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SUSTAINABLE RESOURCE UTILIZATION IN MANUFACTURING OF PRINTED CIRCUIT BOARD ASSEMBLY: EXERGY ANALYSIS OF THE PROCESS

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ABSTRACT OF THE THESIS

SUSTAINABLE RESOURCE UTILIZATION IN MANUFACTURING OF PRINTED CIRCUIT BOARD ASSEMBLY: EXERGY ANALYSIS OF THE PROCESS.

Engineering for sustainable development requires prudent utilization of resources under economic, environmental and societal constraints. Resource utilization must follow a holistic approach. This brings in a need for comprehensive metrics which are simple, standard and universal. Thermodynamics may offer a metric that focuses on both quality and quantity of energy resources which may carry information to be combined with other metrics. This metric may be a thermodynamic property called exergy or available energy, which provides a better insight into resource use in both energy and non-energy producing systems. This thesis is devoted to a study of the exergy concept in manufacturing.

A high volume PCB assembly, manufactured in a state of the art soldering facility is chosen for the study. Various mass and energy resources flowing through the production line were quantified in terms of exergy. On the basis of exergy content and exergy utilization in the production process, the sustainability in terms of resources use is discussed. An early version of this approach was presented at the International Symposium on Sustainable Systems and Technologies, IEEE, Washington DC, in May 2010.

KEYWORDS: Exergy Analysis, PCB Manufacturing, Sustainability Assessment, Soldering process sustainability,

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2nd December, 2010

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Subramaniam Saiganesh

The Graduate School

University of Kentucky

2010

SUSTAINABLE RESOURCE UTILIZATION IN MANUFACTURING OF PRINTED CIRCUIT BOARD ASSEMBLY: EXERGY ANALYSIS OF THE PROCESS

THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in
Mechanical Engineering in the College of Engineering
at the University of Kentucky

By

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Lexington, Kentucky

2010

For Peace and Prosperity of Mankind…

Anbae Sivam
(Love is GOD)

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS USED

(Arranged in alphabetical order)

A - Cross-sectional Area

C - Specific heat of the material

h - Specific Enthalpy

$\dot{H}$ - Total enthalpy flow rate

i - Inlet port or entry conditions

I - Current

j - Outlet port or subsystem exiting condition

k - Constituent Material or element index

$\dot{m}$ - Mass flowrate

n - Subsystem index

P - Pressure

Q - Heat

T - Temperature

t - Time

s - Specific entropy

S - Total entropy

V - Voltage (electrical calculations)

$\dot{V}$ - Volumetric flow rate

v - Specific volume (in work calculations)

v - Velocity of the flow

W - Work

W_E - Electrical work

$\dot{W}$ - Power

ρ - Density of the material

Φ - Phase (electrical calculations)

ε - Available energy or Exergy

λ - Unaccounted energy flows

$\delta\varepsilon$ - Exergy loss or destroyed.

LIST OF FILES

1. ETD Thesis.pdf

1. Introduction to Sustainability

1.1 Sustainable Manufacturing of Printed Circuit Boards (PCB)

1.1.1 Resource Utilization & Sustainable Engineering

Sustainable development is the most widely used term, which has pulled the interest of scientific community across a wide spectrum of professions. With rapid evolution of industrialization, the shortage of resources and need for alternate sources was experienced in many industries like automobiles and electronics, which dominate the lifestyle of the people. Since the energy crisis of 1970s, the necessity for energy conservation and means to efficiently utilize the energy resources are highly prioritized among many other engineering concerns. All these consequences lead to a compelled thrust for sustainable development, a mandatory focus of engineering sphere in twenty first century.

When we talk about energy conservation and utilization, understanding of current scenario is absolutely essential to propel towards better future. Burning of fossil fuels like coal and oil generates most of the energy requirement of the globe. They contribute about 70% of the total power generation in a developed and energy craving countries like United States (USEIA, 2009). Burning of fossil fuels has resulted in other apprehensions like global warming and more harmful pollution concerns. This questions the efficiency and effectiveness of the traditional practices and prolonged lifestyles. Are the current procedures and manufacturing techniques are really worthy to continue?

To simply illustrate that current situation, the automobiles of mid seventies and eighties are today considered as gas-guzzlers and not any more favorite of the consumers. Today, the market is oriented towards an economic product, which helps the communities to live better (ACEEE, 2010). The entire industrial complex is clamoring for green manufacturing where ecological imbalances are minimized during and after the end of life of the product. But to pursue on this mission, there is a need for a metric to assess the current situation and rectify the shortcomings. In this research work, a potential of one such metric called exergy, which may be considered as being more realistic and unbiased, is assessed in a manufacturing environment.

Within the manufacturing science, the product quality is defined as ability to serve its function and fitness to use (Harvey L., 2004-9). Function is the objective of the utility for which the product is designed. Lean manufacturing guides towards the most economic practices mostly within the prescribed functions of the product and associated production systems in an identified manufacturing zone (Feld, 2001). The economic aspects under scope of lean manufacturing include cost of failure, fatigue and reinforcements by overstocking and unwanted wastes in the manufacturing environment. Lean manufacturing principles help in optimizing the resources and provide efficient handling of materials within a prescribed manufacturing location. But imprints of the resources associated with manufacturing are far stretching beyond the manufacturing zone.

A life cycle of a product begins from extraction of the resources from the environment. All the material and energy resources are extracted from the environment (land, water and air) and they are processed to a required form and utilized in manufacturing a product. This product serves it’s utility by performing the designed functions and at the end of life is may be discarded back into the environment. All along its life cycle, it has many interactions with the environment that include other living communities of this earth. So all these interactions with the environment should be safe and be free of threats to the livelihood of living organisms. This adds another constraint to product and process designs, which were initially focused only on the economic aspect of manufacturing. The trepidations of environmental hazards and societal factors are to be addressed along with the economical aspect of the product. This idea of a holistic development in engineering is termed as the engineering for sustainable development (WCED, 1987).

Resource utilization is one of the key factors of engineering sustainability. The attributes of sustainability depend on the characteristics of the resource associated and methods of the resource usage. So the objectives of the sustainable engineering could be ascribed towards resource utilization in manufacturing. But the extent of contribution of this factor may vary from case to case. In other words, the sustainable engineering may also be defined as a prudent utilization of resources for the economic, environmental and societal benefits. But to quantify and evaluate the resource utilization during a product lifecycle, a simple and fundamental metric is required.

In general, the laws of thermodynamics may govern all the interactions between the resources and systems considered. By understanding the thermodynamics of resource utilization, its use can be quantified in terms of a new concept called exergy or available energy. In this research work, potentials of using exergy as a metric to evaluate the manufacturing process for a sustainable development are studied on an identified Printed Circuit Board (PCB) assembly. An early version of this approach was presented and published in International Symposium on Sustainable Systems and Technologies, IEEE, Washington DC, in May 2010 (Saiganesh, S. et al., 2010).

1.1.2 Need for Sustainable Engineering in PCB assembly

With thrust towards miniaturization of electronics, the PCBs are becoming very essential part of all latest electronic gadgets and assemblies. With development of semiconductor electronics, the sizes of all essential electronic components were greatly reduced to typically few milligrams only. Printed Circuit Boards efficiently package all electronic components of the circuit within a small space.

The PCB assembly consists of the printed wiring board which has the circuit design imprinted. On to this circuit, the components are assembled to complete the circuit. The construction of a printed wiring board has three major constituents. They are (1) fabric, (2) resin and (3) metal foil. The fabric is the substrate, which holds the body together and provides rigid support. It is usually electric grade glass fibers and paper upon which flame-retardants are coated. Resin is a dielectric medium between the copper strip and substrate. They are mostly thermosetting plastic. Commonly used resins include epoxies, polyamides and polytetrafluoroethylene (PTFE) (Harper, 1994). Metal foil is the conducting material, which is usually copper. The foil is initially clad to the board and later etched out to make the desired circuit.

The electronic network on the circuit can include a very wide range of components, depending on the circuit design. Common electronic circuits include resistors, capacitors, inductors, diodes, transistors and integrated chips. Most of commercial semiconductors are made from silicon chips. Small quantities of various metals and chemical substances are also added. All these complex material resources help moving towards miniaturization of electronics, but on the other side they hinder waste management and accelerate depletion of secondary resources like process materials and energy resources.

In a globalized economy, the regulations enforced in one part of the world impact the manufactured products beyond geographical boundaries. With alarming increase of waste electrical and electronics equipments (WEEE), their material composition may pose a great hazard at the time of disposal. Usage of various heavy metals and synthesized chemical compounds in making of various components are the major concern for dumping of the wastes in a landfill. The leaching properties of the heavy metals like lead and mercury contaminate the underground water table. For example exposure to lead can cause varied health disorders like vomiting, fatigue, convolutions, irritability, but also a greater damage like kidney failure, coma or even death in case of small children. Lead exposure can affect the unborn children in pregnant women (Health Canada, 2008). Exposure to mercury causes tremors, impairing of cognitive skills etc. (US EPA, 2009[1]). Hence the disposed electronics components are to be considered as toxic wastes, which are to be regulated at disposal after use.

By Resource Conservation and Recovery Act (RCRA) of US Congress, toxicity characteristic (TC) of a material in the waste is considered as a metric to assess the leaching phenomena of hazardous material. US Environment Protection Agency (EPA) is the authorized body to set norms and monitor the leaching of toxic elements in the landfills in United States. According to USA EPA, any waste, which is ignitable, corrosive, reactive or toxic, can be considered as hazardous waste. US EPA also lists the maximum allowed toxic characteristic for various contaminants in landfill (USEPA, 2009[3]).

In Basel convention of 1989, PCBs are identified as carriers of hazardous elements and compounds and therefore disposal of discarded PCB along with electronic wastes are to be monitored and handled efficiently (Basel convention). The hazardous chemicals in a typical PCB assembly include lead, cadmium, mercury, arsenic and polychlorinated and poly-brominated biphenyls. US EPA Toxic characteristic limits for the hazardous chemicals are listed in the table below.

Table 1.1: Toxic Characteristic limits of hazardous chemicals in PCB assembly (USEPA, 2009[3])

Waste Code	Chemical (Symbol)	Allowed toxic characteristic concentration (mg/L or PPM)
D004	Arsenic (As)	5.0
D006	Cadmium (Cd)	1.0
D008	Lead (Pb)	5.0
D009	Mercury	0.2

According to various studies, the lead concentration in toxic characteristic leaching procedure (TCLP) carried out in PCB assemblies used in computer CPUs ranged about 100 to 200 mg/L (Townsend et al, 2001). It is observed that average lead leaching is about 40 mg/l for a typical 15.8g PCB assembly used in a computer CPU. Concentration of lead in the leachate increases with the mass of PCB assembly. These values are way above the permitted limit of 5mg/L. The main source of lead in PCB assembly is lead based solder used for assembling the components on the board.

With increase in usage of electronic products, the proportion of discarded electronic goods in municipal wastes has also increased very rapidly. On an average, the WEEE constitutes about of 8% of municipal wastes (The Economist, 2005). According to EPA study, in 1997 a total of about three million tons of e-wastes were disposed in landfills

(Gable and Shireman, 2001). With swift advancement of technology and increased enhancement of features in electronics products, there is big drop in the average life of products. In 2005 it is estimated that the average life of CPU in PCs has reduced to two years from initial estimates of five years in 1997 (Widmer, R., et al., 2005). This pushes towards increased proportions of obsolete products in the wastes. According to an estimate, in 2004 the total number of obsolete PCs across the globe is about 100 million units.

