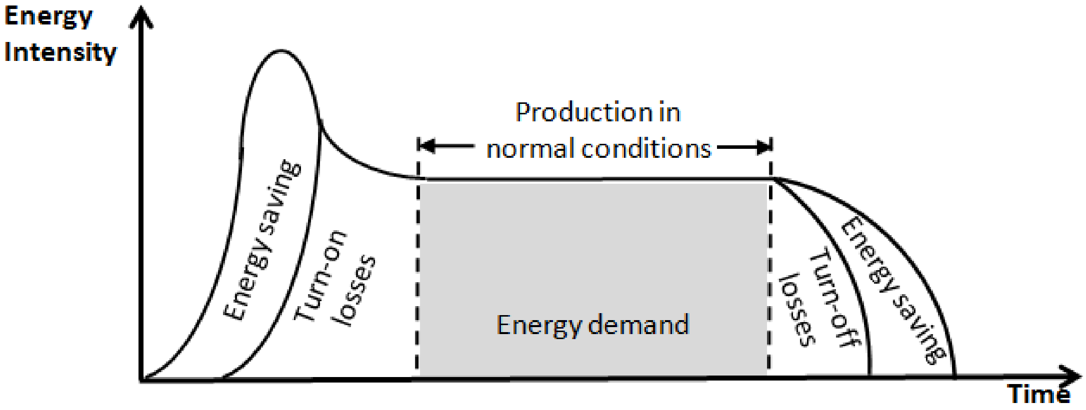


Figure 6.4. Minimizing energy consumption during turn-on and turn-off.

Guideline 5: Energy recovery: The energy used has the ability to be used several times which can be in the same process, in another process or for external reasons directly or indirectly. Utilization of waste heat and heat recovery, use of heat store and use of heat pumps to achieve high temperatures from the low temperatures of the waste heat are the most common measures. The energy recovery process is summarized in Figure 6.5 [95].

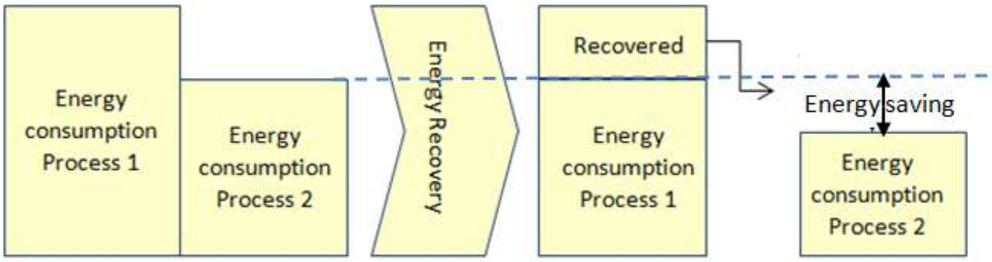


Figure 6.5. Energy recovery.

Guideline 6: Reaching a smoother energy consumption with peak demand shaving: The energy consumption of the factory should be balanced by peak demand shaving as seen in Figure 6.6. Central load management automatically or manually, determination of a priority-list for the shut-down of machinery, planned start times for machines are the methods to employ this guideline [95].

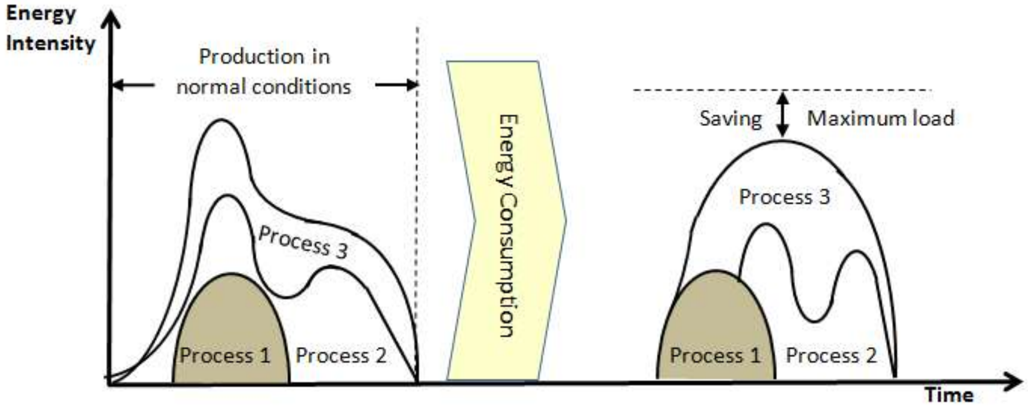


Figure 6.6. Reaching a smoother energy consumption with peak demand shaving.

Guideline 7: Changing the processing sequence of the largest energy consumer: Energy consumption can be minimized by a change in the process sequence as shown in Figure 6.7. Smoothing minimizes the number of changes in energy consumption levels where 7 level changes are reduced to 3 level changes. Largest energy consumers, namely energy guzzlers should be analyzed with their energy consumption and weekly and monthly planning should be done to reduce energy consumption [95].

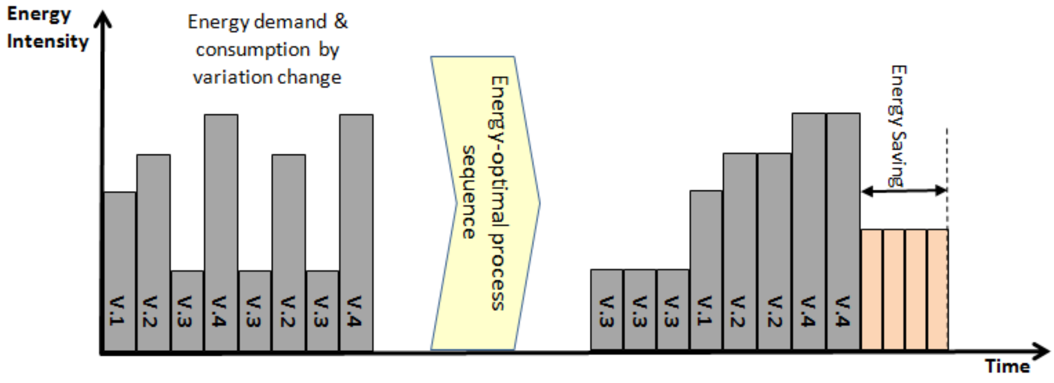


Figure 6.7. Changing the processing sequence of the largest energy consumer.

Guideline 8: Synchronizing the energy supply and consumption: The energy is provided taking into account the respective energy consumption of all processes without distribution losses. Consideration of cross-sectional technologies, breakdown of the total network, decentralized energy production may be the ways to save energy. [95].

6.1. Improvement Opportunities

Just after all the improvement areas are defined in Chapter 5, the factory is re-analyzed and several tables for each department are constructed containing specific improvement opportunities for the factory (See Table 6.1). 270 improvement opportunities are evaluated and provided in an excel sheet which is enclosed electronically to this study. Departments related to the improvement opportunity, equipment, eliminated waste category, match with the design guidelines and estimated improvement in percentage are displayed in this excel sheet. In order to develop a quantitative methodology, electricity use, monthly and annual saving and investment cost are also added with other information.

In this chapter, after Section 6.2 where an economic analysis is carried out, net present value (NPV) of savings, payback period, internal rate of return (IRR), profitability index (PI) are found using the NPV tool which is built as a part of this thesis. Furthermore, in Section 6.3, economic results obtained by Monte Carlo simulation are optimized and the final results are visualized as a future state energy value stream map.

Table 6.1. Identification of specific improvement opportunities.

Department	Machine Code	Machine	Equipment Type	Improvement Opportunity	Targeted Guideline	Eliminated Waste Category	Estimated Improvement (%)
Cutting works	M1	Oil dynamic clicking press	Motor	Regulation of voltage	Manufacturing at an optim	Overprocessing	1- 63%
Cutting works	M2	Laser beam press	Motor	Monitoring & Analysis of Energy Us	Manufacturing at an optim	Overprocessing	1- 63%
Cutting works	M1	Oil dynamic clicking press	Motor	Preventive or Predictive Maintena	Reducing energy demand o	Defect	2-30%
Cutting works	M2	Laser beam press	Motor	Preventive or Predictive Maintena	Reducing energy demand o	Defect	2-30%
Cutting works	M1	Oil dynamic clicking press	Motor	Suitability of motor size	Manufacturing at an optim	Overprocessing	Up to 33%
Cutting works	M2	Laser beam press	Motor	Suitability of motor size	Manufacturing at an optim	Overprocessing	Up to 33%
Cutting works	M8	Compressor	Compressor	Reducing inlet air temperature	Reducing energy demand o	Overprocessing	1-7%
Cutting works	M7	Reinforcement with backer	Motor	Replacement of machine	Reducing energy demand o	Overprocessing	Up to 80%
Cutting works	M7	Reinforcement with backer	Motor	Temperature-Cooling fan inside	Reducing energy demand o	Overprocessing	Up to 20%
Cutting works	M6	Regulator	Motor	Monitoring & Analysis of Efficient R	Manufacturing at an optim	Overprocessing	Up to 10%
Cutting works	M6	Regulator	Motor	Reduced Voltage Irregularity	Manufacturing at an optim	Overprocessing	Up to 10%
Cutting works	M9	Oil Dynamic cutting press with m	Pump	Maintenance	Reducing energy demand o	Defect	2-7%
Cutting works	M9	Oil Dynamic cutting press with m	Motor	Replacement of trolley motor	Reducing energy demand o	Overprocessing	19-20%
Cutting works	M9	Oil Dynamic cutting press with m	Pump	Multiple pumps for varying loads	Reaching a smoother energ	Overprocessing	10-30%
Cutting works	M9	Oil Dynamic cutting press with m	Pump	Replacement of throtting valves wi	Reducing energy demand o	Overprocessing	10-60%
Cutting works	M10	Laser beam cutting press	Motor	Speed Control	Reaching a smoother energ	Overprocessing	1-63%
Cutting works	M10	Laser beam cutting press	Motor	Preventive or Predictive Maintena	Reducing energy demand o	Defect	2-30%
Cutting works	M11	Extractor fan	Fan	Operation schedule	Minimizing energy consum	Waiting	10-50%
Cutting works	M11	Extractor fan	Fan	Demand control	Minimizing energy consum	Overproduction	5-50%

6.2. Monte Carlo Simulation and Forecasting Based Economic Analysis

In the literature, general approach for value stream design is to select pre-determined improvement opportunities to implement. However, there is no analytical background in this procedure and thus a sophisticated and pioneering methodology incorporating an economic point of view is created. The output of this section is economic appraisal of improvement opportunities with major concepts to compare several alternatives in decision making such as profitability index, internal rate of return and payback period. Moreover, an NPV tool with Monte Carlo simulation may not only be used for large data sets but also for the assessment of individual investment decision.

There are two factors that have an impact on the decision whether to retrofit or apply a change in the current system: discounting future value and rising fuel costs. Net Present Value calculation is used to discount future value of money relative to a discount rate r, over t years. The general equation can be written as:

$$NPV = A * \left[\frac{1-\frac{1}{(1+r)^t}}{r}\right] \tag{6.1}$$

where A stands for the cash flow in t years from now.

However, rising electricity costs makes it necessary to transform uniform cash flow formula to geometric cash flow formula. Here, an investment in the beginning of a time horizon will result in higher savings in the future years because of a possible increase in energy prices. This situation is represented in Figure 6.8. Thus, by including a factor g to represent the growth factor, NPV is calculated by:

$$NPV = \frac{A}{r-g} * \left[1 - \left(\frac{1+g}{1+r}\right)^t\right] \tag{6.2}$$

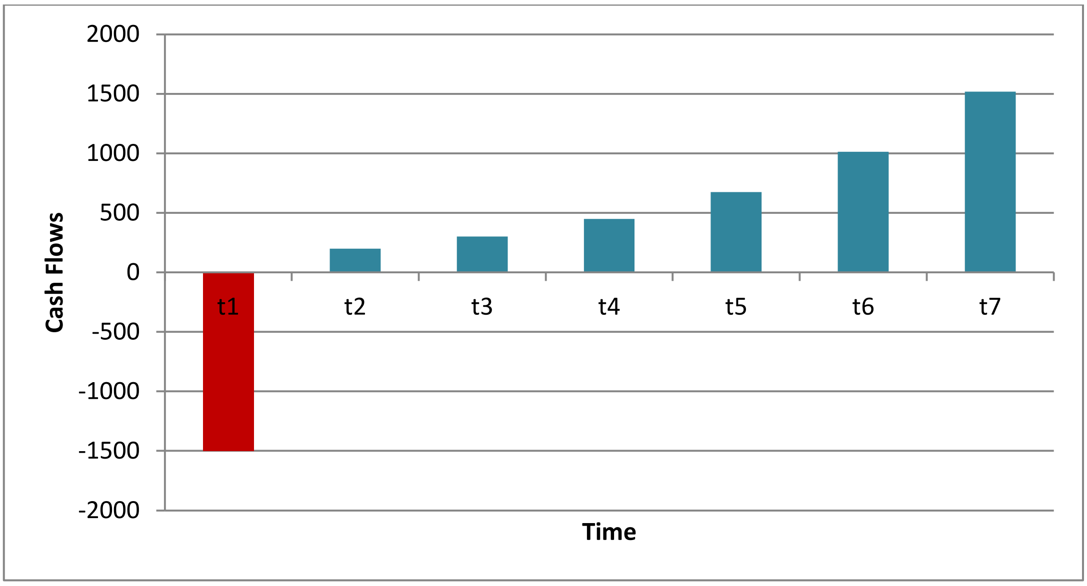


Figure 6.8. Cash flow for energy efficiency investment.

An excel tool has been developed to calculate NPV of all improvement opportunities where initial investment and annual energy cost saving of the first year are entered and Monte Carlo simulation is applied with 1000 replications to estimate the net present value of each improvement opportunity. The discount rate is assumed to be 8.25% on average for the next 10 years. However, there is one more uncertainty in NPV tool which is the increase in electricity prices. To overcome this issue, the underlying mechanism of electricity prices are aimed to be found and the prices for the next 10 years are forecasted. The mean and standard deviation of electricity price increase are calculated using ARIMA (Autoregressive Integrated Moving Average) model. As the steps of a classical time series analysis are taken into account, the data is plotted firstly and the variability, trends and seasonality are described. Secondly, the series are controlled and transformations are performed if a transformation is necessary. Then, the stationarity of the data is achieved if it is not stationary. Lastly, a good model fit is found and the future is forecasted. All these steps are summarized in the following paragraphs.

Historical TEDAS electricity price data from 1995 to 2014 are used to fit an ARIMA model as the basis for the analysis which is also sketched in Figure 6.9. Years are enumerated starting from 1 through 20 in order to make possible a better understanding and it is seen that the consumer electricity price has an increasing trend. Although some references state that at least 30 observations are necessary to apply ARIMA modeling, it was proven that length of series such as long term, medium term and short term are not statistically different. Thus, there is no reason to reject a series because it fails to have more than 30 observations [96].

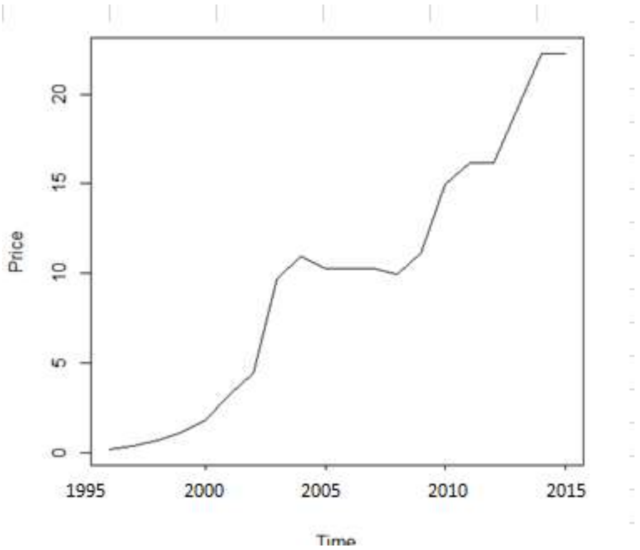


Figure 6.9. Consumer electricity price between 1995 and 2014.

For the determination of model parameters (p, d, q), autocorrelation function (ACF) and partial autocorrelation function (PACF) are examined with the historical data. Since the data is not stationary, differencing can help stabilize the mean by removing changes in the level of a time series. In order to eliminate trend and seasonality, the data is differenced [97]. After the first difference, a stationary situation is obtained in Figure 6.10.

ACF and PACF plots of the stationary time series in Figure 6.11 will be helpful in determining the model parameters *(p, d, q*). The ACF has 1 significant spike at lag 1 but none beyond that lag whereas the PACF tails off. Thus, the ARIMA model has the order of (0, 1, 1).