Certain developed countries, which were aware of the environmental hazards associated with e-wastes, initially tried to push them to the developing world like China, India and few African nations. But Basel convention on trans-boundary movement of hazardous wastes prohibits the movement of e-wastes from waste generating country to a developing country and recommends the generating states to take the responsibility to treat these wastes (Basel convention, 1989). Moreover the fast growing economies are also competing with the developed world in resource consumption and waste generation. It is estimated that domestic volume of e-wastes (WEEE) generated in India is at 146,000 tons and expected to grow rapidly (CII, 2006). All these factors limit the waste handling options of the generating states. In line with these views, European Union’s WEEE regulation of 2002, urge for extended producer responsibility and mandatory take back by the manufacturers themselves (WEEE Directive, 2002).

Along with WEEE directive, European Union also passed the Restriction of Hazardous substances (RoHS) directive, which prohibits and limits the usage of hazardous substances in consumer products. The six hazardous chemical identified are lead, mercury, cadmium, hexavalent chromium, poly-brominated biphenyl and polybrominated diphenyl ether. Usage in consumer electronics is restricted to a maximum allowed concentration is 0.1% by mass of each homogenous material which could be separated from the assembly (RoHS directive, 2002). Similarly USEPA has identified thirty one hazardous chemicals and compounds as priority chemicals (PCs), including lead, mercury, biphenyls and dioxins. Productions of these chemical compounds were annually monitored at industrial facilities and initiatives were undertaken towards elimination of PCs in products and wastes at source by substitution, and substantial reduction through recovery and recycling efforts (USEPA, 2009[3]).

By these initiatives, the overall quantities of toxic substances like lead, mercury, and cadmium in wastes are controlled. Presence of Polybrominated biphenyls and di-phenyl ethers hinders recycling of plastics and so by controlling these elements recycling of discarded plastics is also enhanced. All individual manufacturers were forced to make their own material use policies and guidelines, which encourages more transparency and accountability on the manufacturers.

With restrictions on lead usage, the emphasis for lead free soldering is very much augmented. But lead free alternatives have their limitations in terms of energy usage and also enforce few critical changes in the component designs. Depending on the alternate solder composition, to improve the mechanical characteristics of the joint, component leads are to be coated with tin or other metals. Since lead free solders need higher melting temperature, the delicate components on the board are to be provided with heat shields. Although these efforts increase the overall cost, since July 2006 lead free soldering is mandatory in Europe and Japan.

These regulations and other environmental concerns haunt sustainability of PCB assemblies in long run. Thereby manufacturing of PCB assemblies has drawn the focus of engineering research communities. In the efforts reduce the resource intensity and environmental impacts, the recycling and remanufacturing options are to be further explored. Along with elimination of hazardous chemicals, like lead and biphenyls, the intensity of secondary resources associated with manufacturing process like energy, process materials etc. also to be further investigated.

1.1.3 Assembling of PCB by soldering process

The soldering is the joining technique very widely used for packaging the electronic components on to the printed wiring boards. In this process, a low melting point solder alloy is used to join the component terminal leads with the wiring board at desired locations (pads). The three most popular inline soldering furnaces used in mass production are:

1. Reflow soldering
2. Wave soldering
3. Pot / Selective soldering.

Reflow soldering

In reflow soldering, the solder along with the flux are taken in the form of paste, which is applied on the pads. Then the surface mountable electronic components are stacked over pads. In conventional reflow ovens, this entire unit is heated to the melting point of the solder through preheating and flux activation stages. Flux helps to prepare the surface and enable better soldering at the joints. Entire heating is carried in a nitrogen gas atmosphere, which prevents oxidation at higher temperatures.

The surface mount components, which are reflow soldered have shorter terminal leads compared to the through hole components. This help to save the material resource requirement of the components. But in reflow soldering, the entire mass of the circuit board gets heated through various chambers of the furnace. A typical furnace has three stages, namely preheating, reflow and cooling. In preheating stages, the board and components are pre heated, which helps to activate the flux in the solder paste.

In many latest production ovens, the heat transfer is by both radiation and convection. The heating coils located in the heating zones are the resistive heaters which work by joule heating principle. Radiative heat transfer is easier to control but heating depends on the emissivity and absorptivity of the associated materials. The sensitive materials in the board are usually coated with reflective material and thereby their temperature may be better controlled (Vianco P.T., 2000). The convective heat transfer is through the nitrogen medium. The rapid flow of gases guided through baffles help to improve uniform heating of products.

The preheated components are then passed through the reflow chamber, where they are rapidly heated to the melting temperature of the solder. In this section of the furnace, the molten solder makes joint between the terminals and pads. The temperature is sustained for small duration to enable uniform spreading of the solder on the joining surface. Then thermal energy is slowly recovered from the product as it passes through the cooling chamber. The cooling chambers are the heat transfer units, where the thermal energy from the surrounding gas is removed by using running water and air. As the heat is exchanged, the product is cooled to a temperature slightly higher than the room temperature.

Wave and Pot Soldering

In wave soldering, the terminal leads of the electronic components are located at the holes on the board. The board with the through-hole components on it is passed over a fountain of molten solder alloy. So only the leads come in contact with molten solder, which flows through the gap between the lead and board by capillarity principle. In this process also the flux is applied to the joining surfaces before soldering.

Pot/Selective soldering is also very similar to wave soldering, where molten solder is available in a pot, in which the leads are dipped enabling the solder to flow through the hole. The solder alloy which is available in the form of coils is taken and is melted in the pot. The molten solder in a pot is maintained at higher temperature to prevent localized solidification of the solder. Similar to reflow soldering, the parts are preheated for activation of the flux. To prevent oxidation, the entire soldering operation is carried out in nitrogen atmosphere.

Solder alloy

As the soldering process involves a heating till melting point of the solder alloy, its energy intensity depends on the type of solder alloy used. Generally for uniform melting, eutectic alloys are preferred for solders. Numerous solder alloys are available in the market, with melting point ranging from 95^{o}C to 320^{o}C (Vianco, 2001). But most widely used is the Sn-37Pb alloy which has a well-defined and relatively low melting point of 183^{o}C. Sn-Pb solders have very good wetting and spreading characteristics with Copper, which results in good mechanical strength of the soldered joint. They also have very good thermal reliability to withstand up to 1000 cycles of thermal loading between -65^{o}C to

125^{o}C. Not many other solder alloys possess these fine points, thereby making Sn-37Pb alloy as the most preferred.

Presence of lead in the alloy makes Sn-37Pb alloy, makes it potentially harmful and it needs to be phased out of use. Tin offers good conductivity, low melting temperature and good wettability characteristics and thereby tin alloys are considered. Among various lead free alternatives, the most effective replacements are tin alloys with 2-4% of silver and up to 1% of copper. But these alternatives have higher melting point than Sn-37Pb and perform poorly in terms of wetting and spreading characteristics. These factors affect the mechanical strength and reliability of the solder. Higher melting temperature intensifies energy requirements for the soldering process. On the other hand, in order to improve the mechanical strength of the joint, suitable coatings are required on the soldering surface and terminals of the components. All these lead to an increased utilization of resources.

Energy Utilization

As explained, the soldering process involves heating of parts to higher temperatures and cooling down to room temperature. Because of heat transfer losses and inherent limitation in the process, the energy invested for heating is not available for any further use. In conventional manufacturing setup, the energy carried by exhaust gases, water and the soldered assembly are dumped to the environment by ultimate equalization of temperatures. In continuous production setup, the heat loss during normal production is very common. Because of continuous movement of parts in and out, the heating process cannot be adiabatic. So, the heating coils are to be switched on and off at high frequency to optimize the heating. With the assistance of micro-controllers and PLC circuits, the heaters are controlled precisely with minimum manual intervention.

In case of wave and pot soldering, during normal production the quantity of solder in the pot is to be kept molten irrespective of parts flow. It usually takes very long time to start the furnace from a cold condition, and so they are operational continuously. The energy investment for this non -productive activity usually gets added to the energy capital of the product.

Apart from energy investment, the process also has few additional features which are necessary to improve the productivity and efficiency. Common auxiliary materials associated with soldering process are compressed air, flux, inert medium (gas) and coolant (water). The conveyors and parts handling systems are mostly mechanical conveyors run by a pneumatic system. Let us consider each of these auxiliary flows.

Flux

Flux is a chemical which prepares the surface and prevents oxidation during/after preheating. They help to improve the wetting and spreading characteristics of the solder. Their primary constituents of the flux include corrosive and wetting agents mixed with a water or alcohol. Higher solid contents in the flux may result in residues after soldering, which may necessitate a separate cleaning process. Fluxes with low solid content (as less as 5%) may leave no or very less residue. The corrosive agents disrupt and remove the oxide layer on the substrate metal, while wetting agents help to reduce surface tension of the solder (which improves the wetting and spreading characteristics of the molten solder). In many cases, fluxes also provide a barrier coating on the surface, which helps to prevent oxidation while preheating. Rosin based fluxes, which are commonly used in

PCB assembling are activated at a temperature approximately 130^{o}C.

In reflow soldering, the fluxes are mixed with solder and used in the form of solder paste. In other applications, they are separately applied on the surface before soldering. Effectiveness of fluxes can be improved with increased temperature but on overheating, they can lose their stability and begin to decompose. Thermal decomposition degrades the fluxing action. All fluxes have a preferable, selected range of operating temperature and non-indefinite shelf life. Presence of halide activators makes it absolutely necessary to remove all residues from the product. With introduction of non-halide activators, the above impacts are very much reduced (Vianco, 2001).

The evaporating flux fumes get mixed with the inert medium and are exhausted out to the environment. To reduce the environmental impact, the low boiling vapors are condensed from the exhaust gas and disposed separately. This condensate is one of the harmful waste generated by the process and must be treated separately before discharged to the environment.

Inert medium

To reduce the probability of oxidation during heating, an inert medium blanket is provided for the base materials. The inert mediums commonly used are nitrogen, argon and helium gases. Nitrogen is most preferred because it is the cheapest. Introduction of nitrogen gas in the soldering chamber eliminates the water vapor and reduces oxygen levels to a few hundred PPM. Lowering the partial pressure of oxygen inside the heating chamber favors a reduction reaction on the surface. This helps to remove the oxide layer on the surface.

Extent of nitrogen gas consumption depends on the chamber size and design. The inert medium is very well conserved in batch processing ovens. Because of frequent part movements, the loss of the inert medium to the environment is inevitable in inline furnaces. But they can be minimized with air lock provisions which prevent leakage of gases out of heating chambers.