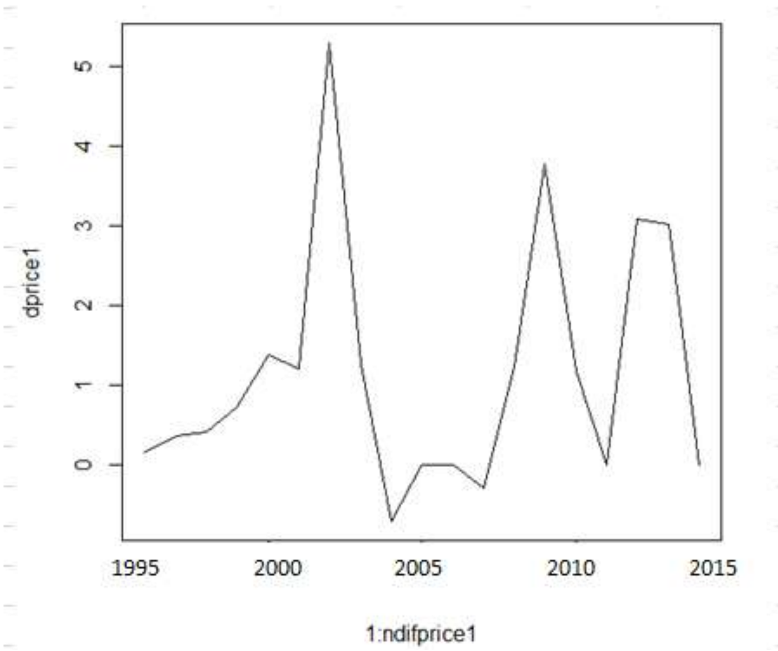


Figure 6.10. Stationarity of time series after first difference.

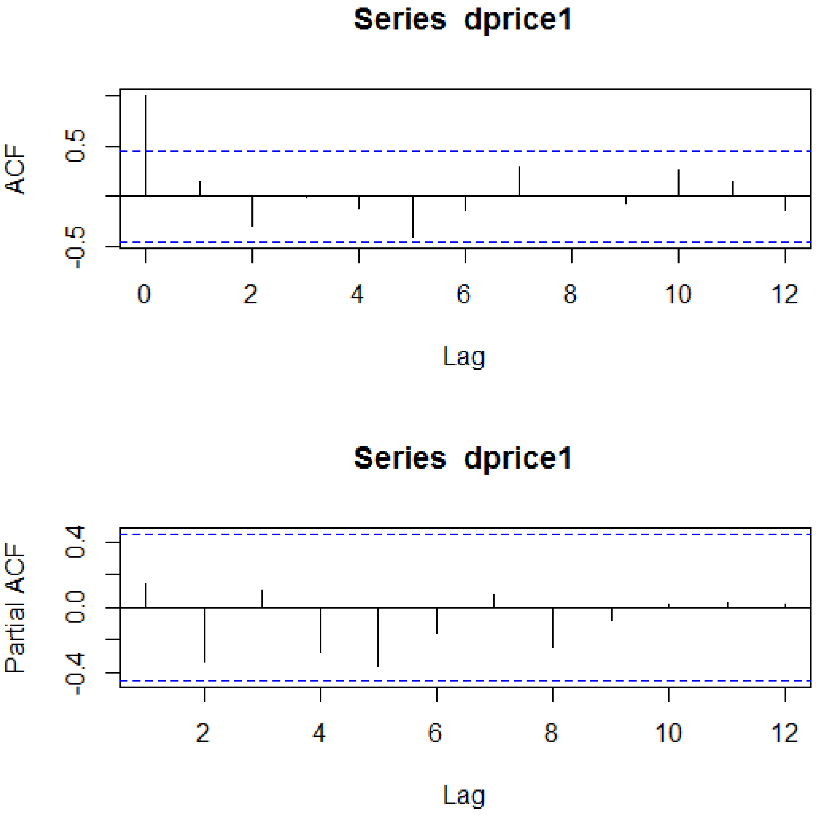


Figure 6.11. Autocorrelation and partial autocorrelation functions.

After fitting the model to the available time series data, future electricity prices are forecasted as in Figure 6.12. The confidence interval indicates that the uncertainty increases with respect to time horizon. Furthermore, it is unlikely that the electricity price will become negative despite the indication of the confidence interval. Very high price scenarios also exist although they have a low probability.

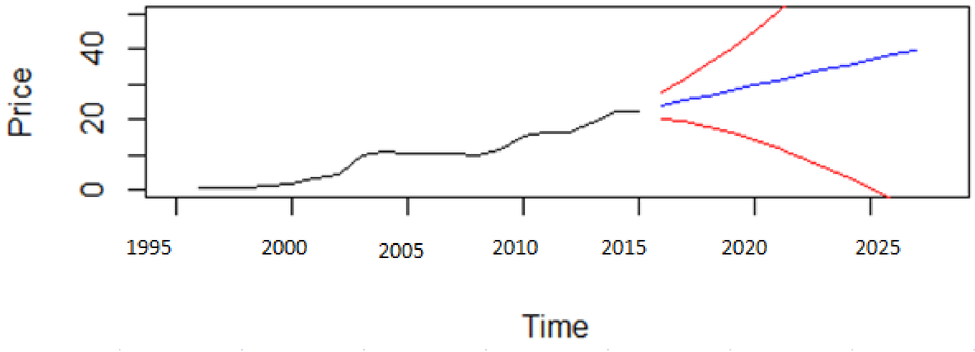
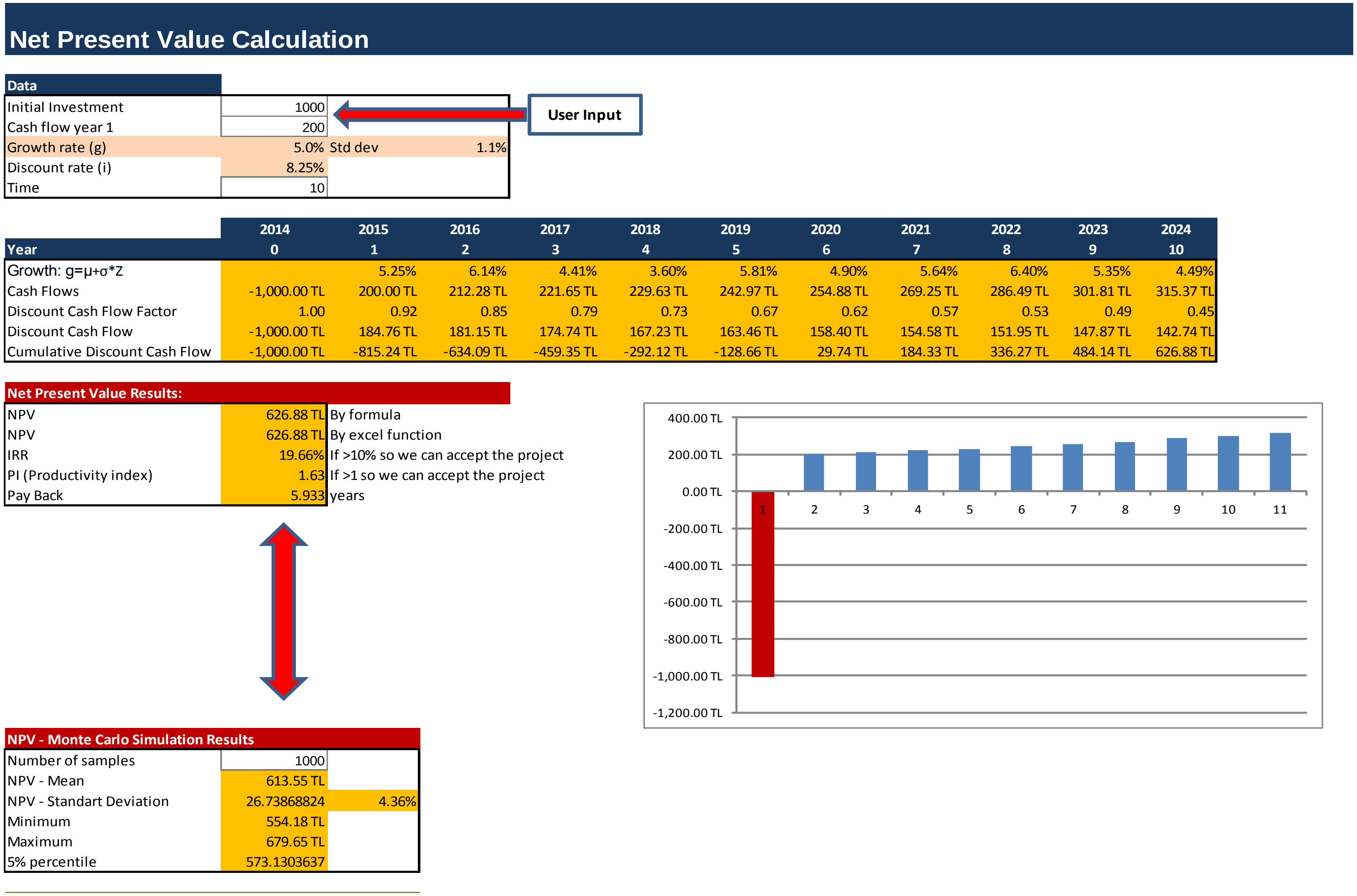


Figure 6.12. Electricity price forecast.

Having obtained the electricity price as the last input in the NPV tool, Monte Carlo simulation can be applied which is a computational algorithm that relies on repeated random sampling. For this reason, simulation runs are replicated to estimate the expected value of electricity price and its effect on the overall NPV with the following working pattern:

- Initial investment and estimated improvement opportunities are fed to the excel sheet.
- Increase in electricity prices have already been defined with a normal distribution with mean of 5 % and standard deviation of 1.1%. Discount rate is assumed to be 8.25%.
- An individual NPV value considering 10 years is calculated as well as internal rate of return, productivity index and payback period.
- The calculation is simulated for 1000 times.
- The result of the NPV calculation is added to the economic analysis excel sheet for each of the 270 improvement opportunities.

In our excel tool for simulation, random numbers are generated for the uncertain electricity price growth and cumulative discounted cash flow is achieved. Since NPV at the end of each run is totally different, 1000 runs are performed for each improvement opportunity to provide convergence to a certain value. This spreadsheet will not only serve for the optimization purposes but can also be used for industrial problems as a basic and powerful tool. Figure 6.13 is an illustration of Net Present Value and Payback Period Calculator where energy growth is used as an input.



Net Present Value Calculation

Data			
Initial Investment	1000		
Cash flow year 1	200		
Growth rate (g)	5.0%	Std dev	1.1%
Discount rate (i)	8.25%		
Time	10		

User Input

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024
Year	0	1	2	3	4	5	6	7	8	9	10
Growth: g=μ+σ*Z		5.25%	6.14%	4.41%	3.60%	5.81%	4.90%	5.64%	6.40%	5.35%	4.49%
Cash Flows	-1,000.00 TL	200.00 TL	212.28 TL	221.65 TL	229.63 TL	242.97 TL	254.88 TL	269.25 TL	286.49 TL	301.81 TL	315.37 TL
Discount Cash Flow Factor	1.00	0.92	0.85	0.79	0.73	0.67	0.62	0.57	0.53	0.49	0.45
Discount Cash Flow	-1,000.00 TL	184.76 TL	181.15 TL	174.74 TL	167.23 TL	163.46 TL	158.40 TL	154.58 TL	151.95 TL	147.87 TL	142.74 TL
Cumulative Discount Cash Flow	-1,000.00 TL	-815.24 TL	-634.09 TL	-459.35 TL	-292.12 TL	-128.66 TL	29.74 TL	184.33 TL	336.27 TL	484.14 TL	626.88 TL

Net Present Value Results:		
NPV	626.88 TL	By formula
NPV	626.88 TL	By excel function
IRR	19.66%	If >10% so we can accept the project
PI (Productivity index)	1.63	If >1 so we can accept the project
Pay Back	5.933	years

NPV - Monte Carlo Simulation Results		
Number of samples	1000	
NPV - Mean	613.55 TL	
NPV - Standart Deviation	26.73868824	4.36%
Minimum	554.18 TL	
Maximum	679.65 TL	
5% percentile	573.1303637	

Figure 6.13. Excel tool for NPV calculation with Monte Carlo simulation.

6.3. Optimization

Considering the improvement opportunities mentioned in the previous section and the current state map of the shoe production presented in Chapter 5, a future state map which optimizes the energy consumption should be achieved. Since there are numerous options and limited investment budget to be allocated for energy saving, an optimization step is embedded into value stream mapping procedure as shown below.

Initially, the objective function was designated as the maximization of expected savings. Nevertheless, to keep accuracy of the quantitative lean energy efficiency methodology, maximization of rating change is also a major issue. Amount of investment and length of payback period were the other issues that could not be ignored. Thus, rather than writing an objective function with several goals, all objectives are combined within an extended objective function. In this objective, a measure to evaluate financial attractiveness of a project was used which is called as productivity index or profitability index. Profitability index is calculated as in (6.3) and adding PI to the initial objective function, the following mathematical model is improved.

$$PI = [NPV + Initial\ Investment]/Initial\ Investment \tag{6.3}$$

$$\max \quad \sum_f X_f \cdot PI_f \cdot R_f \tag{6.4}$$

subject to

$$\sum_f X_f \cdot K_f \leq B_T \tag{6.5}$$

$$\sum_f X_f \cdot PP_f \leq PP_{\max} \tag{6.6}$$

$$X_f = 0 \ or \ 1 \tag{6.7}$$

If PI is written explicitly,

$$PI_f = \frac{K_f + S_f}{K_f} \tag{6.8}$$

where f is the index for improvements. X_f denotes variables for improvement f and K_f means the investment for improvement f. S_f, PI_f: and R_f stand for NPV of future cash flow from savings, profitability index and rating increase respectively. Lastly, B_T is used asa budget constraint for the whole improvement opportunities and PP_{max} is the pre-defined maximum payback period.

The first constraint is that the company is supposed to invest in an energy management project the values such as 1,000, 5,000, 10,000, 20,000, 50,000, 100,000, 200,000 and 500,000 Turkish Liras.

The second constraint is added to the model in order to have a less-than-2-year payback period since the manager in the company looks for short payback periods. Since the decision is to invest or not to invest the decision variable is a 0-1 integer variable.

The improvement opportunities are given in Table 6.2 and Table 6.3 as an example for cutting workshop. As well as improvement opportunities, average improvement, monthly and annual savings, investment costs, net present value of savings, payback period and profitability index also take place in these tables.

Table 6.2. Economic analysis for improvement opportunities.

Machine Code	Machine	Equipment Type	Improvement Opportunity	Targeted Guideline	Eliminated Waste Category	Estimated Improvement (%)
M1	Oil dynamic clicking press	Motor	Regulation of voltage	Manufacturing at an optimu	Overprocessing	1- 63%
M2	Laser beam press	Motor	Monitoring & Analysis of Energy Us	Manufacturing at an optimu	Overprocessing	1- 63%
M1	Oil dynamic clicking press	Motor	Preventive or Predictive Maintena	Reducing energy demand o	Defect	2-30%
M2	Laser beam press	Motor	Preventive or Predictive Maintena	Reducing energy demand o	Defect	2-30%
M1	Oil dynamic clicking press	Motor	Suitability of motor size	Manufacturing at an optimu	Overprocessing	Up to 33%
M2	Laser beam press	Motor	Suitability of motor size	Manufacturing at an optimu	Overprocessing	Up to 33%
M8	Compressor	Compressor	Reducing inlet air temperature	Reducing energy demand o	Overprocessing	1-7%
M7	Reinforcement with backer	Motor	Replacement of machine	Reducing energy demand o	Overprocessing	Up to 80%
M7	Reinforcement with backer	Motor	Temperature-Cooling fan inside	Reducing energy demand o	Overprocessing	Up to 20%
M6	Regulator	Motor	Monitoring & Analysis of Efficient R	Manufacturing at an optimu	Overprocessing	Up to 10%
M6	Regulator	Motor	Reduced Voltage Irregularity	Manufacturing at an optimu	Overprocessing	Up to 10%
M9	Oil Dynamic cutting press with m	Pump	Maintenance	Reducing energy demand o	Defect	2-7%
M9	Oil Dynamic cutting press with m	Motor	Replacement of trolley motor	Reducing energy demand o	Overprocessing	19-20%
M9	Oil Dynamic cutting press with m	Pump	Multiple pumps for varying loads	Reaching a smoother energ	Overprocessing	10-30%
M9	Oil Dynamic cutting press with m	Pump	Replacement of throtting valves wi	Reducing energy demand o	Overprocessing	10-60%
M10	Laser beam cutting press	Motor	Speed Control	Reaching a smoother energ	Overprocessing	1-63%
M10	Laser beam cutting press	Motor	Preventive or Predictive Maintena	Reducing energy demand o	Defect	2-30%
M11	Extractor fan	Fan	Operation schedule	Minimizing energy consum	Waiting	10-50%
M11	Extractor fan	Fan	Demand control	Minimizing energy consum	Overproduction	5-50%

Table 6.3. Economic analysis for improvement opportunities (cont.).