Coolant

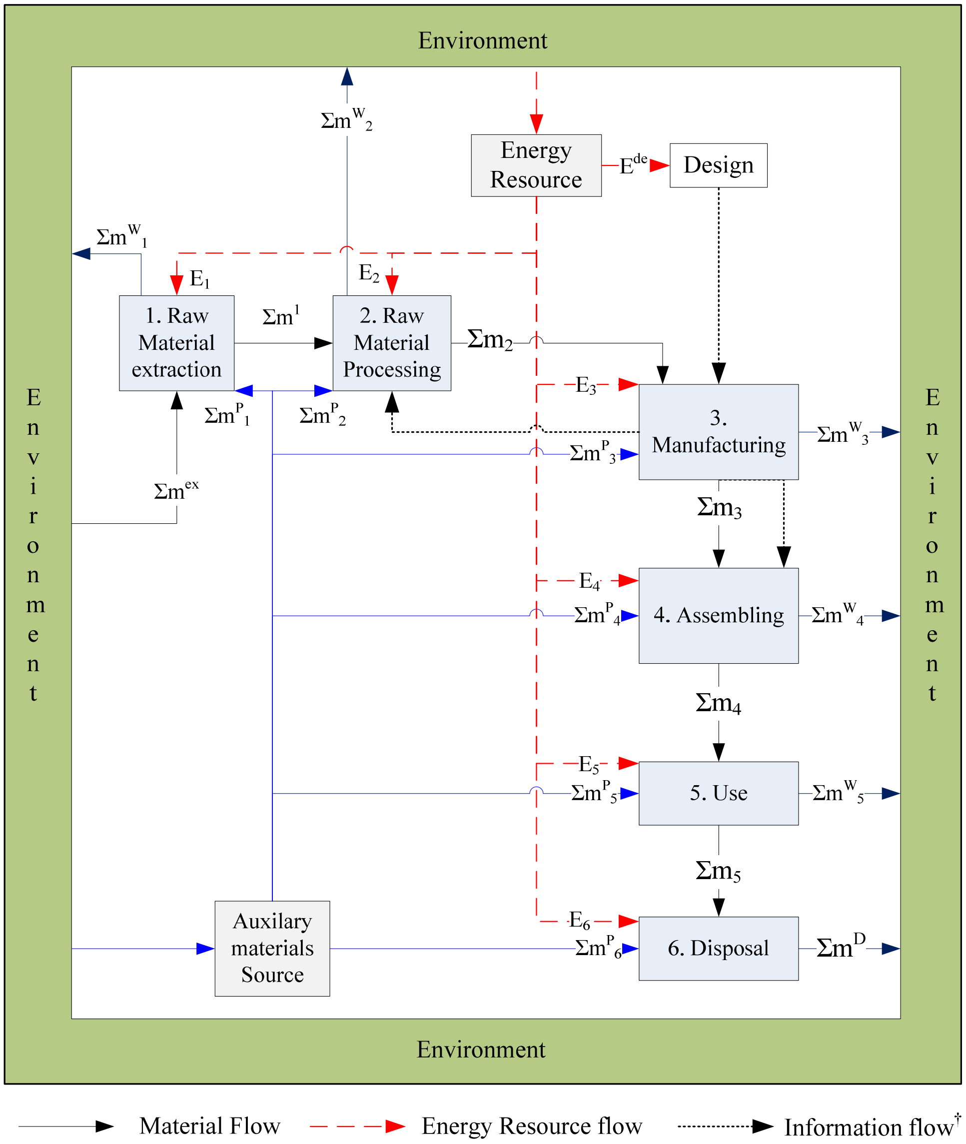
In reflow soldering process, after reaching higher temperatures during soldering, the parts are to be gradually cooled to a temperature near room temperature. The cooled nitrogen and other flux effluents are exhausted to the environment. So, the inline soldering furnace must have a cooling chamber where the heat is removed from the chamber using heat exchangers and fans. Water is used as coolant and it is usually recycled continuously. Some quantities of the coolant may be lost due to evaporation.

These are the major concerns with the resources utilized for soldering processes. The soldering process for the assembling of components onto the PCBs is well established. Since a successful alternate method is not yet established, soldering process is the preferred choice. The product economics gains upper hand over the intensity of these sustainability concerns and thereby the shortcomings continue to prevail in the manufacturing world. Evaluation of these resource consumptions in terms of exergy can help to understand better about their intensities. As a first step towards building sustainable manufacturing techniques, exergy analyzes is carried out in one such state of the art, mass production assembly line.

1.2 Sustainable Lifecycle

1.2.1 Product Lifecycle and Sustainability

Lifecycle of an engineering product can be divided into four phases, namely Pre-production, Production, Use and Post-Use phase. Fig 1.1 explains the resource associations during the lifecycle of a typical engineering product.



m_n – Material Resource required by product at stage 'n'

m^P_n – Auxiliary materials required at stage 'n'

m^W_n – Wastes generated at stage 'n'

m^{ex} – Material resource extracted from environment

m^D – Product mass dumped after end of life

E_n – Energy Resource required at stage 'n'

E^{de} – Energy required for design

Fig 1.1: Resource associations in Product lifecycle

Product lifecycle begins with conceptualization of ideas, which is developed into technical design. This design undergoes various development and validation procedures before getting approved for production. These activities collectively make up the Pre-production phase. Considerable amount energy resources (E^{de}) are required in this phase. A minimal amount of material resource may also be utilized, which is not identified in the Fig 1.1.

Production cycle of a product begins with extraction of resources from the nature. The raw materials ($\sum m^{ex}$) required for the product are extracted by activities like mining from the environment i.e. land, water or atmosphere. This activity may require separate infrastructure which may require auxiliary (process) materials ($\sum m^{P}{}_{1}$) and energy (E_1) resources. This may also produce wastes ($\sum m^{W}{}_{1}$), which is dumped into the environment. Then for refining the raw materials, additional auxiliary material ($\sum m^{P}{}_{2}$) and energy resource, (E_2) may be required. This process may also produce byproducts and wastes ($\sum m^{W}{}_{2}$), which may either continue a separate lifecycle or may be dumped back into the environment as industrial wastes. These processed raw materials ($\sum m^2$) are utilized for manufacturing the necessary subcomponents and associated materials ($\sum m^3$) with the consumption of secondary resources including energy resource (E_3) and auxiliary materials ($\sum m^{P}{}_{3}$). Like the previous stage, this phase may also have process wastes and byproducts ($\sum m^{W}{}_{3}$). These subcomponents and sub-assemblies are assembled into a product ($\sum m_4$), and product enters into Use phase. During its Use phase, product may require energy (E_5) and generate wastes ($\sum m^{W}{}_{5}$) depending on its design and purpose.

At the end of life, the product ($\sum m_5$) enters Post-use phase, where it is dumped in the landfill or disposed into the environment. For a typical consumer product, this is analogous to materials discarded after use. In reality this is not a small number, and as every year pass by it is increasing rapidly. According to USEPA 2008 data, of the 250 million tons of solid municipal wastes, the discarded products (excluding food and other wastes) accounts for 181.14 million tons i.e. about 72.5% (USEPA, 2009[2]).

This is the generic lifecycle of a typical manufacturing product. It could be noticed that all resource interactions during the lifecycle can be assessed in terms of mass and energy units. Unlike representation in Fig 1.1, in all real processes, a significant quantity of energy resources is lost in transfer at each stage, which impacts the overall resource consumption in the lifecycle.

As environment is the principal source for all resources, a resource intense product may have sizable footprint on the environment. Ecological footprint is one of the metrics that helps to assess the human pressure on the environment from the resources consumption data (Schaefer, F., et al., 2006). Moreover, the consumer oriented lifestyles of the developed and developing world accelerate the rate of resource depletion. The per capita eco-footprint of the developed nations is five times of that the rest of the world put together. More alarming forecast is that developing economies are also moving higher on the resource consumption scale (Ewing, B, 2009).

The net quantity of renewable resources offered by the biosphere's regenerative capacity can be termed as Bio-capacity (Schaefer, F., et al., 2006). It actually represents the aggregate output of all the ecosystems of the specified area. With the help of advanced technologies, new alternate resources are discovered or explored, which can help to expand the earth's bio-capacity. But the human demand on the biosphere is also increasing rapidly very rapidly in last forty years. In fact the current human demand on the environment has even surpassed the maximum bio-capacity defined in 2002 (Kitzes, J., et al, 2008). Resource depletion is experienced in many critical fields. These circumstances have urged for viable solutions to manage the resources use. But the solution is not limited to the search of alternate eco-friendly energy resources like solar, wind, geothermal etc. Acute shortage of critical mineral resources is foresighted by many scientific studies. At current rate of exploitation, availability of sufficient resources can be uncertain for the future generations to survive in this world.

On the other side, the disposal of discarded resources during production and use phase is the major concern as it continuously affects the ecological balance and threatens the sustenance of living beings. More than 70% of the global energy resource requirement is met by burning of oil and gas, which results in increased emission of greenhouse gases, causing global warming. The disposal of products at the end of life into landfills also poses serious threats to the environment. Leaching of metals and alloys from landfill contaminates the soil and ground water sources. All these impacts have created an urge for product lifecycle studies.

The very well established practices includes Lifecycle analyzes (LCA), which are holistic approaches to study the environmental aspects and potential impacts all along the product lifecycle, which helps in make informed decisions (ISO 14040:2006),. This is an elaborate process which starts with a defined goal and scope. Goal of LCA, defines the objective or the functional unit of the study in line with the purpose or application of the study. The scope helps to define the boundaries and lists the process not considered for the study. A clear definition of goal and study helps to save resources and time spent on the study (US EPA, 2010).

Then comes the comprehensive data collection phase called as Lifecycle Inventory (LCI). In this phase, an extensive data on quantities of relevant energy and material inputs and their respective discards is collected. The preciseness of the data is very significant for effective decision making in the relevant application, which necessitates extensive knowledge about the resource and the process involved in the chosen lifecycle (Tukker A., 1999). Using this information, optimization of resources for recyclability, waste minimization etc. is facilitated.

Then next stage is about impact assessment with the quantities enumerated in the LCI activity. This phase is about assessing the significance of the numbers or quantities which may affect global aspects (outside the process) like environmental hazards, global warming, pollution etc. The fourth phase is about informed decision making on comparative analysis with other available information, like policy making, alternate resource development, elimination or minimization of harmful substances etc. There are many approach for an LCA, like Economic input output LCA (EIO-LCA), Eco-LCA, Lifecycle energy analyzes (LCEA) etc. All these methods focus on significance of the data generated in LCI with respect to different aspects like economy, ecological footprint, energy utilization etc (Carnegie Mellon University Green Design Institute, 2008).

Although LCA is helpful in comprehensive understanding of various factors of resource use in a product lifecycle, it has few shortcomings as well. The effectiveness of the LCA depends on the goal and scope definition for the relevant application or purpose. And the results depends the depth and extent of the scope and objectives. Although, Life cycle Analysis offers a systematic method to evaluate the environmental impacts, they are resource and time intensive. For assessing certain environmental impacts, the data records over a longer span, say more than 10-15 years may be necessary. So without such extensive information, the assessment may not lead to appropriate results (Finnveden, G., 2000). LCA can only assess potential impacts upon past evidence but cannot exactly predict the outcome. As LCA is a geography depended study and so there can be apprehensions about the availability of required data and their suitability across similar processes (SAIC, 2006).

For widespread industrial application, the method for assessing the resource use should be simple and flexible. The assessment method should be universal for various types of processes and it should be applicable at the level of sub-stages of manufacturing. It should also be very practical and help to find the best direction to proceed for improving resource utilization aspect of sustainability. Exergy analyzes is one such technique, which could be implemented across all processes and thereby it helps to compare and find the better ones.