Machine Code	Monthly Saving (W)	Annual Saving (W/years)	Electricity Price (2014 Base Price) TL/W	Annual Saving (TL/years)	Quantity (units)	Unit Investment Cost ($)	Investment Cost ($)	Investment Cost (TL)	NPV (TL)	Payback Period (years)	IRR	PI	Current Rating
M1	4,200	50,400	0.222424	11,210	35	1,185	41,475	90,830	-431	9.8	0.08	1.0	69.8
M2	2,880	34,560	0.222424	7,687	3	2,142	6,426	14,073	47,830	2.0	0.59	4.4	99.0
M1	2,100	25,200	0.222424	5,605	35	100	3,500	7,665	37,505	1.5	0.77	5.9	69.8
M2	1,440	17,280	0.222424	3,843	3	100	300	657	30,389	0.0	5.90	47.3	99.0
M1	4,331	51,975	0.222424	11,560	35	1,500	52,500	114,975	-21,517	12.2	0.04	0.8	69.8
M2	2,970	35,640	0.222424	7,927	3	5,000	15,000	32,850	31,312	4.8	0.25	2.0	99.0
M8	160	1,920	0.222424	427	1	10	10	22	3,420	-0.1	19.45	157.2	89.3
M7	27,520	330,240	0.222424	73,453	2	24,000	48,000	105,120	489,250	1.5	0.75	5.7	28.1
M7	6,880	82,560	0.222424	18,363	2	3,000	6,000	13,140	135,519	0.7	1.44	11.3	28.1
M6	1,575	18,900	0.222424	4,204	1	1,836	1,836	4,021	29,901	1.0	1.09	8.4	23.1
M6	1,575	18,900	0.222424	4,204	1	800	800	1,752	32,283	0.3	2.45	19.4	23.1
M9	772	9,261	0.222424	2,060	5	100	500	1,095	15,539	0.4	1.92	15.2	36.1
M9	3,087	37,044	0.222424	8,239	5	3,800	19,000	41,610	25,056	6.0	0.19	1.6	48.6
M9	3,087	37,044	0.222424	8,239	5	5,000	25,000	54,750	11,846	8.0	0.13	1.2	36.1
M9	5,402	64,827	0.222424	14,419	5	1,000	5,000	10,950	105,447	0.7	1.37	10.6	36.1
M10	6,720	80,640	0.222424	17,936	1	8,871	8,871	19,427	125,663	1.1	0.96	7.5	100.0
M10	3,360	40,320	0.222424	8,968	1	100	100	219	72,117	-0.2	40.98	330.3	100.0
M11	111	1,332	0.222424	296	1	100	100	219	2,171	0.7	1.40	10.9	46.0
M11	102	1,221	0.222424	272	1	700	700	1,533	665	6.7	0.16	1.4	46.0

The budget allocated in a potential investment determines the results of the optimization process. Table 6.4 shows the number of improvements to be applied, total net present value of savings, total investment cost, average payback period, average profitability index and average rating change for the given budgets.

Table 6.4. Optimization results for different budget levels.

Budget	Number of Improvements	Total NPV of Savings (TL)	Total Investment Cost (TL)	Average Profitability Index	Average Rating Change	NPV/ Investment
1,000	7	254,774	898	243.7	29%	284
5,000	22	562,040	4,949	114.8	37%	114
10,000	35	843,577	9,986	86.2	46%	84
20,000	48	1,238,409	19,951	70.1	47%	62
50,000	95	2,458,814	51,686	47.7	35%	48
100,000	124	2,869,339	99,949	38.8	39%	29
150,000	149	3,611,551	149,774	36.3	39%	24
200,000	170	4,035,996	199,855	33.2	37%	20
500,000	223	5,120,922	499,388	26.3	37%	10

Figure 6.14-Figure 6.17 can be interpreted as the results of the optimization process. Firstly, number of improvements increase with increased investment budget as expected and this is seen in Figure 6.14. Secondly, savings also increase with investment and the level of this increase can be measured with profitability index. Figure 6.16 indicates that savings does not increase in the same amount as investments and thus, lower investments are inevitably more profitable compared to high amount of investments. Rating change does not have a regular trend upward or downward and can be interpreted to be almost stationary as seen in Figure 6.17.

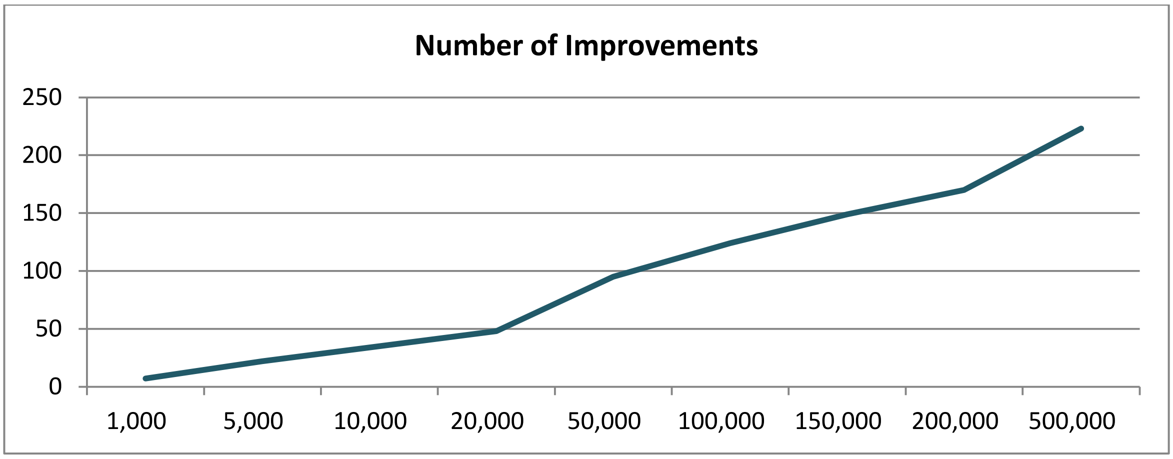


Figure 6.14. Number of improvement with respect to budget.

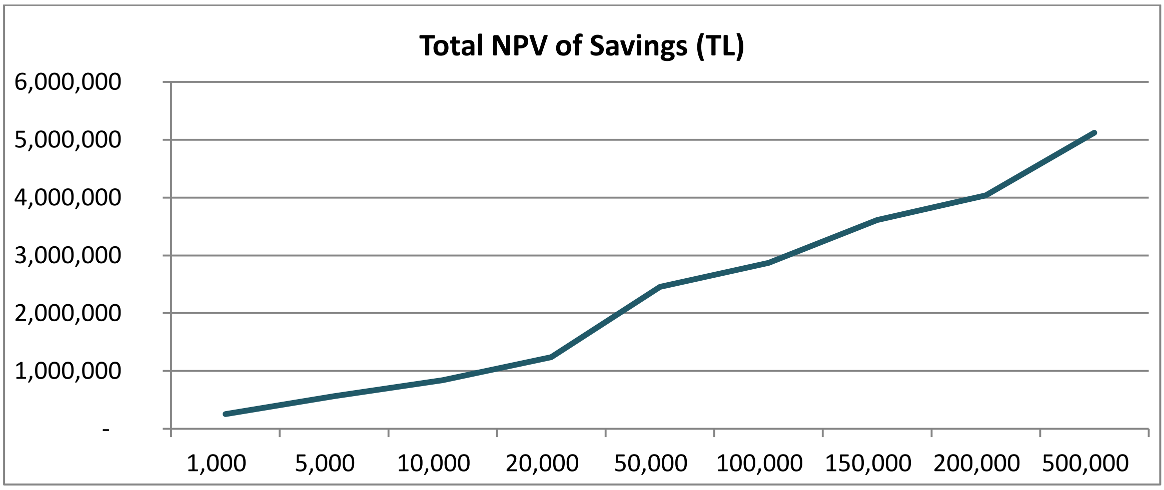


Figure 6.15. Total NPV of savings with respect to budget.

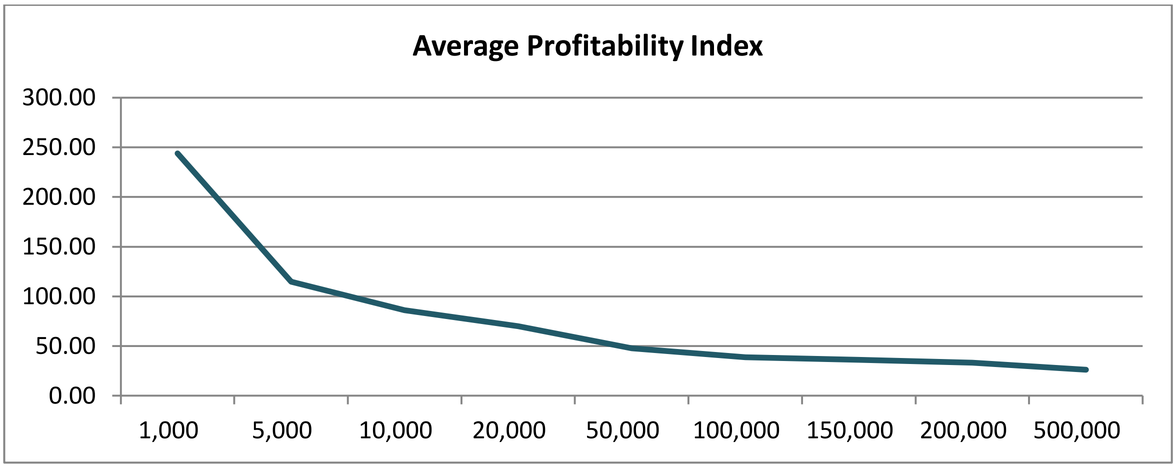


Figure 6.16. Average profitability index with respect to budget.

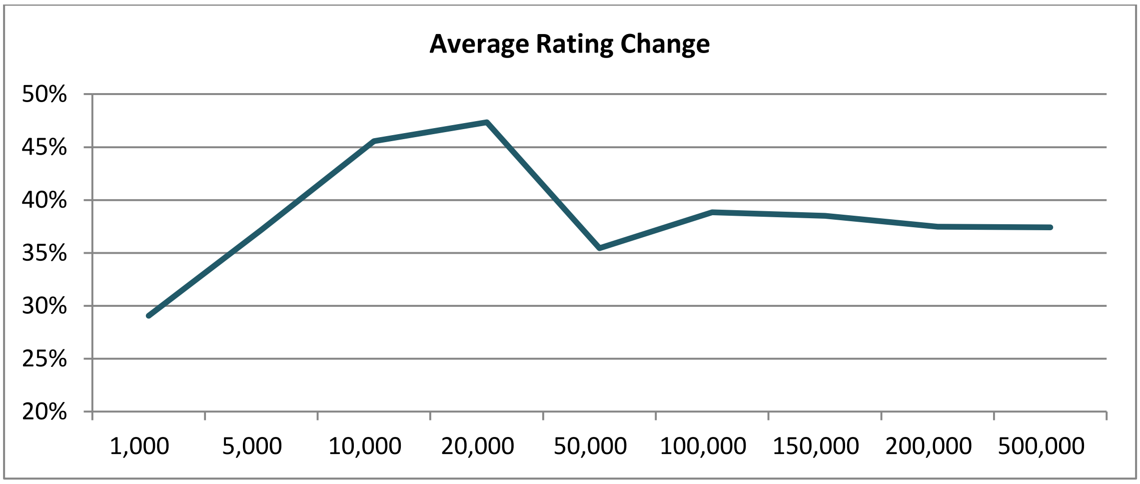


Figure 6.17. Average rating change with respect to budget.

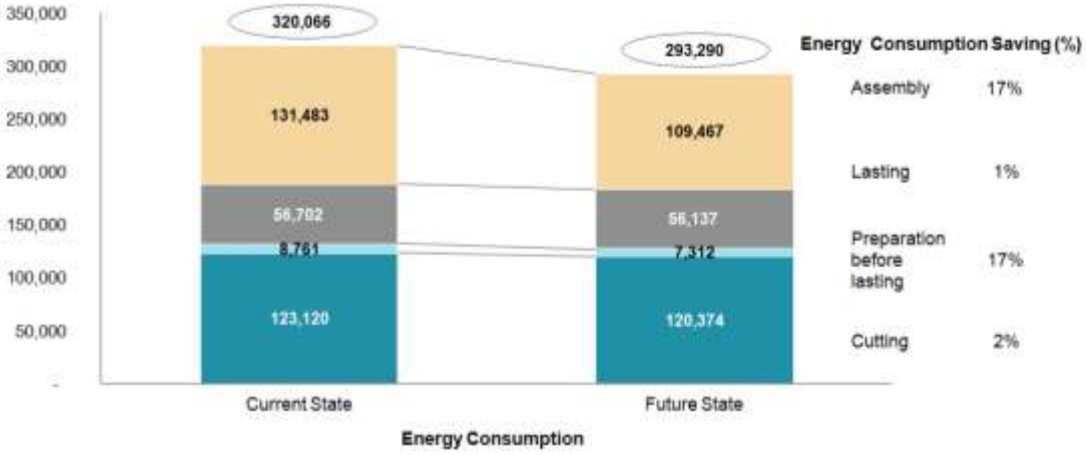
6.4. Visualization of the Future State Map

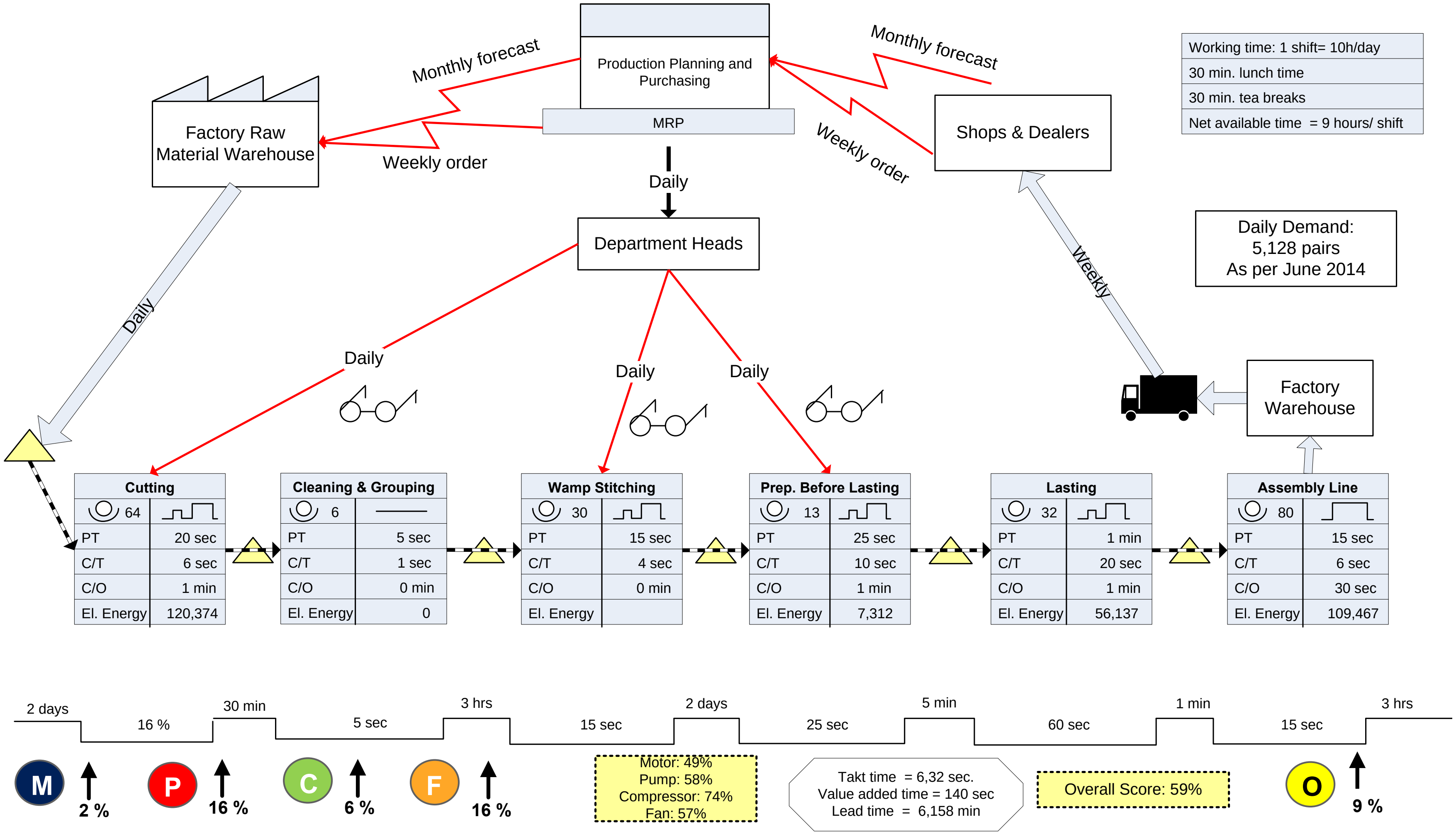
The illustration of the future energy value stream map is given in Figure 6.18 concerning the budget level of 20,000 TL as an example. Several future state maps can be drawn for different budgets. For this case, rating of the current system was able to be increased in the levels written in Table 6.5.

Table 6.5. Rating change of scorecards with 20,000 TL investment.

Reduction in electricity consumption is also available at the end of lean methodology for energy saving. Electricity saving can be seen in Table 6.6.

Table 6.6. Energy consumption saving with 20,000 TL investment.





	Cutting	Cleaning & Grouping	Wamp Stitching	Prep. Before Lasting	Lasting	Assembly Line
	64	6	30	13	32	80
PT	20 sec	5 sec	15 sec	25 sec	1 min	15 sec
C/T	6 sec	1 sec	4 sec	10 sec	20 sec	6 sec
C/O	1 min	0 min	0 min	1 min	1 min	30 sec
El. Energy	120,374	0		7,312	56,137	109,467

Figure 6.18. The future state energy value stream map.

7. SUMMARY AND CONCLUSIONS

Energy efficiency studies have always been applied in energy intensive sectors. However, the investigation and case study proved that there are significant improvements towards energy efficiency in a shoe factory although it was supposed to produce minor improvements as a non-energy intensive facility.

In this study, for waste elimination, lean methodology is applied which has become popular recently also in energy topics. Energy value stream mapping is one of the methods to apply lean philosophy for energy based improvements. In classical energy value stream mapping applications, after current system map is drawn, improvement opportunities are defined and they are implemented in the future state map. There does not exist a quantitative method that gives scores for the efficiency of the value stream and tries to increase this rating in the future state. This can be stated to be the second significance of this thesis. Statistical techniques and weight optimization were applied for the execution of this section.

Another important contribution of this thesis is that rather than applying improvements without monetary considerations, an economic analysis and optimization technique is embedded to value stream mapping. This economic analysis takes into account the increasing energy prices forecasted with ARIMA and calculates NPV of the energy efficiency investments in a 10-year project time. A simple Monte Carlo simulation tool was designed both to be used individually for any company to assess the effect of any retrofit decision and also collectively for the optimization purposes. NPV calculations with Monte Carlo simulation were used as a basis of the optimization. NPV of the savings were aimed to be increased whereas the investments were aimed to be decreased. Thus, a ratio called profitability index was intended to be optimized as the objective function. Rating change gained throughout the energy value stream mapping was also inserted to the objective function as a factor multiplied with profitability index.

The output of the optimization procedure revealed that an enormous amount of budget is not always necessary for a remarkable energy efficiency improvement.

Moreover, small amount of investments provide more profitable results. Just a 20,000 Turkish Liras was allocated to serve to energy saving opportunities for the footwear factory. Even with such a modest budget, energy consumption was reduced by 8% whereas the overall scorecard rating was increased by 9% with the highest increase in pumps and fans by 16%.

A point to emphasize is that energy efficiency improvement should be integrated to the management model of the company which will result in a continuous improvement cycle. As in the methodology, the energy consumption should be controlled on a regular basis and compared with the standards and new technologies. If there occurs a room for improvement, then the same procedure should be followed again. Finally, shared lean philosophy notion should be disseminated throughout the company by training programs, workshops and related announcements.

In this thesis, due to the lack of sufficient and reliable data on other sources of energy, value stream mapping application is applied solely on electrical energy consumption. A future study may take into account all sources of energy throughout the processes to enhance the classical value stream mapping approach. Another blind side of this thesis is that it does not incorporate the lifecycle assessment of shoes and leather from energy perspective. A more extensive study may consider all processes starting from the suppliers sourcing the raw materials to the end of life activities including recycling.

APPENDIX A: THE COMPANY INFORMATION

The ABC Group’s first operations started in a small workshop in Gaziantep in the early 60’s at which time it was making shoes to order. After a while, shifting to mass production on a minor scale, the company set its course for Istanbul in the 1970’s and mass production of sports shoes at ABC Footwear started in 1985. It signed contracts with Germany and Finland for footwear production just after delivering its first export to Greece in 1988. The acceleration gained in growth in 1989 led to the cross-border expansion of the ABC Group’s manufacturing operations with the acquisition of a shoe factory in Germany.

The Group currently exports to 29 countries. Shoe store concept has been changed after ABC has entered the market with the XYZ brand in 2001. The retail leap initiated in 2011 triggered the group to 260 stores across Turkey with the pioneering brands.

The 7 companies in the ABC Group provide employment to 5,000 people for sales of 20 million pairs of shoes per year. The manufacturing plants are as wide as 70,000 sqm with the capacity to turn out 120,000 pairs of soles and 18 tons of sole liners per day [98].

The manufacturing plant investigated in this thesis is ABC Group's İkitelli plant. The location of the plant is shown in Figure A.1 while plant layouts of the two floors are also depicted in Figure A.2 and Figure A.3.

Figure A.1. Location of the case factory.

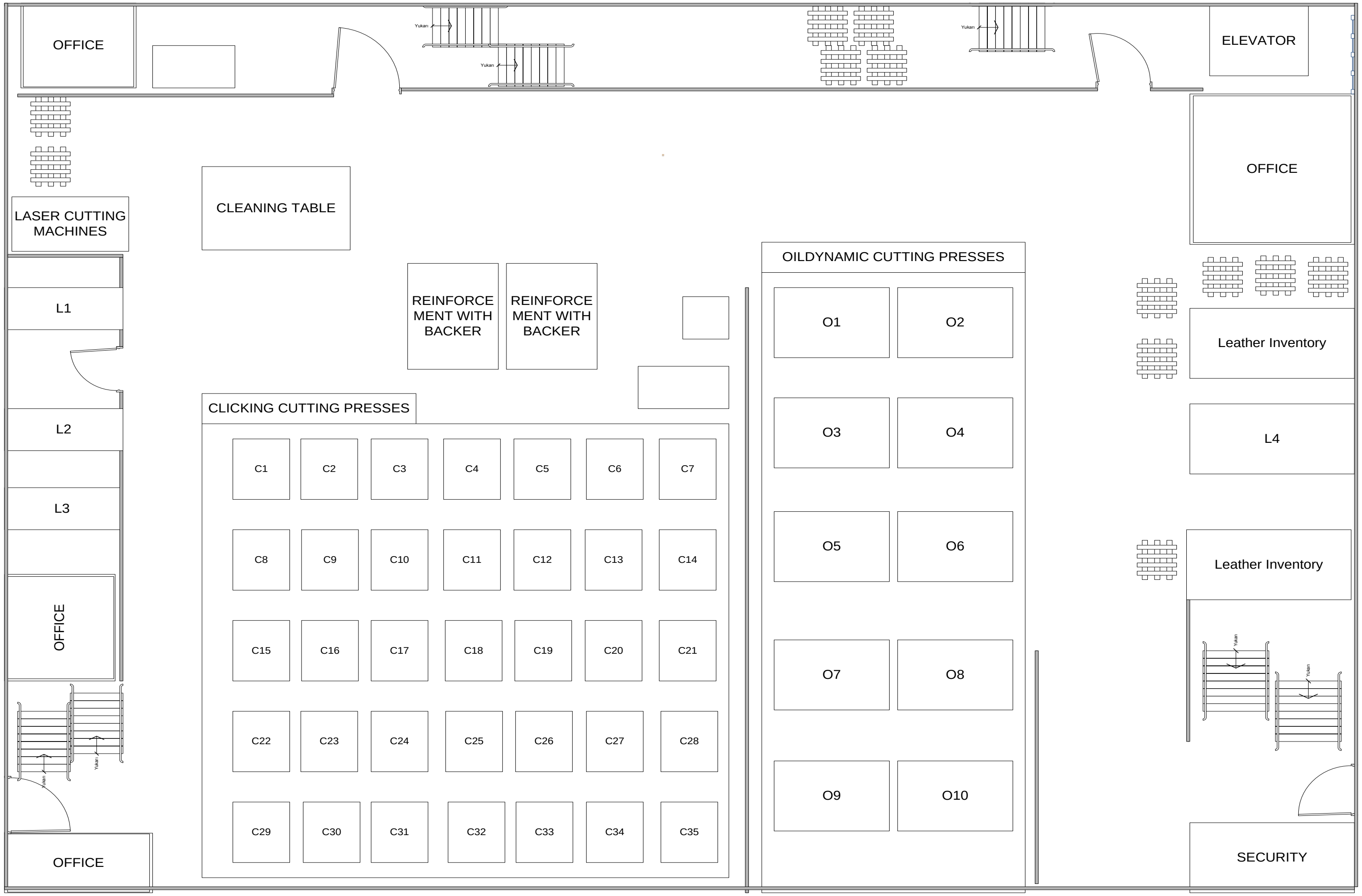


Figure A.2. Plant layout of the first floor.

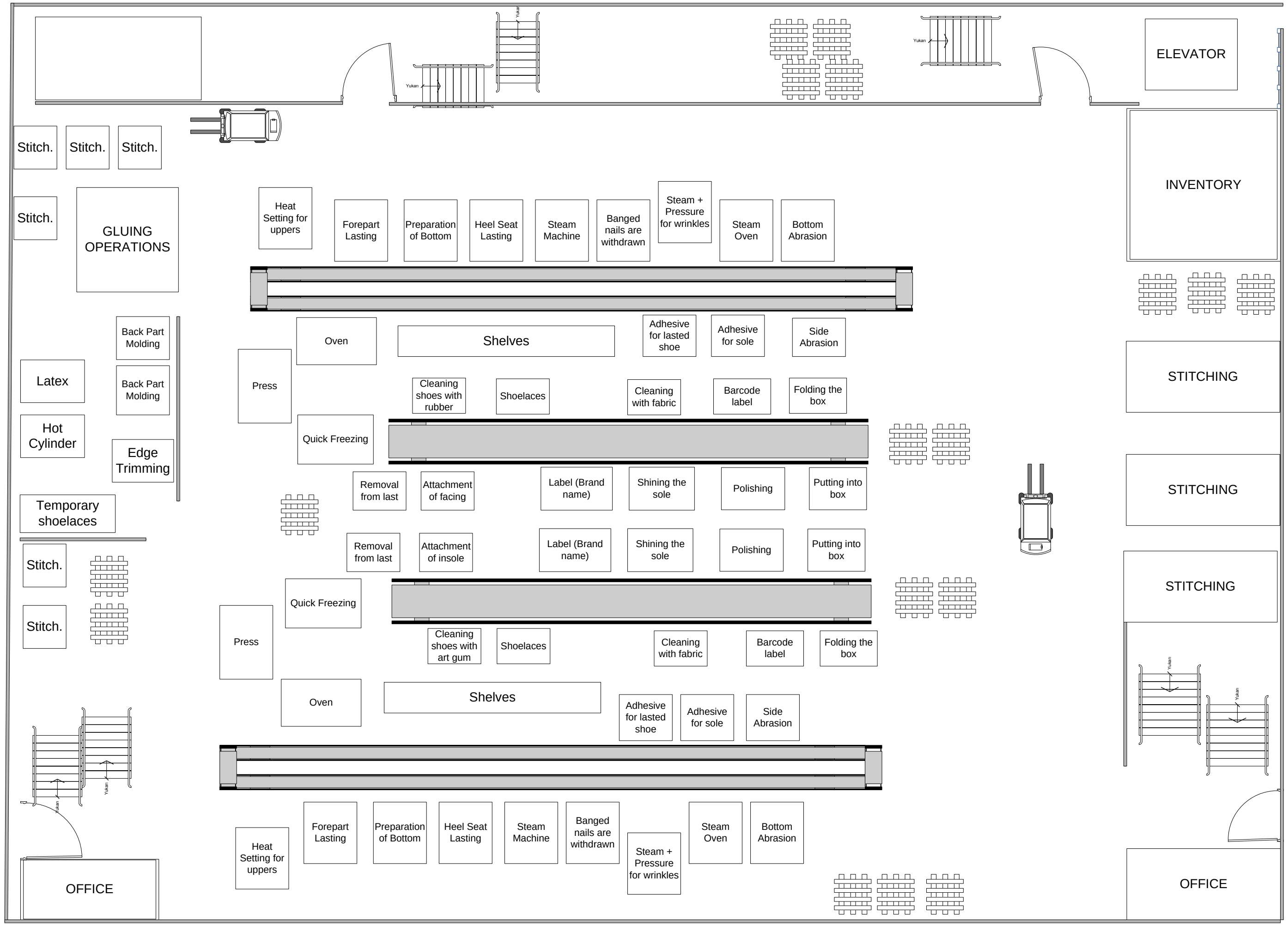


Figure A.3. Plant layout of the second floor.

APPENDIX B: PRODUCT AND PROCESSES

The purpose of this chapter is to give further information about the product, processes and their energy consumption.

B.1. Product Information

Parts of a classical shoe is given in Figure B.1. The upper is the leading part of the shoe, attached to the insole and the sole through stitching and/or glue. Leather, fabric or less valuable materials can be used in the production of the upper [99]. A basic upper consists of three basic parts; the wamp which covers the toes and forepart or front of the shoe, the quarters which enclose the back of the foot and the topline which surrounds the opening for the foot [100].

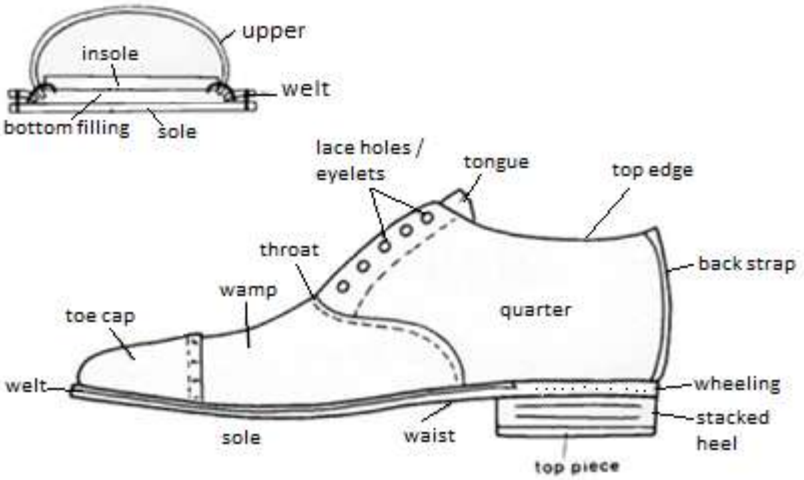


Figure B.1. Parts of a shoe.

Bottom as opposed to the upper is a term which refers to the whole of the bottom of the shoe. It generally includes insole, sole, heel and some other parts such as welt, bottom filling, runner and top piece [100]. From a functional point of view, insole is the most critical bottom component since it is the base of the shoe, it is where the foot plant lays and is the junction element between upper and sole. The sole is the part laying on the ground and nails, glue or stitching is used to attach it to the upper. Finally, the heel is the support applied to the back part of the sole in the heel area whose height range from a few millimeters to several centimeters [99].

In addition to the components of a shoe, another breakdown of shoe can be in shoes' mass by part and by material as given in Figure B.2 and Figure B.3. In addition, GHG emissions from footwear manufacturing are expected to stem from three sources such as: electricity use, fuel combustion and waste disposal. As seen in Figure B.4, waste disposal has minimal effect whereas the burden is nearly equal for electricity use and fuel combustion [101].

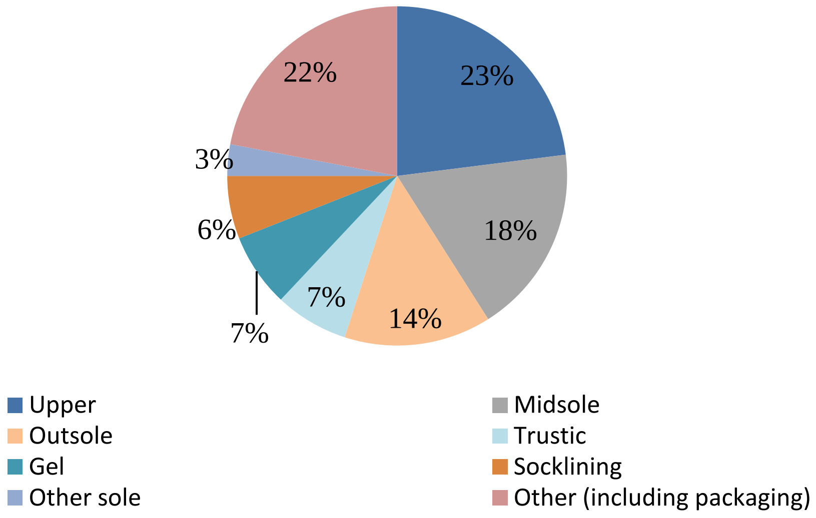


Figure B.2. Breakdown of shoe mass by shoe part.