These lifecycle studies in many cases help to showcase the actual state of existing systems and associated resource intensiveness of manufacturing products and processes. But to improve from the current state, there are various strategies or approaches which may guide towards a sustainable development in the lifecycle of the product.

1.2.2 R-strategies for sustainable development (6R Approach) in Product Lifecycle

For sustainable development, optimum resources are to be utilized in the product lifecycle. The interactions with the environment are expected to be considerably reduced. Across several fields, various methods and procedures have been evolved to uncover the strategies for addressing the sustainability concerns. Among them, one of the widely discussed tactics is often termed as the ‘R-strategies’ or ‘6R approach’. This idea is an expansion of popular three R-terms namely Reduce, Reuse and Recycle, a model for eco-friendly (or green) engineering. From the terms, it could be understood that objectives of green manufacturing include reduction of potentially harmful interactions with environment. It is believed to be achieved by encouraging secondary lifecycles for a discarded resource by reuse and recycling options. But one of the major limitations is reusability and recyclability of the discarded resource. The resources used in the designs of existing engineering products, processes and systems may not exhibit many technically and economically encouraging viabilities. This creates a necessity to generate opportunities to explore within the domains of existing lifecycle.

Along with the existing three options, three new avenues, namely Recover, Remanufacturing, Redesign can be included. These new three R-terms are focused on encouraging the possible means of secondary lifecycles for a discarded resource (Jawahir, I.S., 2006). Depending on the objective and scope of the endeavor, the sustainability efforts can be categorized under different R-terms. But poor interpretation and commonalities of objectives can causes ambiguities between the R-terms. In reality, the R-terms identified in this approach are different avenues for sustainable development that complement and sometimes overlap each other.

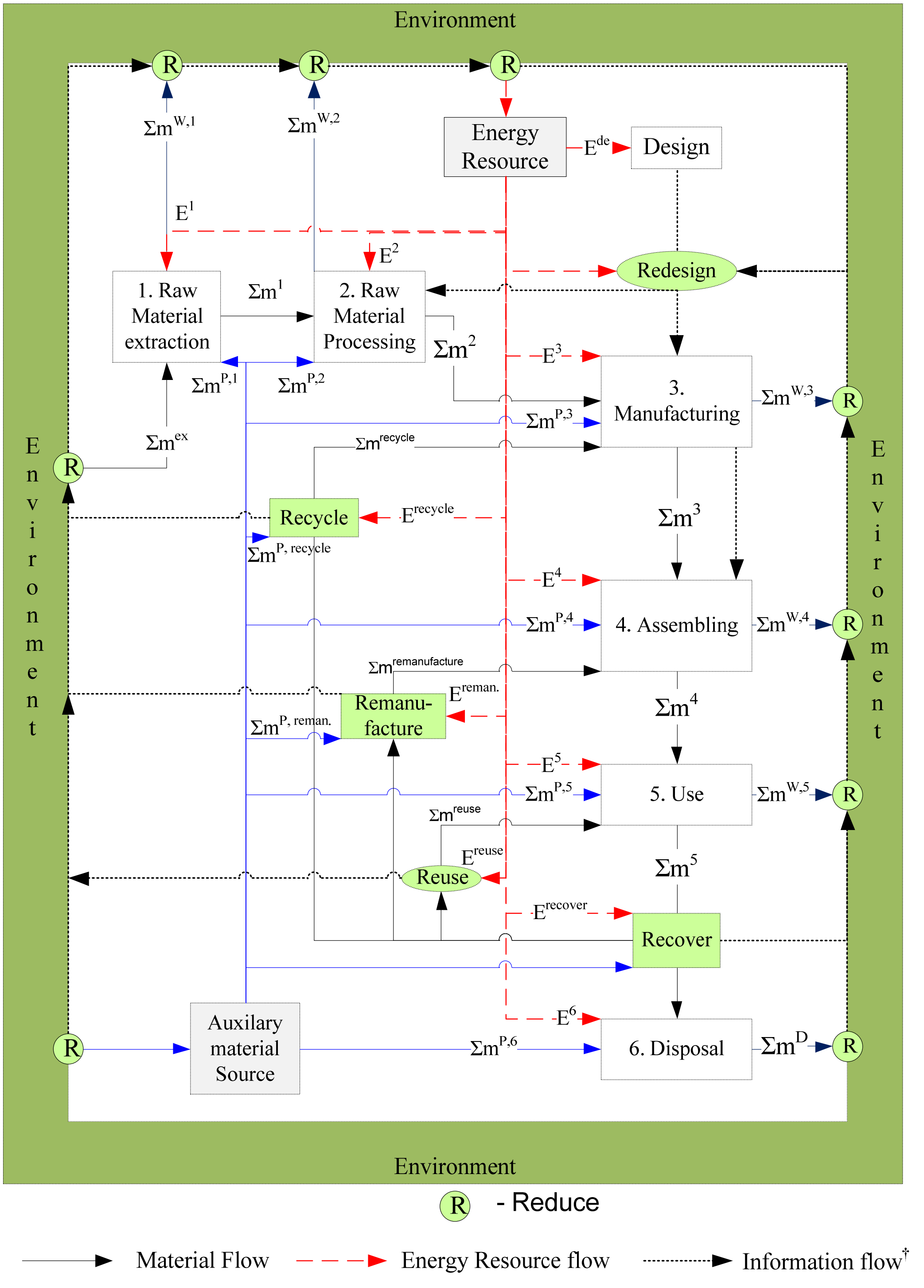
Depending on the product type, these R-term strategies may follow sequential or parallel paths along the product lifecycle for sustainable development. Using these R-terms, the efforts for sustainable development can be streamlined and organized effectively. Employability of these R-terms as parallel avenues for prudent resource utilization in a product lifecycle is discussed in detail in this section (Refer Fig 1.2).

Reduce

Addressing the tenets of sustainable development, namely environmental, societal and economic benefits, the foremost objective will be to reduce the impacts of resources associated with the existing products, processes and systems on the environment. This infers to reduced mining and dumping of resources from/into the environment. As the first step to reduce the impact, various harmful substances have been identified and mandated and/or suggested to limit their usage in the resources associated with products and processes. Directives like RoHS, clearly limit the use of various hazardous substances in consumer products. To reduce the green house gases and energy dependence on oil resources, alternative fuels and eco-friendly methods of power generation are encouraged. Moreover rapid depletion of fossil fuels and mineral resources has enforced a need to build systems that utilize resources prudently for sustainable development.

Another important research front is miniaturization of products, moving towards micro and nano technologies to reduce the material requirement. But in terms of energy usage, the sustainability of nano-scale engineering with current techniques may be energy intensive and needs to be scrutinized (Gutowski, T., 2010). But with focused efforts, eco-footprints of these new technologies may be trimmed.

Yet another important research focus is to extend the use phase of the product through better design, advanced materials etc. But to meet the growing needs, along with reduction efforts, alternate resources are to be identified or generated. The most eco-friendly method would be reusing the discarded resources, which will be the primary focus for the other R-terms for sustainable development.



m^n – Material Resource required by product at stage ‘n’

$m^{P,n}$ – Auxiliary materials required at stage ‘n’

$m^{W,n}$ – Wastes generated at stage ‘n’

m^{ex} – Material resource extracted from environment

m^D – Product material dumped after end of life

E^n – Energy Resource required at stage ‘n’

E^{de} – Energy required for design

† Product and related processes design information

Fig 1.2 R-strategies for sustainable lifecycle of a typical product

Recover

During Pre-Use and Use phases, the wastes and effluents generated are discharged into nearest environmental sinks, like landfills, water bodies or atmosphere. In a cradle to grave cycle, the product itself is sent to landfill after the end of life. These wastes not only disturb the ecosystem, but they are also potential resources. In the year 2008, about 54% of 250 million tons of US Municipal Solid Wastes were discarded after material and energy recovery for recycling (US EPA MSW 2008 Facts, 2009).

In the first place, all these resources are to be recovered. Mandatory *take-back policies* are administered in European Union. In USA and Japan, the manufacturers are encouraged to take back the older versions, when upgraded products are offered. These initiatives opened up new research interests in the field of a reverse logistics, design for disassembly and modularity etc. (Klausner, M., et al, 2000). Industries like Nokia, Xerox etc. are working towards taking back all outdated and discarded products and accessories, which they are planning to put into another utility.

Special disassembly factories are under evolution, which aims at maximum recovery of resources for a second lifecycle (Seliger, G., 1996). The recovered parts are categorized depending on their potentials for reusing, remanufacturing, recycling and energy recovery options. The discarded resources which cannot be recovered are processed for safe disposal. But the product varieties pose many challenges for effective recovery of all discarded resources.

Reuse

Reuse signifies putting the discarded material directly into another use phase, prolonging its lifecycle. This kind of system is in practice for a long time in spare parts industry. When a product reaches its end of life, all its sub-components need not be in same condition. Many a times, they have a longer service life and find a utility in some other appliance. Compared to recycling and remanufacturing, the secondary resource requirement for reuse option is the least. Compared to the original new product, the material and energy expense to pursue this avenue is almost negligible. But reliability of the reused product is the big question. After the first life cycle, along with the product or material resource many uncertainties on performance and service life come with it.

To enhance the reuse option, improving reliability of the product is very important. A highly reliable component could find a better value in its second lifecycle (Anityasari, M. et al, 2008). With this notion, reliability studies take prime importance which helps to design better products that serve longer. This exercise can be a subset of the efforts to improve fatigue life of the product.

Remanufacture

Remanufacturing is about module level recovery and reusing of sub-assemblies and components from a discarded product. This is one of the vastly discussed modes for prolonging the utility of the product. Moreover, this is the most favorable means for products that failed to serve its full service life and where the extent of damage is reversible or repairable. The products that take up their second lifecycle are notably called by many popular jargons like refurbished, refurnished goods etc. The remanufactured products are expected to serve as good as new products. This activity was in practice for a longtime in production of machine tools, off-road massive vehicles etc which were refurbished and sold to developing countries for after their first lifecycle. Recently this trend is becoming very popular for heavy diesel engines, printer cartridges, many consumer goods and electronic products, etc.

But remanufacturing is very much a product-specific approach and prospectus of remanufacturing is to be considered in the product design phase. For efficient remanufacturing, the need for concepts like modular designs and design for disassembly and remanufacture are all to be applied extensively. Subsequently, the sustainability of existing designs and technology are to be reviewed in line with their prospect for remanufacturing. Often the existing joining processes like welding, soldering etc hinder the prospects of implementing remanufacturing. Economic models are under development to evaluate the significance of remanufacturing on the product features like cost, modularity, etc. for commodities that obsoletes faster like personal computers (Ferrer, G., 1997).

Remanufacturing is more favorable than recycling, because the secondary resource requirement along the remanufacturing route is much lesser than the recycling option. So it should be pursued over recycling options. Although the quality of remanufactured product is expected and assured to be as good as a new one, the market reception for remanufactured goods is uncertain.

Recycle

Recycling for some years was the first choice of a sustainable resource use. Recycling is oriented towards extraction of materials at the level of elements and compounds. In this pursuit, efforts and resources spent on building the forms and shapes of the product are marginalized. As the focus is on material content, not on the forms or quality of the product, it may look simpler than remanufacturing options.