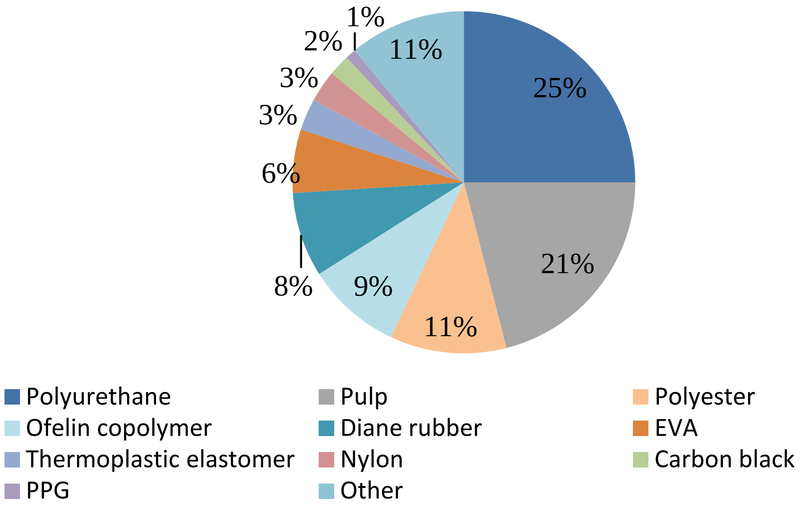


Figure B.3. Breakdown of shoe mass by material.

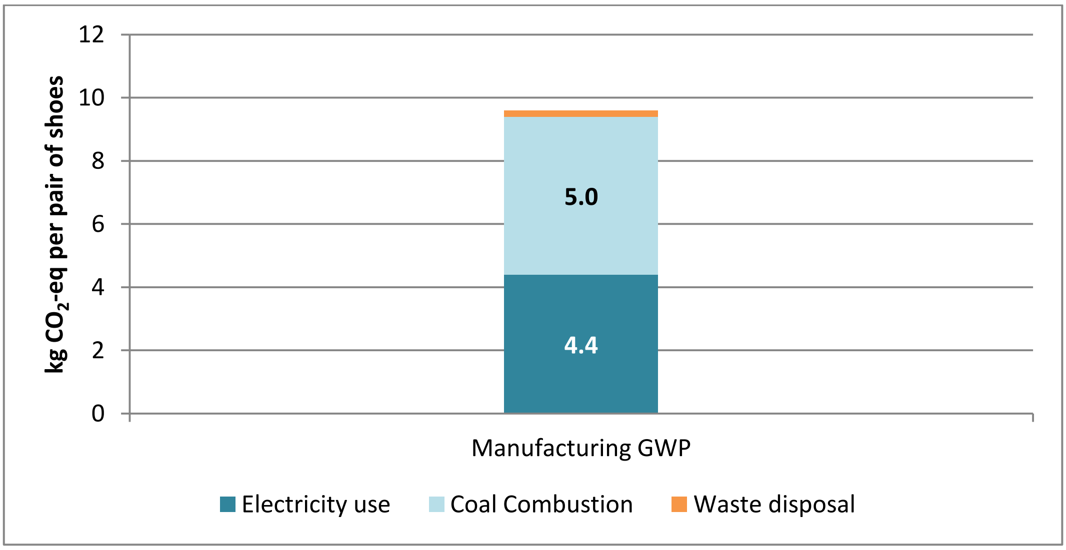


Figure B.4. Effects of electricity, coal combustion and waste disposal.

B.2. Work Flow

The general work flow listed in Section 4.1 is detailed in this part of the thesis in Figure B.5 to Figure B.9.

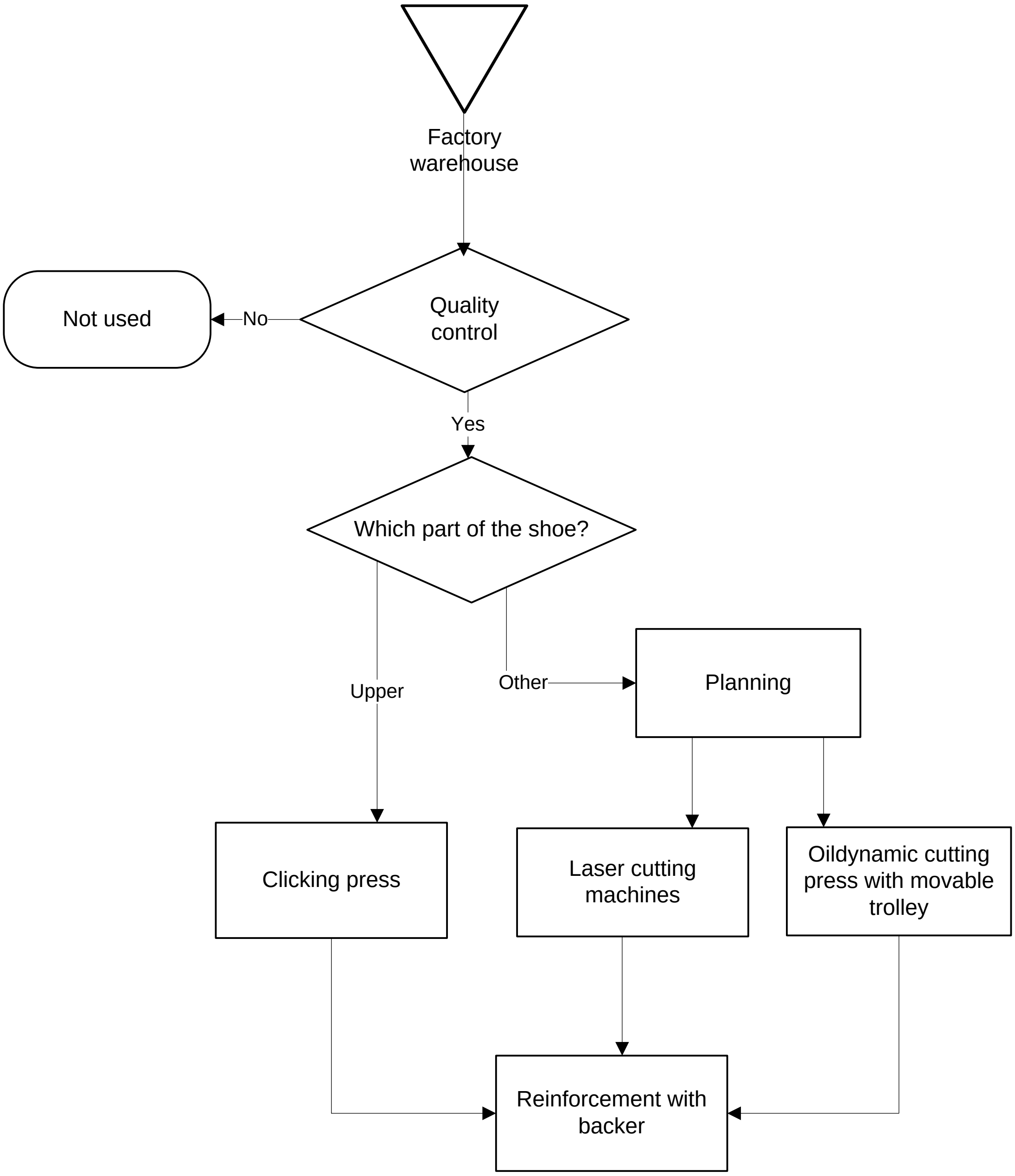


Figure B.5. Workflow of the cutting department.

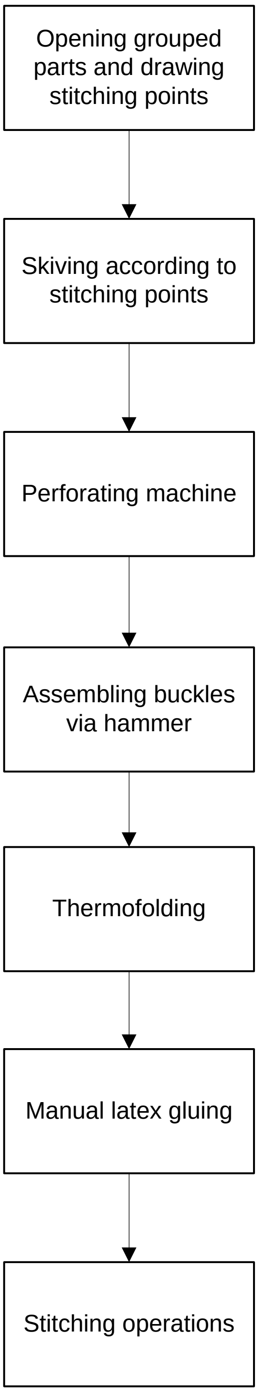


Figure B.6. Workflow of the wamp stitching department.

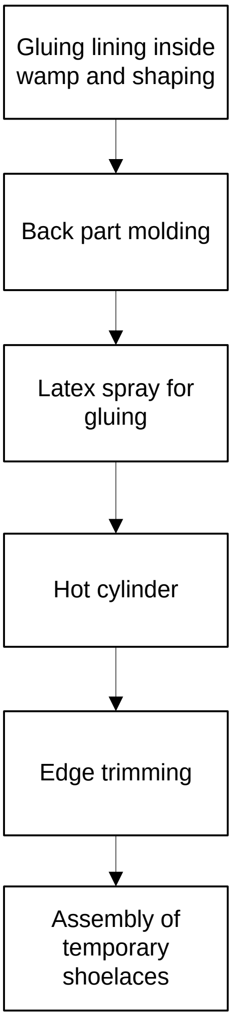


Figure B.7. Workflow of the preparation before lasting department.

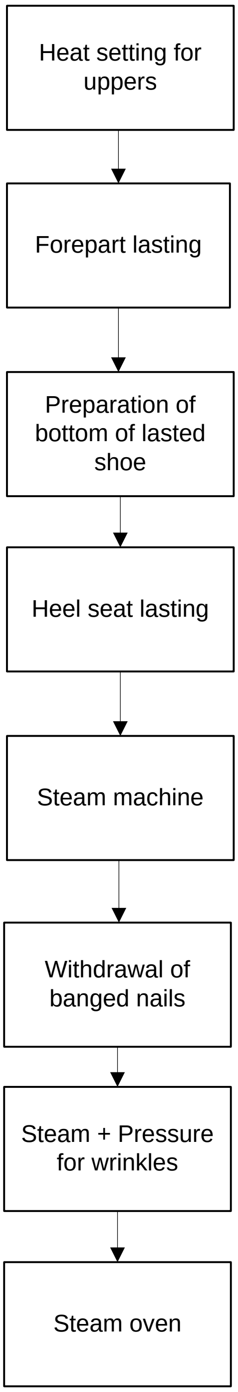


Figure B.8. Workflow of the lasting department.

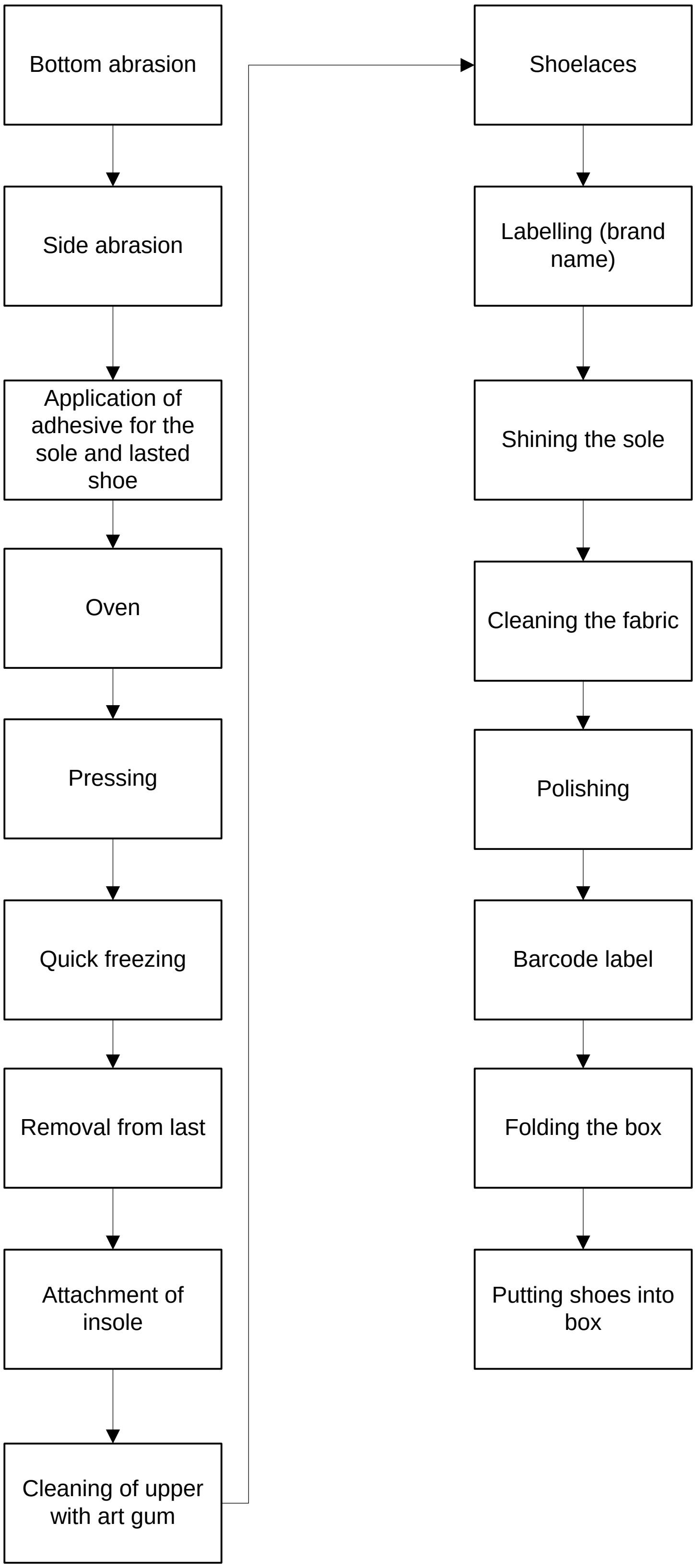


Figure B.9. Workflow of the assembly line.

B.3. Processes and Machinery

Clicking room is the part of the factory where different parts for the upper of the boot and the shoe are cut from leather or other materials. Clicker is the operator who does the actual cutting out. The work performed in the clicking room is very important for two reasons. Firstly, the clicker will be cutting a valuable material which costs high and as a result affects the profitability of the company. The second reason is that clicking operation may affect a greater number of subsequent operations than any other single operation. Thus, clickers must have some abilities such as good reasoning ability, spatial perception, color realization and decision making. Since no two skins have the same shape, size and thickness and no two skins have blemishes in exactly the same place, clickers cannot have a blue-print to follow while cutting up leather and able to reason this himself [100]. Since wastes would not be preferred in an expensive leather clickers should plan the cutting operation to achieve the maximum number of cut components from a skin while they also distinguish blemishes and defects on the surface. In the company there are 35 oildynamic clicking presses with turning arm. These clicking presses have automatic stroke-end setting-up that enables cutting different heights with knives without any adjustment. For the safety of the operation there are control buttons with built-in device that adjusts operation time with some seconds of delay. Best cutting precision is achieved with the potentiometer's right cutting power selection. The type of oildynamic clicking press with turning arm is represented in Figure B.10.

Figure B.10. Oildynamic clicking press.

Laser cutting machines are widely used for cutting operations in leather and textile industry since most of the organic and inorganic materials can be cut with a laser beam. Laser cutting machines provide results which are failure-free, without wrinkles and more precise. The light energy of the laser beam is converted into heat and it cuts with the minimal area of slotted straight edge, smallest adjacent trimming zone and minimal local deformation. In the company there are 4 laser cutting machines, one of which has been recently purchased. Two workers work in the same machine as shown in Figure B.11 and there is a screen to control cutting.

Figure B.11. Laser beam cutting press.

There are also 10 oil dynamic cutting presses with movable trolleys which are controlled with pushbuttons (time interlock synchronization while cutting) for the safety of operators. Laser cutting machines and oil dynamic cutting presses are not used to cut upper parts of a shoe since they are the most visible parts of the shoe and a more careful inspection is needed for such expensive leathers. Energy consumption of dynamic cutting presses is low and power continuity is high. As in laser beam cutting, cutting is again more precise than clicking press. Figure B.12 shows the oil dynamic cutting press with movable trolley.