The product is usually shredded and segregated often by mechanical methods. The components separated to their nearest stable states by different method using electro-magnetic and chemical properties. The secondary refining process involves thermo-chemical processes like smelting etc. All these subsequent processes, as a rule may increase the secondary resource requirement. Effectiveness of recycling vastly depends on the quality of the scrap that is recycled. More cleaner is the scrap (devoid of unwanted substances), better are the results in terms of quality, resource capital and cost. These factors signify the importance of resource recovery after disposal.

In assessing the sustainability of a product, the recyclability properties of materials play a major role. For example on recycling, aluminum can undergo about eight lifecycles, whereas steel can successfully undergo only about two or three lifecycles. Thereby making aluminum more preferable than steel. Moreover, using secondary materials (i.e. in their 2nd or more lifecycle) results in higher energy savings in the production process (Das, S. et al, 2007). Recycling also offers a better choice for non-degradable (plastics) and hazardous substances, which dangerously threaten the environment.

But process of recycling is not very glamorous as it appeals. Not many safe and economical methods of recycling were fully established for all kinds of materials in use. It is often considered as dirty and deported to developing countries, where very crude methods were employed. Many cases of poisoning and environmental damages were frequently reported from the recycling zones (Puckett, J., et al., 2002).

Redesign

Product design holds key for its sustainability. Suitable and economical manufacturing processes and associated systems are decided by the product design. Most of the significant character, which affects health, safety, and environmental aspects, are determined at the design stage. This signifies the importance of the product design. For a successful sustainable engineering, existing designs are to be assessed for their sustainability throughout the lifecycle and they are to be suitably redesigned. A complex product design with advanced materials and high end technological requirements has shown greater impact on the environment during the production and disposal stages.

With implementation of RoHS, many hazardous materials were banned or controlled. This initiated a pursuit to identify a suitable, environmentally benign alternative like lead free solders. But implementation of new systems like Pb free soldering, necessitated a chain of changes and up-gradations including redesign of pad sizes, associated fluxes, process parameters, tools, test procedures, etc. All these efforts would finally ensure that the threat is nullified. Similar is the case, when there is a material change from existing to a recyclable material used for a product. Successful implementation of other five strategies are effectively enhanced and controlled in redesign option.

Even after all these efforts, there will always be some residue which needs to be extracted or dumped in to the environment. Designing a hundred percent sustainable product is always a myth like Ouroboros serpent. Ouroboros serpent is an isolated system which survives by eating its own tail. This is possible only when all interactions are purely reversible, which is not possible with real processes. Laws of thermodynamics limit all real processes to have some loss, which is attributed to the entropy generation in the process. With this limitation in place for all available real processes, the objective of sustainability studies should be for utilizing the maximum potential available in a resource. This maximum available potential in a resource can be assessed in terms of exergy. So it becomes evident that exergy studies are essential for understanding the current scenario and work towards the best results, practically possible.

1.2.3 6R approach in Life cycle of Printed Circuit Boards

To explore the tenacity and potentiality of R-strategies, these concepts were applied in the typical lifecycle of printed circuit boards. A typical PCB undergoes a usual ore to landfill life cycle except for very limited recycling options under current practice. In this system, possible avenues are identified and their probable challenges in the current state of technology are briefly explored. Many discrepancies are identified in the existing lifecycle and a sustainable PCB assembly is expected to overcome the discrepancies. Using the R strategies, an ideal lifecycle for PCB assembly is hypothesized (Fig. 1.3) which may open opportunities to resolve the discrepancies. This figure is an extension of Fig. 1.2, which is applicable to the lifecycle of PCB assembly. From the extracted and processed raw materials, various sub components (electronic components) are manufactured and assembled to the board, conventionally by soldering process.

Reduce

With implementation of RoHS and other standards, the manufacturers in electronic industry have moved towards lead-free soldering. Alternative lead-free solders considered are mostly tin based solder alloys with few additives. It is estimated that in USA for the Sn-Pb solders, Tin is consumed at a rate of 9.2×10^6 kg/year. It is also estimated that worldwide switching to lead free solders will increase the Sn consumption by about 60% (Gordon, R.B., et al., 2006). With about 15×10^9 kg of known tin reserves, it may not impact the manufacturing sector in near future. But with current rate of usage, it will not last beyond next century. There is definitely a need to develop systems more efficient systems for reusing and recycling the discarded PCB assemblies. But methods to optimally use the material and energy resource in different phases of PCB lifecycle is the need as identified in Fig 1.3. At the end of life (EOL), to reduce the dumping, the tack-back option is encouraged and possibilities of reuse/remanufacturing/recycling are also envisaged.

Reuse

To reuse, the first stage is to recover the PCB assembly from their respective products. Once it is recover as PCB assembly, the viabilities of reusing the board is to be assessed. But currently the options for reusing of PCBs are very limited because of the uncertainties about the product quality. PCB assembly is made up of numerous minute electronic components mostly consisting of semiconductors and ceramics. Reliability of these components after the first life cycle is uncertain. Each PCB assembly is designed for specific application, with a defined electronic circuit. So, interchangeability of PCB assembly for different products (distinctively different in function) is minimum. Hence component-wise recovery options are to be considered.

Recover

In case of PCB assembly, the soldered joints hinder efficient disassembling of components from the board. Many researches are conducted on building robotics assisted intelligent remanufacturing systems to perform the salvaging operations (Feldmann K., et al., 1995). Except for complicated and costly high-end VLSI chips like processors, other small components do not fetch profitable return on investment. But on building efficient component recovery methods, the possibility of remanufacturing is encouraged.

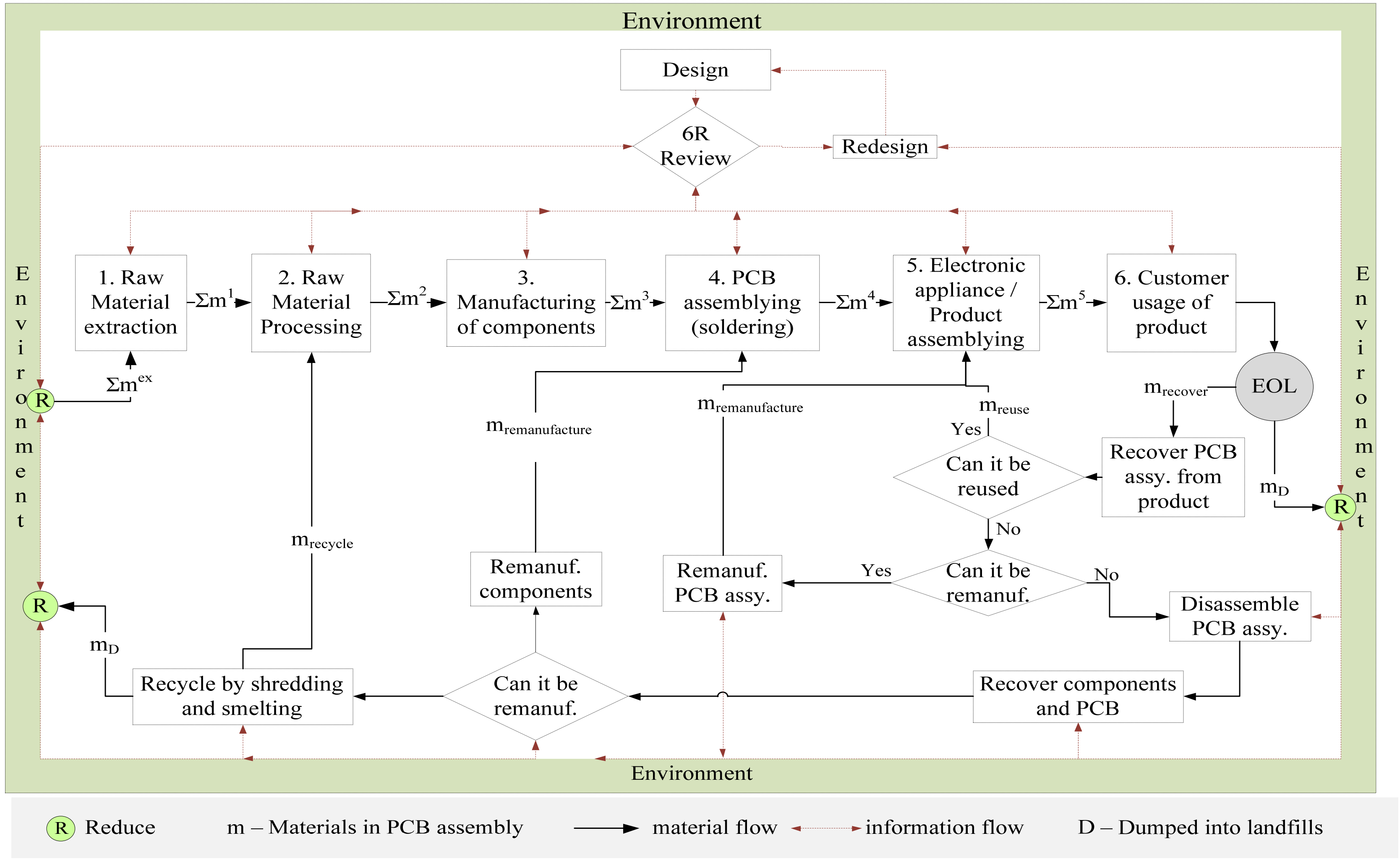


Fig 1.3: R-strategies for sustainable resource utilization in lifecycle of PCB Assembly

Note: The above lifecycle focuses only on product materials. All above stages consumes energy and auxiliary materials as indicated in Fig. 1.2. These resources play important role in product and process sustainability, which are appropriately tackled in different R strategies.

Remanufacture

With good worth for recovered components, the PCB assembly can be remanufactured. So there is an opportunity to study and develop better components that can sustain multiple lifecycles through reuse and remanufacturing. But with existing designs, the worthiness of the recovered components is doubtful. This leaves recycling as the only plausible option to improve the sustainability of PCB assembly.

Recycle

The discarded PCB assemblies are collected from the waste products and undergo special treatment where the recycling options are considered. Most of the PCB waste treatment sites follow non-sophisticated ways to recycle the printed circuit boards. The PCB assembly is heated in open setup to desolder the components, which results in toxic fumes of lead oxide, etc (Puckett, J. et al., 2002). Of all the material contents, only very small quantities like copper and few other precious metals carry good value for investments in recycling. And the rest of it is dumped into the environment. To successfully overcome these hurdles, the most effective approach can be to redesign the existing design of the PCB assembly and manufacturing processes associated with it.

Redesign

The redesigning of the existing product and associated processes can take place at various levels with specific objectives which focuses on sustainable development. In Fig. 1.3, the redesign activity is marked near the design phase to signify the importance of pre-emptive thinking about ecological and economic benefits associated with the complete lifecycle. The lead-free options, reliable designs for secondary lifecycle, design for disassembly, remanufacturing and recycling, are some of the objectives of focus.

But treading these avenues of sustainable development in existing PCB lifecycle can be an arduous endeavor. Probably the best objective to focus will be the resource utilization in the manufacturing of PCB assembly. This needs the auxiliary material and energy requirements of the processes to be optimized along the lifecycle. For that, the maximum of the potentials available from the resources are to be fully utilized. To pursue on these objectives, the current status of resource utilization is to be evaluated with a basic, unambiguous metric. As a first step towards this mission, in this study on PCB assembly, the manufacturing (assembling) stage is chosen for evaluating the sustainability.