Figure B.12. Oildynamic cutting press with movable trolley.

Certain parts of the shoe may need to be reinforced or an extra substance could be added by sticking a fabric backer beneath the upper. Backer is generally a cellulose fiber board which has little or no bonding agent and produces a rigid board in various grades.

Skiving is reduction of thickness in certain edges of upper parts to improve the appearance of the finished upper, to provide comfort, to reduce awkwardness and to aid stitching operations. When all parts to be gathered together are ready, stitching operations are done with several sewing machines. When all the wamp is complete, it is then ready to send to the assembly department.

Preparation before lasting starts with manual gluing of lining inside wamp to increase the strength of the wamp and shaping wamps are the first operations that take place. There are 6 workers who are responsible for this process. The working environment can be seen in Figure B.13.

Figure B.13. The first step of preparation before lasting: Manual gluing.

Back part molding is the process where the back part of the shoe is formed. The machine could be with one, two or four posts and heat moulds, cold moulds or as a combination of cold and heat moulds. In the factory there are two four post back part molding machines and each has two cold and two heat moulds. For each machine a single worker works with small displacements. Generally the maximum heat for heating moulds are 200 °C and freezing temperatures are up to - 30 °C. For instance, leather shoes are worked on with 120 °C heat moulds and the machine works with air compressor. 100% jointing of wamp with last is aimed in this process. There is an easy-to-understand electronic control display for each mold. Since the working height can be adjusted and there is no need to change settings for women and men shoes, it is ergonomic and easy-to-use. The back part molding machine in the factory can be seen in Figure B.14.

Figure B.14. Back part molding machine.

Latex spray is used after back part molding is finished to ease the gluing process after which hot cylinders are used to melt the latex poured and a better form is achieved for the forepart. There are single workers for each of the latex and hot cylinder processes. The latex spray works with the help of air pressure and the hot cylinder machine works with electricity. The factory has a latex spray cementing machine which is vintage and not ergonomic. In the footwear machinery market, newer machines can be found for the purpose and with no more energy consumption than these. The latex cementing machine is seen in Figure B.15.

Figure B.15. Latex cementing.

In the edge trimming (profiling) step, the sole edge is profiled to give the desired effect using a rotating abrasive stone. Through a presser foot, the sole traverses in the machine and has a contact with the stone. In this process traces of latex from the previous steps are cleaned. After one worker performs this task, another worker classifies the trimmed soles. Afterwards, two workers tie the temporary shoelaces to give a shape to the sole for the next operations. The temporary shoelaces can be string or just plastic bones and they are taken out later. The edge trimming operation is performed with the machine seen in Figure B.16. Since the machine is old, it is not efficient as the new machines in the market.

Figure B.16. The edge trimming machine.

Heat setting for uppers is the process where toe upper steaming machine is applied to soften shoes upper/linings. There is a simple control panel for the operator with two control positions; operator put uppers on, then machine starts working automatically. The upper mould can be moved downward whereas the lower mould is stable. The degree of the upper mould can be adjusted according to the fabric of the sole. Upper conditioner has the aim of reactivating toe cap before lasting with steaming. Forepart lasting machine and heel seat lasting machines are used later for lasting operations of shoes' different parts.

Forepart lasting machines require a degree of skills in accurate positioning of the upper into the machine. When this is correctly done and the machine is properly adjusted, the machine carries out the rest of the operation. After conditioning, the upper is initially stretched over the toe of the last and then placed into the machine so that the lasting allowance can be gripped by a series of machine pincers. As the machine works, the upper is correctly drafted into position over the last. Holding the upper securely against the last, a Teflon-coated toe band then engages around the toe area just above the feather edge. Following this stage, heated metal blades move inwards in a horizontal plane under the bottom of the forepart so wipes the upper material against the insole and sticks it down securely. The menu of the machine is easy to understand with a touch-panel on it and the machine has hydraulic/pneumatic operation. After the operation of the worker is completed a worker stretches the bottom of the lasted shoe with the help of a pliers for the ease of heal seat lasting.

Heal seat lasting operation is also carried out with a similar machine as forepart lasting. The shoes are lasted in seat and shank area in one operation. Shank is the supportive structure between the insole and outsole. This machine works both with air compressor and with hydraulic system. The nail system works with air pressure and nails are banged in the bottom of the shoe. In addition, the pressure system which stretches the shoe works with the hydraulic system. For some non-leather products just before the heal seat lasting, steaming operation is performed to soften the material again by the same operator.

There are 4 forepart lasting and 4 heel seat lasting machines in the plant and all of them have the same power as 3630 W. Figure B.17 illustrates both machines for lasting.

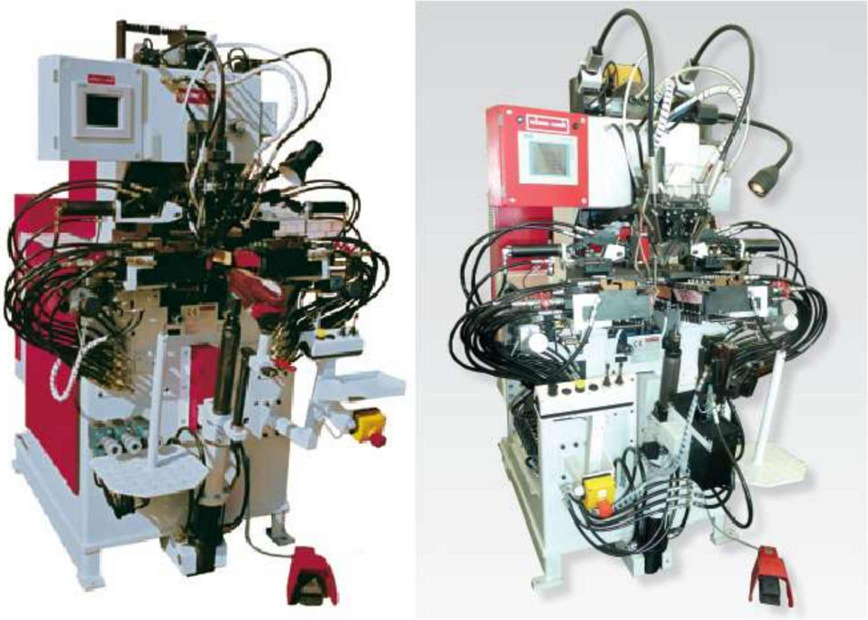


Figure B.17. Forepart and heel seat lasting machines.

Since the upper and sides of the shoe are visible and important for the quality, wrinkles and creases should be wiped out. For this purpose, steam oven is used where the shoe is heated and the wrinkles are eradicated. Sometimes, when the upper has too much wrinkles to operate, another steaming and pressure machine is also used by the same operator to ease the next operation and get a better result.

Bottom and side abrasion are the processes performed for the better fitness of upper on the sole. Since the upper will be glued on the sole, the grain surface of the sides and the bottom of the upper should be removed to form an absolute seal. Each abrasion operations are performed by different workers in sequence. After the upper is abraded for cementing, an adhesive is applied both to the bottom of the upper and the sole manually by two workers. They are then sent to the oven which is seen in Figure B.18 separately but adjacent to each other to make their adhesive melt so as to have a better seal. The heat of the oven is adjusted according to the fabric of the shoe such as 120-130 °C for rubber, 70-80 °C for thermoplastic and 100-110 °C for polyurethane. There are two motors inside the oven of which one is circulation motor while the other is the motor for the movement of the conveyor inside.

Figure B.18. Oven.

Glued and heated uppers and soles are brought together and pressed with the pressing machine shown in Figure B.19 which works with electricity. The time and the pressure need to be changed for different products.

Figure B.19. Pressing machine.

After shoes are pressed, they are sent through a quick freezing shaping machine in which there is a conveyor and shoes are cooled. Cooled shoes are ready to be removed from their lasts which are used to shape them rigidly. This operation is performed manually and shoes are transported to the production line. The quick freezing machine is shown in Figure B.20.

Figure B.20. Quick freezing machine.

In the production line, the first operation is the attachment of insole which is the inner sole of the shoe and next to the foot under the sock. Secondly, the shoe is cleaned with an art gum. Then, real shoelaces are tied. Brand name label is joined onto the shoe. The sole is shined just before the upper is cleaned with a fabric and a cleaning liquid. Later on, the shoe is polished and barcode is attached. Lastly, the box is folded and the shoes are packed in the box. The boxes are then stored to send into factory warehouse at the end of the line which is seen in Figure B.21.

Figure B.21. Assembly line.

The transportation inside cutting workshop are completed with containers as in Figure B.22. This procedure is also the same for wamp stitching and preparation before lasting. On the other hand, in lasting and some part of assembly department transportation is done with the handling system seen below in Figure B.23 where there are movable shelves. When these shelves are full, they are pushed to the upcoming workstation. In one piece of the shelf, maximum capacity is 12 shoes and when the shelf is fully loaded, the next one also stays where it has been which result in some waiting. The operator must push the shelf to bring an empty shelf to himself.

Figure B.22. Containers used for transportation.

Figure B.23. Moving shelves used for storage.

In addition to the moving shelves in lasting and assembly, there are also storage shelves next to the conveyor band since there may be overload sometimes in the conveyor band. Workers just collect some of the work in the shelves to complete later in order to reach a balanced conveyor band. An example of such a situation is shown in Figure B.24. Furthermore, an overloaded assembly line can also be seen in Figure B.25.

Figure B.24. Storage next to the assembly line in case of an overload.

Figure B.25. An overloaded assembly line.

Factory lighting is another energy consumer with a 5% share for manufacturing. All lights in the company are fluorescent lights. There are two tubes in each ballast and in the manufacturing environment, the lights are switched off when there is no production such as lunch times and 15-minute breaks. In these times, just the lights in the corridors are on. Furthermore, when a single operation is not working, switching the light just above that station is also possible as seen in Figure B.26.

Figure B.26. General lighting in the factory.

Compressors, steam generators and boilers are placed in basement and on top floor. Some figures from these energy consumers are given in Figure B.27.

Figure B.27. Compressors and boilers.

B.4. Energy Consumption Profile

The cutting workshop and all other processes except wamp stitching are located in the main building whereas the outsourced wamp stitching workshop is in the adjacent building. Facility layout can be visited for a further information in Appendix A. The machines and other energy consuming units are summarized in Table B.1 to Table B.7 with the power of the machinery, quantities, uptime and effective power.

Table B.1. Energy consumption of cutting workshop.

Location	**Machine**	**Power (W)**	**Quantity**	**Total**	**Uptime**	**Effective power**
Cutting workshop	Clicking press	750	35	26250	50%	13125
	Laser beam cutting press	10000	3	30000	30%	9000
	Wamp crimping machine	1500	2	3000	50%	1500
	Ventilation motor	1500	1	1500	100%	1500
	Fluorescent Lamps	40	82	3280	100%	3280
	Regulator	22500	1	22500	70%	15750
	Reinforcement with backer	17200	2	34400	100%	34400
	Compressor	4000	1	4000	100%	4000
	Oil dynamic cutting press	2205	10	22050	70%	15435
	Laser beam cutting press	70000	1	70000	30%	21000
	Extractor fan motor	370	1	370	100%	370
	Fluorescent Lamps	40	50	2000	100%	2000
	Thermocementing machine	650	1	650	50%	325
	Thermocementing machine	850	2	1700	50%	850
	Thermocementing machine	1270	1	1270	50%	635

Table B.2. Energy consumption of preparation before lasting.

Location	Machine	Power (W)	Quantity	Total	Uptime	Effective power
Preparation before lasting	Back part molding machine	2300	2	4600	80%	3680
	Latex spray cementing	500	1	500	80%	400
	Toe puff and reinforcing	450	1	450	70%	315
	Edge Trimming	620	1	620	80%	496
	Wamp crimping machine	1800	2	3600	70%	2520
	Dust absorber	1100	1	1100	100%	1100
	Fan coil unit	250	1	250	100%	250

Table B.3. Energy consumption of lasting and assembly department-1.

Location	Machine	Power (W)	Quantity	Total	Uptime	Effective power
Lasting 1	Upper conditioner	400	1	400	70%	280
	Forepart lasting machine	3630	1	3630	70%	2541
	Heel seat lasting machine	3630	1	3630	70%	2541
	Steam ironing machine	2000	1	2000	30%	600
	Steam oven	12500	1	12500	50%	6250
	Lasted shoe bottom roughing machine	1500	1	1500	70%	1050
	Lasted shoe side roughing machine	700	1	700	70%	490
Assembly 1	Oven	13500	1	13500	70%	9450
	Pressing	2500	1	2500	80%	2000
	Cooling machine	4590	1	4590	60%	2754
	Fluorescent Lamps	40	132	5280	100%	5280
	Extractor fan motor	1500	1	1500	70%	1050
	Sole shining machine	2250	1	2250	30%	675
	Polishing cabin	750	1	750	60%	450
	Finishing band	750	1	750	100%	750
	Fan coil unit	130	3	390	100%	390
	Odor absorber	2500	3	7500	70%	5250
	Extraction funnel	370	1	370	100%	370
	Yarn removing	850	2	1700	30%	510
	Dust absorber	2500	2	5000	100%	5000
	Dust absorber	1500	1	1500	100%	1500

Table B.4. Energy consumption of lasting and assembly department-2.

Location	Machine	Power (W)	Quantity	Total	Uptime	Effective power
Lasting 2	Upper conditioner	200	4	800	70%	560
	Forepart lasting machine	3630	1	3630	70%	2541
	Heel seat lasting machine	3630	1	3630	70%	2541
	Steam ironing machine	2000	1	2000	30%	600
	Steam oven	10490	1	10490	50%	5245
	Steam oven	15740	1	15740	0%	0
	Lasted shoe bottom roughing machine	1470	1	1470	70%	1029
	Lasted shoe side roughing machine	1100	1	1100	70%	770
Assembly 2	Oven	10200	1	10200	70%	7140
	Pressing	3600	1	3600	80%	2880
	Cooling machine	4590	1	4590	60%	2754
	Fluorescent Lamps	40	140	5600	100%	5600
	Extractor fan motor	1500	1	1500	70%	1050
	Sole shining machine	2250	1	2250	30%	675
	Polishing cabin	1500	1	1500	60%	900
	Finishing band	660	1	660	100%	660
	Fan coil unit	400	3	1200	100%	1200
	Odor absorber	1500	1	1500	70%	1050
	Odor absorber	250	1	250	70%	175
	Extraction funnel	370	1	370	100%	370
	Dust absorber	1500	2	3000	70%	2100
	Dust absorber	1100	1	1100	70%	770
	Yarn removing	850	4	3400	30%	1020

Table B.5. Energy consumption of lasting and assembly department-3.

Location	Machine	Power (W)	Quantity	Total	Uptime	Effective power
Lasting 3	Upper conditioner	200	4	800	70%	560
	Forepart lasting machine	3630	1	3630	70%	2541
	Heel seat lasting machine	3630	1	3630	70%	2541
	Steam ironing machine	2000	1	2000	30%	600
	Steam oven	15620	1	15620	50%	7810
	Lasted shoe bottom roughing machine	1100	1	1100	70%	770
	Lasted shoe side roughing machine	700	1	700	70%	490
	Lasted shoe side roughing machine	500	2	1000	0%	0
Assembly 3	Oven	13000	1	13000	70%	9100
	Pressing	3600	1	3600	80%	2880
	Cooling machine	2450	1	2450	60%	1470
	Fluorescent Lamps	40	80	3200	100%	3200
	Extractor fan motor	2870	1	2870	70%	2009
	Sole shining machine	2250	1	2250	30%	675
	Polishing cabin	1100	1	1100	60%	660
	Finishing band	250	1	250	100%	250
	Fan coil unit	130	3	390	100%	390
	Odor absorber	250	3	750	70%	525
	Extraction funnel	370	1	370	100%	370
	Dust absorber	1500	1	1500	70%	1050
	Yarn removing	850	3	2550	30%	765

Table B.6. Energy consumption of lasting and assembly department-4.

Location	Machine	Power (W)	Quantity	Total	Uptime	Effective power
Lasting 4	Upper conditioner	400	1	400	70%	280
	Forepart lasting machine	3630	1	3630	70%	2541
	Heel seat lasting machine	3630	1	3630	70%	2541
	Steam ironing machine	4000	1	4000	30%	1200
	Steam oven	12500	1	12500	50%	6250
	Lasted shoe bottom roughing machine	1500	1	1500	70%	1050
	Lasted shoe side roughing machine	700	1	700	70%	490
Assembly 4	Oven	13000	1	13000	70%	9100
	Oven with pallet	8165	1	8165	70%	5715.5
	Pressing	1800	1	1800	80%	1440
	Cooling machine	10750	1	10750	60%	6450
	Fluorescent Lamps	40	92	3680	100%	3680
	Extractor fan motor	1500	1	1500	70%	1050
	Sole shining machine	2250	1	2250	30%	675
	Polishing cabin	550	1	550	60%	330
	Finishing band	3000	1	3000	100%	3000
	Fan coil unit	130	3	390	100%	390
	Odor absorber	250	10	2500	70%	1750
	Extraction funnel	370	1	370	100%	370
	Conveyor motor	11000	1	11000	70%	7700
	Dust absorber	2200	1	2200	70%	1540
	Yarn removing	850	1	850	30%	255
	Drying	1800	1	1800	50%	900

Table B.7. Energy consumption of warehouse and others.

Location	Machine	Power (W)	Quantity	Total	Uptime	Effective power
Warehouse & Other	Hydrophore	2500	3	7500	70%	5250
	Fan coil unit	250	7	1750	100%	1750
	Fluorescent Lamps	40	32	1280	100%	1280
	Odor absorber	1500	4	6000	100%	6000
	Odor absorber	250	1	250	100%	250
	Compressed air dryer	580	1	580	50%	290
	Compressor	4000	1	4000	100%	4000
	Compressor	18500	1	18500	100%	18500
	Compressor	10000	1	10000	100%	10000
	Compressor	37500	1	37500	100%	37500
	Lift	4400	1	4400	20%	880
	Packing machine	46000	1	46000	100%	46000

Considering the energy use, motors spend the greatest amount of energy in the manufacturing plant whereas compressors are the second, and fans and pumps are the last. Figure B.28 depicts a chart for percentage energy consumption.

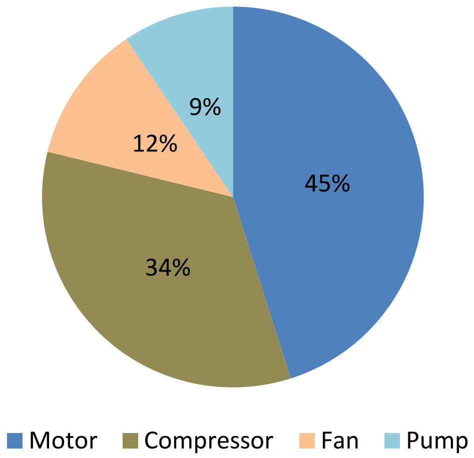


Figure B.28. Energy consumption shares.

APPENDIX C: LIGHTING

C.1. Basic Parameters and Terms in Lighting

The general terminology in lighting is as follows [102]:

Luminous Flux: The total light output of a light source (in all directions). Its units of measurement is lumen (lm).

Light intensity: The light output in a specified direction. Its unit is candela(cd).

Illuminance: Amount of light falling onto a surface or in other words, the luminous flux per unit area. Its unit is lux which is lumen per square meter.

Visible surface: Surface brightness which depends on the visible surface area and the light reflected by the surface to the eye. It is measured in units of candela per square meter.

Basic parameters of lighting can be seen in Figure C.1.

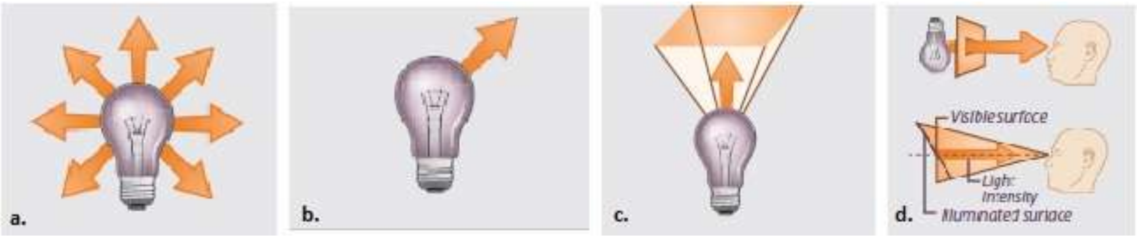


Figure C.1. a. Luminous lux b. Light intensity c. Illuminance d. Visible surface.

Circuit Watts: Total power drawn by lamps and ballasts (W).

Luminous efficacy: The ratio of luminous flux emitted by a lamp to the power consumed by the lamp. It is a reflection of efficiency and measured with the unit of lumens per lamp Watt (lm/W).

Color rendering index (CRI): The measure of the effect of light on the perceived color of objects. CRI is typically expressed as a number, where most true to life color rendering is represented by 100.

Correlated color temperature (CCT): The color appearance of the light source is represented by CCT which is often shown on lamps with the unit of Kelvin (K). The higher the CCT, the cooler or blue the light is. For instance, 2500 K has a warm, yellow appearance whereas 4000 K has a cool blueish light.

C.2. Types of Lamps

The most commonly used lamp types are described briefly as follows according to their light emitting principles [62,98]. Each lamp has advantages and disadvantages in its usage, and is used according to intended purposes.

C.2.1. Incandescent lamps (General lighting service (GLS)):

Normal incandescent lamps are general lighting service lamps in which the principal parts are tungsten filament, bulb, the fill gas or vacuum and cap as given in Figure C.2. They produce light by means of a wire or filament heated to incandescence by the flow of electric current through it. The filament is enclosed in an evacuated glass bulb filled with a gas that helps to increase the brilliance of lamp.

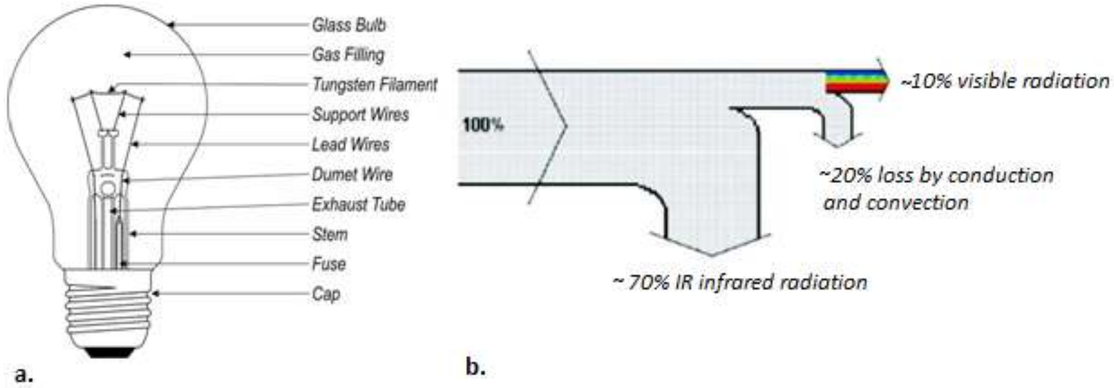


Figure C.2. Incandescent lamp and energy flow diagram.

Like incandescent lamps, halogen lamps also contain tungsten filament and a bulb filled with gas (See Figure C.3). They also contain iodine which prologs lamp life and allows the filament to generate a larger amount of heat and thus is becomes whiter. Halogen lamps have an increased efficiency compared to traditional incandescent lamps.

Figure C.3. Halogen lamp.

C.2.2. Fluorescent lamps

A fluorescent lamp is a glass tube that can be in various forms containing mercury vapor. It has two filaments, one at each end of the tube and when the electrical supply is switched on, the contacts of the starter open and the filaments heat up the gas in the tube. Figure C.4 shows a general fluorescent lamp. The luminous flux of fluorescent lamps is 3 to 5 times as efficient as incandescent lamps and their lifetime is 10 to 20 times longer. Fluorescent lamps distinguish according to their diameters and efficiencies. T5 & T8 lamps offer a 5% increase in efficiency over 40-Watt T12 lamps and are the most popular fluorescent lamps.

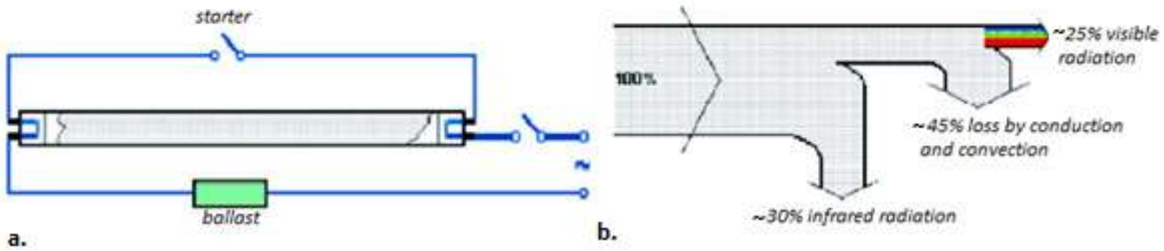


Figure C.4. a. Fluorescent tube lamp b. Energy flow.

Linear tubes

- T12 - 38 mm
- T8 - 25 mm
- T5 - 16 mm
- T2 - 6 mm

U-bent tubes

- T12 - 38 mm
- T8 - 25 mm

Circular tubes

- T12 - 38 mm
- T5- 16 mm

Compact fluorescent lamps are compact/miniature versions of fluorescent lamps and operate in a very similar way. They are designed for replacement of incandescent lamps and fit into all most existing light fixtures where incandescent lamps are used.

C.2.3. High Intensity Discharge (HID) Lights

One type of HID lamps are mercury vapor lamps and since they use mercury and phosphors they are very similar to fluorescent tubes as given in Figure C.5. In new buildings, metal halide lamps are preferred rather than mercury vapor lamps as they are more energy efficient and offer better light quality. These lamps generate a blueish light and were commonly used in high bay fittings and old style street lights and occasionally used in downlights within large spaces such as the foyers of tower buildings.

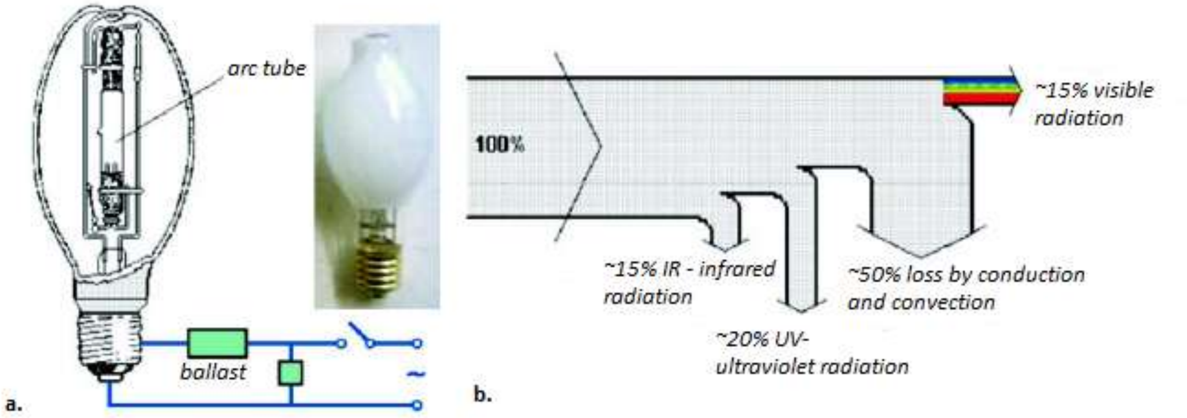


Figure C.5. a. Mercury vapor lamp b. Energy flow.

Another type of HID lamps are sodium vapor lamps which are divided into two groups as high pressure sodium vapor (HPSV) lamps and low pressure sodium vapor (LPSV) lamps as in Figure C.6. Although LPSV lamps are similar to fluorescent lamps since they also use low pressure, they are commonly classified in HID family. They are the most efficient lights but they produce the poorest quality of lighting and everything seems as white, black or shades of grey. LPSV lamps are used in street lighting or stairwells. HPSV lamps are widely used in outdoor and industry as the light is yellowish. Its high efficiency makes it popular to metal halides when color rendering is not important.

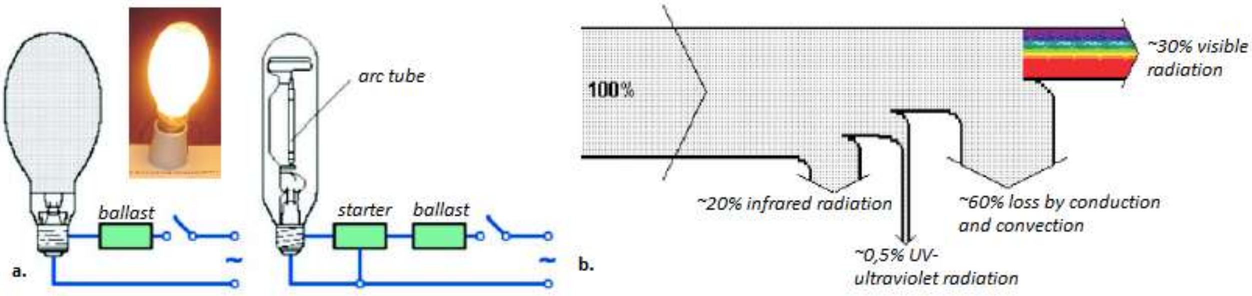


Figure C.6. a. Sodium vapor lamp b. Energy flow.

The last HID lamp type is metal halide lamp which is given in Figure C.7. Over the last years, these lamps have become quite popular due to advances in technology. They contain a number of different metal halides which produce different wavelengths within the visible spectrum and generate a white light. Because of their efficiency and long life they have a wide area of use.

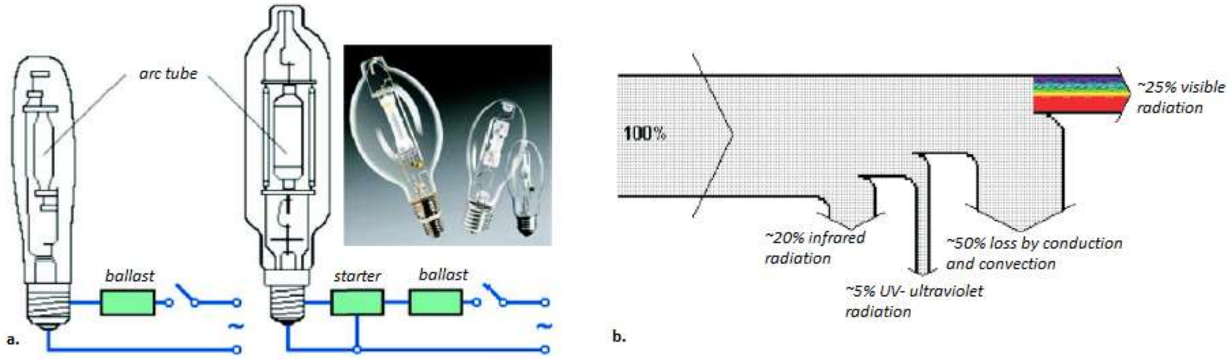


Figure C.7. a. Metal halide lamp b. Energy flow.

C.2.4. Light emitting diodes (LED)

LEDs are semiconductor devices, filled with gases and coated with different phosphor materials and used for artificial lighting. LEDs can produce more white light per unit of energy than metal halide, sodium vapor, fluorescent and halogen lamps. They are useful for special purposes like traffic signs and cars' indicating light.

REFERENCES

1. Barker, T., P. Ekins, and N. Johnstone, *Global Warming and Energy Demand*, Taylor & Francis e-Library, London, 2005.

2. Solzhenitsyn, S., K. Schneiker, J. Slezak, D. Malyarov, and E. Sleyn, "Pathways to an Energy and Carbon Efficient Russia", Moscow, 2009.

3. Gallogly, S. J., M.-A. Delannoy, E. J. Olsen, and A. M.-T. Gálvez, "Energy Policies of IEA Countries: Turkey 2009 Review", Paris, 2009.

4. TurkStat, "Turkstat Main Statistics-National Accounts-Gross Domestic Product by Production Approach", 2014, http://www.turkstat.gov.tr/UstMenu.do?metod=temelist, [Accessed July 2014].

5. Deloitte, "Turkish Energy Industry Report", Republic of Turkey Prime Ministry Investment Support and Promotion Agency, Ankara, 2010.

6. TEİAŞ, "Türkiye Elektrik Enerjisi 5 Yıllık Üretim Kapasite Projeksiyonu (2013-2017)", Ankara, 2013.

7. World Commission on Environment and Development, "Our Common Future", Oslo, 1987.

8. Carley, S., "Energy Demand-Side Management: New Perspectives for a New Era", *SSRN Electronic Journal*. 2011.

9. Sorrell, S., M. Alexandra, and S. Nye, "Barriers to Industrial Energy Efficiency: A Literature Review". Vienna, 2011.

10. Mukherjee, K., "Energy Use Efficiency in the Indian Manufacturing Sector: An Interstate Analysis", *Energy Policy*, Vol. 36, No. 2, pp. 662–672, 2008.

11. Mukherjee, K., "Energy Use Efficiency in U.S. Manufacturing: A Nonparametric Analysis", *Energy Economics*, Vol. 30, No. 1, pp. 76–96, 2008.