1.3 Sustainable Resource Utilization in Manufacturing

1.3.1 Energy and Exergy flows in Manufacturing

The manufacturing processes involve conversion of raw materials into required products at the expense of materials and energy resources. Any manufacturing process requires energy resources to perform the intended function. The association of the secondary materials and energy resources during the lifecycle of the product is explained in chapter 1.2. Manufacturing processes interact with material and energy resources to perform the functions (Fig 1.1).

The depletion of critical resources and the need to conserve was briefly discussed in in previous sections. Optimizing the overall resource use is very significant for resource conservation and sustainable development. But for quantifying the current utilization rate a universal metric is required. The metric must be applicable to all involved processes. It should not give rise to ambiguities and it should be consistent under all situations.

Thermodynamics offers one such metric called available energy or exergy.

Exergy is the maximum available energy of a considered system, which in principle could be fully extracted and converted into useful work (Szarguts, J., 2005). It will be denoted as ‘ε’ and it is measured in joules (J), the same as energy. Exergy of resources interacting with the manufacturing process can be of three forms: (1) exergy of heat flow, (2) exergy of work flow and (3) exergy of material flows. Heat and work are different forms of energy in transition. Material resources can carry different form of energies like the potential energy, kinetic energy, thermal energy (enthalpy), chemical potentials etc. If these properties are represented as extensive properties, the total value will be proportional to their mass or mass flow rate. But the associated energy quantities are not necessarily fully available for exploitation. Thermodynamic principles help to quantify and evaluate the portion of energy which is available for further use. By using exergy as metric, any resource interacting with a defined system can be quantified in suggested manner. Thereby all resource interactions of a system can be expressed in terms of exergy flows. As exergy is not conserved, the difference in net exergy flows represents the loss of available energy inside the system. This loss of availability helps to rate the resource use potential of the system.

In case of material resources, the total exergy or available energy is made of two portions. The quotient of exergy which corresponds to the physical potentials like position, temperature, pressure differences etc. is termed as physical exergy. But the availability of these potentials varies from kind to kind. The potential and kinetic energies are fully available for further conversion. But the enthalpies will not be fully available for further use. A portion of it is restricted by the irreversibility associated with the real conditions.

Every material has a chemical potential in the given state, by the virtue of difference with its ultimate dead state or the state of natural occurrence (state of equilibrium with the environment). This potential expressed in terms of available energy is called as *"chemical exergy"*. All material resources are extracted from the environment which includes lithosphere, hydrosphere and atmosphere. So the materials or chemicals used for manufacturing or for any other process are extracted from any of these sources, and processed to required conditions. The difference which is created in processing of materials from their state of natural occurrence accounts for the chemical exergy.

Exergy carried by the resources amounts to a maximum reversible work possessed by the resources in their current state which can be fully recovered and utilized (Bakshi B. et al, 2008). Due to an irreversibility associated with the process, a certain quantity of available energy is destroyed. Irreversibility in a system can be caused by friction, diffusion, throttling, combustion processes, absorption and emission of thermal radiations, heat transfer with finite temperature gradient and chemical reactions. All these phenomena could result in exergy loss (Szargut, J., 2005). So the net exergy carried by all the output resources is always less than the net exergy flowing in to the system. This ratio between the net exergy flowing out to net exergy flowing in gives the extent of exergy destruction. So the exergetic efficiency (η_ε) of the system, which will be the measure of process sustainability, may be defined as follows.

$$\boldsymbol{\eta_\varepsilon = \frac{\sum \varepsilon^{out}}{\sum \varepsilon^{in}}} \qquad (1.01)$$

Amount of exergy lost ($\delta\varepsilon$) in the system can be calculated from the environment temperature (T_0) and net entropy generated (ΔS_{irr}) by the irreversibility.

$$\boldsymbol{\delta\varepsilon} = \boldsymbol{T_0} \sum \Delta S_{irr} \tag{1.02}$$

Apart from this exergy which is lost inside the system, the other discarded (unutilized) resources generated in the process add to the total exergy lost in the process. In this context, the wastes include all the resource streams which are not utilized and are dumped into environment. As long as there is exergy loss in a system, there would be a possibility for improvement.

Exergy concept offers a comprehensive tool for analysis of sustainable development by considering the importance of resource flows in economics and ecological aspects of manufacturing process. The phenomenon of entropy generation within a considered system is common for all processes. This quantity is directly or indirectly evaluated during exergy analyzes. In thermodynamics, entropy is defined as a measure of irreversibility property of a system. All real process will impact the entropy property of the system through entropy generation and only in a completely reversible process the entropy generation could be restricted to zero.

The concept of exergy for evaluation of a process is not novel. Exergy is used to assess the irreversibility associated with energy conversion processes. For designing and developing optimized energy system, exergy analyzes are carried out frequently. But recently, the significance of exergy analyzes is applied in various non-energy producing processes and manufacturing processes like chemicals and fertilizers industry, steel industry, cement production processes etc. Compared to energy-based analyzes, exergetic analyzes of a system provide better insight of resource consumption, particularly the quality aspects. This opens new avenues for development, which may improve the overall sustainable development.

In case of a production system, the quality of the output in terms of meeting the functional requirements and costs associated are often alone considered for optimized manufacturing. Resource requirement of such a manufacturing process is usually added to the capital expense of the process and considered as inherent to the process. But curbing the resource capital to the possible minimum is one of the foremost objectives of manufacturing for sustainable development. Thereby it creates a scope for exploiting exergy based methods in production systems.

1.3.2 Balancing of mass, energy and exergy flows

Well-defining a system is an important premise which is absolutely necessary for performing an exergy analyzes. A thermodynamic system is said to be well-defined, if its control volume and system boundary are clearly defined and the system constituents and their specifications with the features of the system are specified. If the boundary of the system is not clearly marked, it may lead to ambiguities while defining the state of the system. If the boundary of the system is well defined, then any interaction between the system and the surroundings can be identified clearly. This is the first step for any exergy analysis.

In a well-defined system, the state of the system must be defined. In such a system, the various interactions (resource flows) may be crossing the boundary. These resources along with their state properties must be identified. At the end of this exercise, the physical conditions of the material flows with respect to the environment are defined.

For exergy balancing, all the material and energy flows are to be quantified in terms of exergy carried by them. To do that, their mass and energy quantities are to be determined. For both steady state and transient conditions, the flow rates of energy and materials must be balanced.

Mass Balance equation in a steady state system ‘n’ is given as

$$\left[\frac{dM}{dt}\right]^{n} = \sum_{j} m_{j}^{n,in} - \sum_{j} m_{j}^{n,out} = 0 \tag{1.03}$$

$$\sum_{j} \dot{m}_{p}^{n,in} = \sum_{j} \dot{m}_{p}^{n,out} \tag{1.04}$$

Where M represents the mass of the system and $\dot{m}$ represents the mass flows crossing the boundary of the system. With the calculated mass quantities, the mass flow diagram for the system can be specified. Next stage is to quantify the energy flows.

Under steady state conditions, net energies flowing in and out are equal ($E_1 = E_2$). The energy flows interacting with manufacturing system can be in the form of heat, work (mechanical or electrical) and energy carried by the resources flows. Heat and work can quantified from their mode of transfer and efficiency details. Similarly, the potential and kinetic energy possessed by a material resource can be negligible in many conventional manufacturing processes. Enthalpy (H) is a function of thermodynamic state of the resources, which represents the combination of internal energy (U) and boundary work (Pv) possessed by the material flows (Cengel, Y.A, 2006).

$$H = U + Pv \tag{1.05}$$

Internal energy (U) can be determined by the difference between heat possessed (Q) and work done (W) by the system.

$$\boldsymbol{U = Q - W} \tag{1.06}$$

The work done (W) and the boundary work (Pv) can be considered negligible in simple solids or incompressible liquid or ideal gases. In other words, it represents thermal energy content in a material resource (Cengel, Y.A, 2006). If this thermal energy content in a body is purely in form of sensible heat for a body that is not undergoing any phase change, then the specific enthalpy (h) carried by material resources, which are considered as simple solids or incompressible liquids or ideal gases at a given state i, can be determined by their heat capacity (C_i) and temperature (T_i).

$$\boldsymbol{h_i = \int_0^{T_i} C.\, dT = C_i \cdot T_i} \tag{1.07}$$

Total Enthalpy flow rate ($\dot{\boldsymbol{H}}$), is calculated with mass flow rate.

$$\boldsymbol{\dot{H}_i = \dot{m} \times h = \dot{m} \cdot \int_0^{T_i} C.\, dT = \dot{m} \cdot C_i \cdot T_i} \tag{1.08}$$

With these energy flow quantities, energy balance is drawn for all the systems together.

$$\boldsymbol{\frac{dE}{dt} = \sum_n \dot{Q}^{n,in} - \sum_n \dot{W}^{n,out} - \sum_n \dot{Q}^{n,out} + \sum_i \dot{H}_i^{in} - \sum_i \dot{H}_i^{out}} \tag{1.09}$$

Under steady state condition,

$$\boldsymbol{\frac{\mathrm{dE}}{\mathrm{dt}} = 0}. \tag{1.10}$$

Energy is always conserved, but exergy is not conserved. Rather it is destroyed in all real processes. Depending on the nature of resource, different methods are to be employed for exergy calculations. The exergy balance is drawn with the quantities of exergy available in each resource streams.

Exergy of Heat ($\boldsymbol{\varepsilon_Q}$) flowing in or out of the system can be determined by taking the carnot co-efficient between temperatures at which heat is executed and the environment temperature (T_0).

$$\dot{\varepsilon}_Q = \dot{Q}\left(1 - \frac{T_0}{T_i}\right) \tag{1.11}$$

Energy quantities carried by the mechanical (W_M) or electrical (W_E) work are fully available for further exploitation. Therefore exergy of work ($\boldsymbol{\varepsilon_W}$) flowing in or out of the system is equal to the quantity of work available.

$$\dot{\varepsilon}_W = \dot{W} \tag{1.12}$$

As discussed earlier, the exergy carried by the material flows are consequence of two potentials. They may be physical, chemical or both. The flow exergy of a material (ε_i) is given as below.

$$\varepsilon_i = \varepsilon_i^{phy} + \varepsilon_i^{che} \tag{1.13}$$

Physical exergy, also called as availability function, is calculated from the enthalpy (h_i), and entropy (s_i) of the material in the given state and with respect to the environment (h_0, s_0). Environment is also called restricted dead state. Like explained earlier, when enthalpy represents the thermal energy content in the material, then entropy of the material helps to determine the unavailability of that thermal energy for conversion into work (DOE handbook, 1992). The physical exergy is the maximum possible energy than can extracted till the system is in equilibrium with surroundings (T_i=T_0). Then specific physical exergy ($\boldsymbol{\varepsilon_i^{phy}}$) of a substance at a temperature Ti, can be determined by the following.

$$\varepsilon_i^{phy} = b_i - b_0 = (h_i - h_0) - T_0 \cdot (s_i - s_0) \tag{1.14}$$

Where

T_0 – Environment temperature

h_i & s_i – Enthalpy and entropy of the system at given state i, respectively.

h_0 & s_0 – Enthalpy and Entropy of the system in equilibrium with environment (P_0, T_0)

The chemical exergy is calculated from the chemical potential of the substance at current state with respect to the ultimate dead state (Szargut, J., 2005). Then specific chemical exergy of a substance can be calculated with chemical potentials and mole fraction of the particular substance.

$$\varepsilon_i^{che} = (\mu_i - \mu_o)\chi \tag{1.15}$$

Where,

μ_i – Chemical Potential of material at current state

μ_0 – Chemical Potential of material at ultimate dead state

χ – Mole fraction of the material.