12. Paulus, M. and F. Borggrefe, "The Potential of Demand-Side Management in Energy-Intensive Industries for Electricity Markets in Germany", *Applied Energy*, Vol. 88, pp. 432–441, 2011.

13. Pardo Martínez, C. I., "Energy Efficiency Development in German and Colombian Non-energy-Intensive Sectors: a Non-parametric Analysis", *Energy Efficiency*, Vol. 4, No. 1, pp. 115–131, 2011.

14. Greening, L. A., G. Boyd, and J. M. Roop, "Modeling of Industrial Energy Consumption: An Introduction and Context", *Energy Economics*, Vol. 29, No. 4, pp. 599–608, 2007.

15. Tol, R. S. J. and J. P. Weyant, "Energy Economics’ Most Influential Papers", *Energy Economics*, Vol. 28, pp. 405–409, 2006.

16. Ang, B. W. and F. Q. Zhang, "A Survey of Index Decomposition Analysis in Energy and Environmental Studies", *Energy*, Vol. 25, No. 12, pp. 1149–1176, 2000.

17. Zhou, P. and B. W. Ang, "Linear Programming Models for Measuring Economy-wide Energy Efficiency Performance", *Energy Policy*, Vol. 36, No. 8, pp. 2911–2916, 2008.

18. Sorrell, S. and J. Dimitropoulos, "The Rebound Effect: Microeconomic Definitions, Limitations and Extensions", *Ecological Economics*, Vol. 65, No. 3, pp. 636–649, 2008.

19. Lescaroux, F., "Decomposition of US Manufacturing Energy Intensity and Elasticities of Components with Respect to Energy Prices", *Energy Economics*, Vol. 30, No. 3, pp. 1068–1080, 2008.

20. Lee, K. and W. Oh, "Analysis of CO2 Emissions in APEC Countries: A Time-series and a Cross-sectional Decomposition Using the Log Mean Divisia Method", *Energy Policy*, Vol. 34, No. 17, pp. 2779–2787, 2006.

21. Frei, C. W., P.-A. Haldi, and G. Sarlos, "Dynamic Formulation of a Top-down and Bottom-up Merging Energy Policy Model", *Energy Policy*, Vol. 31, No. 10, pp. 1017–1031, 2003.

22. Schumacher, K. and R. D. Sands, "Where Are the Industrial Technologies in Energy–Economy Models? An Innovative CGE Approach for Steel Production in Germany", *Energy Economics*, Vol. 29, No. 4, pp. 799–825, 2007.

23. Daniëls, B. W. and A. W. N. Van Dril, "Save Production: A Bottom-Up Energy Model for Dutch Industry and Agriculture", *Energy Economics*, Vol. 29, No. 4, pp. 847–867, 2007.

24. Miranda-da-Cruz, S. M., "A Model Approach for Analysing Trends in Energy Supply and Demand at Country Level: Case Study ofIndustrial Development in China", *Energy Economics*, Vol. 29, No. 4, pp. 913–933, 2007.

25. Babusiaux, D. and A. Pierru, "Modelling and Allocation of CO2 Emissions in a Multiproduct Industry: The Case of Oil Refining", *Applied Energy*, Vol. 84, No. 7–8, pp. 828–841, 2007.

26. Lund, P., "Impacts of EU Carbon Emission Trade Directive on Energy-İntensive Industries — Indicative Micro-economic Analyses", *Ecological Economics*, Vol. 63, No. 4, pp. 799–806, 2007.

27. Henning, D. and L. Trygg, "Reduction of Electricity Use in Swedish Industry and Its Impact on National Power Supply and European CO2 E Missions", *Energy Policy*, Vol. 36, No. 7, pp. 2330–2350, 2008.

28. Boyd, G. A. and J. X. Pang, "Estimating the Linkage Between Energy Efficiency and Productivity", *Energy Policy*, Vol. 28, No. 5, pp. 289–296, 2000.

29. Sarıca, K. and I. Or, "Efficiency Assessment of Turkish Power Plants Using Data Envelopment Analysis", *Energy*, Vol. 32, No. 8, pp. 1484–1499, 2007.

30. United States Environmental Protection Agency, "Lean, Energy & Climate Toolkit: Achieving Process Excellence Through Energy Efficiency and Greenhouse Gas Reduction", 2011.

31. Torres, A. S. J. and A. M. Gati, "Environmental Value Stream Mapping (EVSM) as Sustainability Management Tool", in *PICMET 2009 Portland International Conference on Management of Engineering & Technology*, 2009, pp. 1689–1698.

32. Faulkner, W. and F. Badurdeen, "Sustainable Value Stream Mapping (Sus-VSM): Methodology to Visualize and Assess Manufacturing Sustainability Performance", *Journal of Cleaner Production*, pp. 1–11, 2014.

33. Baysan, S., E. Çevikcan, and Ş. I. Satoğlu, "Assessment of Energy Efficiency in Lean Transformation: A Simulation Based Improvement Methodology", in *Assessment and Simulation Tools for Sustainable Energy Systems-Theory and Applications*, Vol. 129, Cavallaro, F., Ed., Springer London, London, pp. 357–379, 2013.

34. Schmidtke, D., U. Heiser, and O. Hinrichsen, "A Simulation-enhanced Value Stream Mapping Approach for Optimisation of Complex Production Environments", *International Journal of Production Research*, Vol. 52, No. 20, pp. 6146–6160, 2014.

35. Keskin, C., U. Asan, and G. Kayakutlu, "Value Stream Maps for Industrial Energy Efficiency", in *Assessment and Simulation Tools for Sustainable Energy Systems-Theory and Applications*, pp. 381–394, 2013.

36. Kumbaroğlu, G. and R. Madlener, "Evaluation of Economically Optimal Retrofit Investment Options for Energy Savings in Buildings", *Energy and Buildings*, Vol. 49, pp. 327–334, 2012.

37. Erlach, K. and E. Westkämper, *Energiewertstrom: Der Weg Zur Energie-effizienten Fabrik*, Fraunhofer Verlag, Stuttgart, pp. 11–46, 2009.

38. Womack, J. P., D. T. Jones, and D. Roos, *The Machine That Changed The World*, Macmillan Publishing, New York, 1990.

39. Womack, J. P. and D. T. Jones, *Lean Thinking*, Free Press, New York, 2003.

40. Özkan, K., S. Birgün, and P. Kılıçoğulları, "Müşteriden Tedarikçiye Değer Yaratma: Otomotiv Endüstrisinde Değer Akışı Haritalandırma Uygulaması", in *V. Ulusal Üretim Araştırmaları Sempozyumu*, 2005, pp. 307–312.

41. Dolcemascolo, D., *Improving The Extended Value Stream, Lean for the Entire Supply Chain*, Productivity Press, New York, 2006.

42. Rother, M. and J. Shook, *Learning to See: Value Stream Mapping to Create Value and Eliminate Muda*, The Lean Enterprise Institute, Cambridge, 2008.

43. Tapping, D., T. Luyster, and T. Shuker, *Value Stream Management: Eight Steps to Planning, Mapping and Sustaining Lean Improvements*, Productivity Press, New York, 2002.

44. Erlach, K., *Wertstromdesign: Der Weg Zur Schlanken Fabrik*, Springer-Verlag, Heidelberg, 2010.

45. Erlach, K., "Increasing Energy Efficiency Using Energy Value Stream Mapping", in *National Energy Efficiency Conference and EENP*, 2011, No. May, pp. 1–30.

46. Reinhardt, S., "Energy Value Stream Mapping", *Berkeley University of California-Institute for Machine Tools and Industrial Management*, 2011.

47. Belton, V. and T. j. Stewart, *Multiple Criteria Decision Analysis: An Integrated Approach*, Springer Science+Business Media Dordrecht, 2002.

48. Woolley, R. and M. Pidd, "Problem Structuring-A Literature Review", *The Journal of the Operational Research Society*, Vol. 32, No. 3, pp. 197–206, 1981.

49. Sterman, J. D., *Business Dynamics: Systems Thinking and Modeling for a Complex World*, Irwin/McGraw-Hill, Boston, 2000.

50. IBISWorld, "Global Footwear Manufacturing Industry Report", 2010.

51. Lawrence Berkeley National Laboratory, "China Energy Databook Version 7.0", California, 2008.

52. U.S. DOE, "Manufacturing Energy Consumption Survey (MECS)-2010", Washington, 2013.

53. TEDAŞ, "2010 Turkey Electricity Distribution and Consumption Statistics", 2010, http://www.oib.gov.tr/tedas/tedas.htm, [Accessed September 2014].

54. Koç, E. and E. Kaplan, "An Investigation on Energy Consumption in Yarn Production with Special Reference to Ring Spinning", *Fibres &Textiles in Eastern Europe*, Vol. 15, No. 4, pp. 18–25, 2007.

55. Hasanbeigi, A., "Energy-Efficiency Improvement Opportunities for the Textile Industry", 2010.

56. Pellegrino, J. L., N. Margolis, M. Justiniano, and M. Miller, "Energy Use , Loss and Opportunities Analysis: U.S. Manufacturing & Mining", California, 2004.

57. Takei, Y., "Energy Saving Lighting Efficiency Technologies", *Science & Technology Trends Quarterly Review No.32*, pp. 59–71, 2009.

58. Southeast Asia Network of Climate Change Focal Points, "Energy Efficient Lighting System (Industries, Public Utilities & Residential Buildings)", 2010.

59. Navigant Consulting Inc., "2010 U.S. Lighting Market Characterization", California, 2012.

60. Energy Manager Training, "Energy Efficiency in Electric Utilities", New Delhi, 2005.

61. Saidur, R., "A Review on Electrical Motors Energy Use and Energy Savings", *Renewable and Sustainable Energy Reviews*, Vol. 14, No. 3, pp. 877–898, 2010.

62. International Energy Agency, "Tracking Industrial Energy Efficiency and CO2 Emissions", Paris, 2007.

63. Fleiter, T., W. Eichhammer, and J. Schleich, "Energy Efficiency in Electric Motor Systems: Technical Potentials and Policy Approaches for Developing Countries". Vienna, 2011.

64. UNEP, "Energy Efficiency Improvements for Motors & Its Drive Systems", 2011.

65. EASA, "The Effect of Repair/Rewinding on Motor Efficiency", St. Louis, 2003.

66. Chan, D. Y.-L., K.-H. Yang, C.-H. Hsu, M.-H. Chien, and G.-B. Hong, "Current Situation of Energy Conservation in High Energy-consuming Industries in Taiwan", *Energy Policy*, Vol. 35, No. 1, pp. 202–209, 2007.

67. Kong, L., L. Price, A. Hasanbeigi, H. Liu, and J. Li, "Potential for Reducing Paper Mill Energy Use and Carbon Dioxide Emissions Through Plant-wide Energy Audits: A Case Study in China", *Applied Energy*, Vol. 102, No. December 2011, pp. 1334–1342, 2013.

68. Ibrik, I. H. and M. M. Mahmoud, "Energy Efficiency Improvement Procedures and Audit Results of Electrical, Thermal and Solar Applications in Palestine", *Energy Policy*, Vol. 33, No. 5, pp. 651–658, 2005.

69. Consortium for Energy Efficiency, "Motor Planning Kit-Strategies, Tools, and Resources for Developing a Comprehensive Motor Management Plan Version 2.2", 2012.

70. Waide, P. and C. U. Brunner, "Energy-Efficiency Policy Opportunities for Electric Motor-Driven Systems". Paris, 2011.

71. U.S. DOE, "The MotorMaster+ Software Tool", Washington, 2010.

72. European Commission Joint Research Centre, "The European Database of Efficient Electric Motors", 2007, http://re.jrc.ec.europa.eu/energyefficiency/eurodeem/index.htm, [Accessed May 2013].

73. Natural Resources Canada, "Technical Fact Sheet CanMOST- Canadian Motor Selection Tool", 2004.

74. Mckane, A., J. Mollet, R. Aylwin, P. Bertoldi, J. Cockburn, and C. Cockrill, "IMSSA : Creating an International Standard for Motor Software", in *Energy Efficiency in Motor Driven Systems-4th International Conference*, 2005, No. September.

75. U.S. DOE, "Energy Tips: Motor Systems Tip Sheet #5 - Replace V-Belts with Notched or Synchronous Belt Drives", 2012.

76. CEA Technologies Inc. (CEATI), "Compressed Air Energy Efficiency Reference Guide", 2007.

77. Lawrence Berkeley National Laboratory and Resource Dynamics Corporation, "Improving Compressed Air System Performance: A Sourcebook for Industry", Washington, 2003.

78. U.S. DOE, "Energy Tips-Compressed Air Tip Sheet #1: Determine the Cost of Compressed Air for Your Plant", Washington, 2004.

79. Falkner, H. and M. Slade, "Categorising the Efficiency of Industrial Air Compressors", in *6 th International Conference eemods ' 09 : Energy Efficiency in Motor Driven Systems*, 2010, Vol. 2, No. September 2009, pp. 651–654.

80. U.S. DOE, "Energy Tips-Compressed Air Tip Sheet #3: Minimize Compressed Air Leaks", Washington, 2004.

81. Kaya, D., P. Phelan, D. Chau, and H. İ. Saraç, "Energy Conservation in Compressed-air Systems", *International Journal of Energy Research*, Vol. 26, No. 9, pp. 837–849, 2002.

82. U.S. DOE and Resource Dynamics Corporation, "Improving Pumping System Performance: A Sourcebook for Industry", Washington, 2006.

83. U.S. DOE, Hydraulic Institute, and Europump, "Variable Speed Pumping: A Guide to Successful Applications", Washington, 2004.

84. UNEP, "Energy Efficiency Guide for Industry in Asia: Pump & Pumping Systems", 2006.

85. Sustainability Victoria, "Energy Efficiency Best Practice Guide: Compressed Air Systems", Melbourne, 2009.

86. Kaya, D., E. A. Yagmur, K. S. Yigit, F. C. Kilic, A. S. Eren, and C. Celik, "Energy Efficiency in Pumps", *Energy Conversion and Management*, Vol. 49, No. 6, pp. 1662–1673, 2008.

87. Towsley, G. S., "Assessment and Optimization of Pumping Systems in Commercial Buildings", in *International High Performance Buildings Conference*, 2010.

88. Lawrence Berkeley National Laboratory and Resource Dynamics Corporation, "Improving Fan System Performance: A Sourcebook for Industry", Washington, 1989.

89. Radgen, P. and C. Schmid, "Market Study for Improving Energy Efficiency for Fans", Karlsruhe, 2002.

90. Nash, M. A. and S. R. Poling, *Mapping the Total Value Stream: A Comprehensive Guide for Production and Transactional Processes*, Taylor & Francis, New York, 2008.

91. Erlach, K. and M. Lickefett, "Energiewertstrom Zur Steigerung Der Energieeffizienz". Stuttgart, 2014.

92. Shannon, C. E., "A Mathematical Theory of Communication", *The Bell System Technical Journal*, Vol. 27, pp. 379–423, 1948.

93. Kendall, M. G., "A New Measure of Rank Correlation", *Biometrika*, pp. 81–89, 1938.

94. Pihur, V., S. Datta, and S. Datta, "RankAggreg, an R Package for Weighted Rank Aggregation", 2014.

95. Erlach, K. and F. I. Produktions-, "Steigerung Der Energieeffizienz Mit Der Energiewertstrom-Methode". Stuttgart, pp. 1–38, 2012.

96. Lusk, E. J. and J. S. Neves, "A Comparative ARIMA Analysis of the 111 Series of the Makridakis Competition", *Journal of Forecasting*, Vol. 3, No. 3, pp. 329–332, 1984.

97. Hyndman, Rob J. Athanasopoulos, G., "Forecasting: Principles and Practice", *Online Open-Access Textbooks*, 2014, https://www.otexts.org/fpp/8, [Accessed September 2014].

98. Ziylan Group, "Ziylan Group Web Page", 2014, http://www.ziylan.com.tr/en, [Accessed August 2014].

99. Danese, G., S. Dulio, M. Giachero, F. Leporati, and N. Nazzicari, "A Novel Standard for Footwear Industrial Machineries", *IEEE Transactions on Industrial Informatics*, Vol. 7, No. 4, pp. 713–722, 2011.

100. C. & J. Clark Ltd., *Manual of Shoemaking*, Clark, Bristol, 1989.

101. Cheah, L., N. D. Ciceri, E. Olivetti, S. Matsumura, D. Forterre, R. Roth, and R. Kirchain, "Manufacturing-focused Emissions Reductions in Footwear Production", *Journal of Cleaner Production*, Vol. 44, pp. 18–29, 2013.

102. Office of Environment and Heritage, "Energy Saver: Energy Efficient Lighting Technology Report", State of NSW, Sydney, 2012.