With these exergy quantities, the exergy balance can be defined for a system. From the exergy balance, the rate of exergy destruction is determined as the difference between the exergies flowing in and out of the system.

$$\frac{d\varepsilon}{dt} = \sum_n \dot{\varepsilon}_Q^{n,in} - \sum_n \dot{\varepsilon}_W^{n,out} - \sum_n \dot{\varepsilon}_Q^{n,out} + \sum_n \dot{\varepsilon}_i^{n,in} - \sum_n \dot{\varepsilon}_i^{n,out} - \delta\dot{\varepsilon}_{loss} \tag{1.16}$$

This exergy destruction ($\delta\varepsilon_{loss}$) is attributed to the entropy generation inside the system during the process. This value will be the metric to assess the efficiency of the manufacturing process in line with the sustainable resource utilization. This exergy loss is inherent in the process by its design which cannot be recovered externally.

Under steady condition, $\frac{d\varepsilon}{dt} = \mathbf{0}$. Then rate of exergy destruction ($\dot{\delta\varepsilon}_{loss}$) can be determined from rest of the balance.

$$\dot{\delta\varepsilon}_{loss} = \sum_{n} \dot{\varepsilon}_{Q}^{n,in} - \sum_{n} \dot{\varepsilon}_{W}^{n,out} - \sum_{n} \dot{\varepsilon}_{Q}^{n,out} + \sum_{n} \dot{\varepsilon}_{i}^{n,in} - \sum_{n} \dot{\varepsilon}_{i}^{n,out} \tag{1.17}$$

With all resource flows along the product lifecycle are quantified in terms of exergy, the lifecycle diagram in section 1.2 (Fig 1.1) can be modified in terms of exergy flows (Fig 1.5). It could be evidenced that materials and energy resources carry exergy throughout their lifecycle. For this academic work, only the assembling process of a PCB assembly is studied in detail. All exergy flows associated with this stage of the lifecycle, were evaluated to study and enumerate the methodology of exergy analyzes for sustainable development.

Before extraction, the resources that are in their natural states have their exergy potentials at a minimum. All along the lifecycle in making of a product, at various processing stages more exergy is invested into each products/material and subsequently it is also lost. At the end of life cycle, the imbedded exergy is still available with the resource particularly chemical exergy, which is often dumped into the environment. Similarly all resources discarded at each stage carry a quantity of exergy along with it. This may be destroyed when the resource attains thermal and chemical equilibrium with the environment (dead state).

1.3.3 Exergetic efficiencies and Significance of Exergy

In an exergy analysis, the quantity of resources consumed and quality of process outputs may be connected to the exergy quantities associated with them. Exergy loss corresponds to a loss of a useful resource which results in an increased resource consumption. Exergy analysis helps to identify a system with minimum entropy generation which has better resource use. Many products involving recent technological advancements like semiconductor chips, carbon nano-tubes etc. fail to address this aspect (Williams, E.D., et al, 2002; Gutowski, T.G., et al 2010). For example it is observed that resources used in making of carbon nano-tubes indicate a very large intensity. So, exergy analysis may assist in evaluating the specific resource use for advanced technologies.

In recent past, the Carbon footprint is widely appreciated as a metric to evaluate the ecological footprint of a product. Carbon foot print is developed to study the impact of a product on the overall greenhouse gases emissions and global warming effects (Wiedmann, T., et al, 2007). Using this method the energy consumption in manufacturing of a product may be quantified in kilograms of Carbon Dioxide. Based on the type of power generation, equivalent carbon emission values for generating this energy required can also be evaluated.

In traditional energy resource evaluations, different forms of energy are lumped together and compared. Although they carry the same units of measurement, the quality of the energy associated with each type may differ. For example quality of a unit heat is different from that of a unit mechanical work. In case of mechanical work, the quantity of available work is fully available. But in the case of heat, only a portion of it is available for further conversion, given by the exergy. By using exergy metrics, these kinds of ambiguities can be avoided during the analysis of a system.

Exergy is a measure which indicates how far away a resource or a system is from the state of natural occurrence or state of equilibrium with environment. As explained in Fig. 1.5, all discarded resources, wastes and byproducts generated from a process carry some quantity of exergy with them, which indicates their current state which may be different from the state of equilibrium. A resource in perfect equilibrium with an ultimate dead state will carry no exergy (Bejan, A., 2002). When a resource with some exergy is dumped into the environment, it may not be in equilibrium with the environment. This exergy difference impacts the environment but the significance of impact depends on the potential of the resource and many studies are being carried out regarding this aspect (Dincer, I. et al. 2007). In other words, exergy could be used as a measure to assess the damage potential carried by waste streams.

When material streams are not in equilibrium with the environment, the tendency to affect the environment is certainly higher. One of the basic tenets for designing a sustainable system is to minimize damage to the ecosystem. Exergy analysis may help to asses this aspect of sustainable development that a product or system may have. This means, all or maximum of the potentials available in the waste streams ideally are to be extracted before dumping. But availability of practical techniques and economic viability of potential technologies represent the big challenge for utilizing the available exergy potentials in auxiliary material and work flows. For example, not many techniques are available to fully utilize the chemical potentials hidden in material resources.

An economic analyzes of exergy streams flowing through a system is sometimes called as “exergonomics” or “Thermo-economics” which is slowly getting more popularized. Using this, the resource use can be optimized with objectives to minimize the overall cost and cost of exergy losses. Because of the inherent irreversibility associated with real processes, it is difficult to exactly determine the cost of exergy lost. So a comparative cost analyzes is preferred (Szargut, J., 2005). The exergy losses are to be accounted as depletion of capital or added capital cost. There are few methods under close scrutiny which were critically reviewed for their suitability across all processes (Tsatsaronis, G., 1987; El-Sayed, Y.M., et al. 1989). One of the challenges for a wide spread industrial application is that the suggested method should be simple and universal. This may not be the case for the use of advanced procedures based on second law of thermodynamics.

In a manufacturing setup, numerous resource streams flow in and out of the processing center. Each resource stream along with it carries an energy potential called as exergy. Current manufacturing practices are designed to meet the product requirement s at an economical way. For sustainable development in manufacturing, the resources are to be prudently used, which means the maximum potential of the resource is to be utilized. Manufacturing systems are to be designed to perform at the optimum thermodynamic efficiency of resource use, constrained by product quality, cost etc. In line with this notion, current manufacturing processes are to be assessed and evaluated for their measure of resource utilization. One such illustrative study is carried out in Printed Circuit Board assembling process and discussed in this thesis.

2. Resources utilized in Manufacturing of PCB Assembly

2.1 Printed Circuit Board Assembly manufacturing process

2.1.1 Manufacturing (Assembly) line

The printed circuit board chosen for the study is a small but very instrumental unit of an automotive control system. This 90g weighing PCB assembly is a part of an electronic control unit of passenger cars. Each circuit board consist of 293 subcomponents (see Appendix 1) made up of 64 different materials including metals, alloys, ceramics, metal oxides, organic compounds and polymers (as declared by manufacturers). All these components are provided by different suppliers from different parts of the world. Each board has a heavy connector unit, weighing 35g. This most massive component is a through-hole component, and all others are surface mounts. All the surface mount components are reflow soldered and the connector is selectively soldered separately in the end. In the identified manufacturing line, all these components are bonded to the board by using lead solder. The lead-free option is also under production in a separate manufacturing line. This is a high volume product, produced at a rate of 400,000 units per annum during its peak demand. The assembly line is run for two shifts a day at 10 hours a shift.

The manufacturing process is carried out in panels comprising two circuit boards each. After assembling and testing, the panel is cut and individual boards are packaged into their casings. The manufacturing line is fully automatic and designed to the state of art with minimum human interference. The manufacturing (assembling) process is carried out in a controlled environment where temperature, humidity and dust levels are monitored. The manufacturing area is maintained at a temperature of 20 ± 3^{o}C. There are six stations involved in manufacturing process, which are arranged in a U-shaped production/assembly line. Between the stations, the movement of products is assisted by multiple conveyors. Apart from the linear movements, products need to move at right angles at two points in the U-shaped assembly line. For that purpose, rotary conveyors are also used. Material movement between the stations is electronically controlled with sensors and logic controllers.

2.1.2 Manufacturing (Assembling) sequence

At the first stage, traceability barcodes are etched on each circuit board of the unpopulated panel. This is carried out by a laser etching process with 30W fiber laser marker. The panels are picked from the stack and placed on the conveyor with the help of a pneumatic assisted pick and place system. The etch dust is removed from the work area using a vacuum pump. The etched dust is collected separately and safely disposed in accordance with industrial standards. Then the etched panel is moved to the next station. In this station, the solder paste is applied on to the specified locations (pads) of the board using the specifically designed stencils. Due to similarities with screen printing technique, it is also called as solder paste printing process.

The solder paste contains eutectic 63Sn-37Pb solder alloy with low/no residue flux, i.e. upon heating, the flux is fully vaporized and leaves no visual residue on the board. Solder paste is also maintained in controlled conditions at a temperature of 16^{o}C. The entire operation is carried out using pneumatically assisted mechanical systems. The solder paste printing equipment is also equipped with visual inspection feature to verify the quality of the process. Subsequently, the etched PCBs with the paste deposited on their pads are moved to the next station.

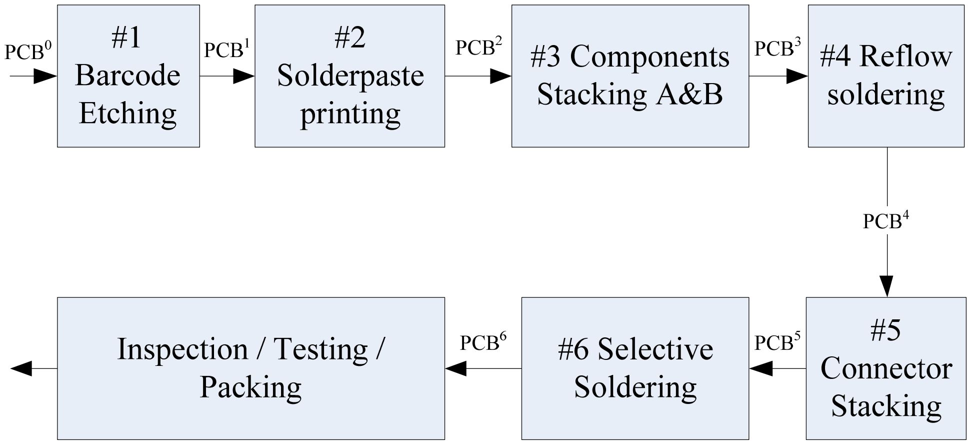


Fig. 2.1 Manufacturing (Assembling) Sequence of the PCB Assembly

In the next stage, the components are stacked on their respective pads as required by the circuit design. Components are received in reels, from which they are picked and placed on their respective pads assisted by the stacking equipment. The equipment uses electro-pneumatic systems to control the pick and place mechanisms. To the break the operation time and enable parallel operations, the components stacking operation is divided into two stages (A&B). The stacking units used in these two stages are very similar and are place consecutively in the assembly line. In the first stage, many smaller components are stacked and in the next, the heavier components are handled. At both the stages visual sensors and warning systems are available to qualify the products leaving the station for reflow soldering process.

The panels with all surface mount components and solder paste positioned in place are sent through the reflow furnace. This is a 10-stage oven with two cooling zones. Like a typical reflow process, product undergoes preheating, activation and reflow conditions during the ramping of temperature at different zones. In the furnace, the temperature is ramped from room temperature to a maximum of 232^{o}C at reflow zones. The heating process is carried out in inert condition, provided with nitrogen gas by monitoring the oxygen levels inside the furnace. Electric joule heating is used for heating and the thermal energy carried by the product is partially removed as heat in the cooling zones with help of heat exchangers. Water is used as the medium in these heat exchangers. The reflow process is designed to have a cycle time of 35 seconds. As the reflow oven has long startup time of about three hours, it is run continuously and shut only for a couple of hours at the end of the day. At the end of the reflow line, a small pneumatics assisted PCB stacker is available. A maximum of about ten panels can be stacked in this unit. In case of the line stoppages, the boards are accumulated in this stacking unit. This helps to balance the product flow in the assembly line.

The connector unit, which is bigger than other components, is stacked separately on the reflowed PCB assembly in its specified position. This is carried out in a custom built pneumatic machine, which is like a typical pick and place system. Then the board is sent to the selective soldering oven. In selective soldering, the board with the through-hole component (connector unit) is dipped in the molten solder alloy. By capillary action the solder alloy fills the gaps and makes joints. Before passing the PCB assembly through the selective soldering oven, minute quantity of flux is sprayed onto the pins of the connector. Inside the oven, the board is placed on a chain conveyor, which takes it through the preheating and activation zones before reaching the solder alloy pot. In the pot, the eutectic 63Sn-37Pb alloy is kept in a molten state at 380^{o}C. To avoid oxidation, the selective soldering oven chamber is supplied with nitrogen gas. The hot PCB assembly coming out of furnace is air cooled and sent for inspection and packaging.

Similar to the reflow oven, because of long start up times, the selective soldering oven is made to run continuously and the solder in the pot is maintained at the operating temperature. Selective soldering oven is shut down only during the annual inter sessions and long maintenance breaks.

2.2 Resource flow mapping

The first activity in energy and exergy balancing is to identify the resources associated with respect to a defined system boundary. The PCB manufacturing line can be divided into six sub-systems with boundaries of these sub-systems selected around the individual processing equipment. This includes all tools that assist in the assembling process, like pneumatic pick and place systems, internal conveyors (located inside the machines) etc. The identified assembly line is divided into six subsystems to representing different stage of the manufacturing (assembling) processing. Each subsystem can be interpreted as an individual thermodynamic system, characterized by their corresponding resource flows.

A resource flow map, see Fig 2.2, is prepared to schematically indicate the resource flows through individual sub-systems. On the basis of their utility, the various material flows can categorized into two, namely product and auxiliary materials. Product materials include all the materials that constitute the final product through their mass contributions. Auxiliary materials are the process requisites which help to improve the process performance. The product and auxiliary materials, relevant to the identified assembly line are listed below.

Product Materials

1. Printed Circuit board (PCB)
2. Electronic components ($\sum EC$)
3. Solder alloy (S)
4. Connector (Co)

Auxiliary Materials

1. Compressed air (A)
2. Nitrogen (N)
3. Water (CW)
4. Flux (F)

In the above list, the flux is included in process materials because in this case, it does not leave residue. Moreover, it is not a part of the product design requirements. Flux is used only improving the performance of soldering process.

The energy resource for processing units and conveyors are provided by the electric power. So electrical work (W) is the primary source of the energy resource supplied to the assembly line. With the above listed resources, the resource flow map is prepared (Fig. 2.2).

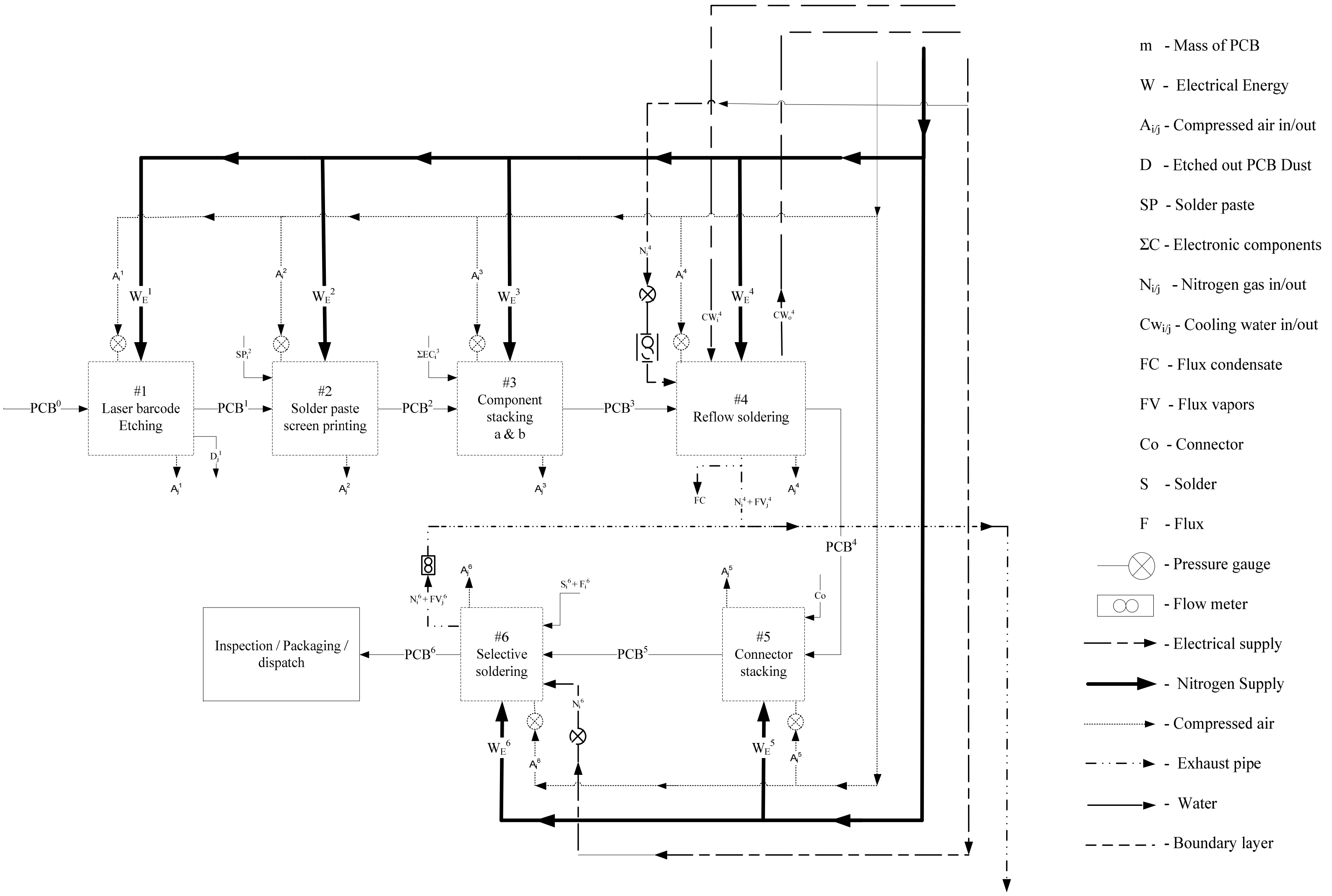


Fig. 2.2 Resource Flow Map of PCB Assembly line

2.3 Assessment of mass and energy flows

2.3.1 Mass flows

The bulk flow materials flowing across the sub-system boundaries carry enthalpies and exergies as their intensive thermodynamic properties. Along with physical properties, the mass quantities of material flows are required to express the enthalpies and exergies as extensive properties. The physical quantities of various material flows crossing the boundary are quantified by direct and indirect measurement methods. Direct measurement methods are the methods of mass measurement with an instrument or gauge e.g. weighing scale. Indirect methods are the evaluation techniques, where mass or mass flow rates of the materials are calculated from physical conditions of the material.

The other method for determining the masses is the by the mass balance of the system. It is assumed that the subsystems are in steady state condition. If in and out conditions are denoted by 'i' and 'j', then under steady state conditions, the mass balance equation for the assembly line can be written as following.

$$\frac{dM}{dt} = 0 = \sum_{n=1}^{6} \dot{m}_i^n - \sum_{n=1}^{6} \dot{m}_j^n \qquad (2.01)$$

Using electronic weighing scale (LC = 0.0001g), the mass of a printed circuit board (m_{PCB}^n) is measured at the entry and exit of the each sub-system. The 42.0 g PCB (m_{PCB}^0) that enters the assembly line, upon all the components addition reaches 90.0 g (m_{PCB}^6) at the end of the assembly process. Assuming steady state, all the other associated material flows are determined using mass the balance equation (eqn. 2.01). The uncertainty associated with this method of measurement is less than 0.05 grams and it can be considered insignificant for evaluation purpose.

Table 2.1: Mass of product materials estimated by mass balance equations

Sys. #	Material Flow	Balance Equation	Mass per unit PCB assembly (g)
1	PCB dust etched out	$\mathbf{m}^{1}_{D,j} = \mathbf{m}^{1}_{PCB} - \mathbf{m}^{0}_{PCB}$	0.01
2	Solder Paste	$\mathbf{m}^{2}_{SP,i} = \mathbf{m}^{2}_{PCB} - \mathbf{m}^{1}_{PCB}$	1.00
3	Electronic Components	$m^{3}_{\Sigma EC,i} = \mathbf{m}^{3}_{PCB} - \mathbf{m}^{2}_{PCB}$	11.50
4	Flux removed in reflow oven	$m^{4}_{\mathrm{FV,j}} = \mathbf{m}^{3}_{PCB} - \mathbf{m}^{4}_{PCB}$	0.10
4	Solder alloy in the paste	$m^{4}_{\mathrm{S,i}} = \mathbf{m}^{2}_{SP,i} - \mathbf{m}^{4}_{FV,j}$	0.90
5	Connector	$m^{4}_{\mathrm{Co,i}} = \mathbf{m}^{5}_{PCB} - \mathbf{m}^{4}_{PCB}$	35.00
6	Solder alloy	$m^{7}_{\mathrm{S}} = \mathbf{m}^{6}_{PCB} - \mathbf{m}^{5}_{PCB}$	0.60

Mass flow rate of auxiliary materials were estimated based on the manufacturing conditions (Appendix 3). All equipment is supplied continuously with a compressed air at a pressure ($P_{A,i}$) of 690 kN/m^2 (100 Psi) through connecting ¼" pipes. Compressed air consumption sequence is closely observed and the durations of consumption were recorded for each process. Temperature of the compressed air is measured using Omega digital thermometer, which is 17°C consistently. The nominal flow rate ($\dot{\boldsymbol{V}}$) in a 25 mm (¼") diameter pipe is estimated to be at 8Nlps (0.008 m^3/s) (engineeringtoolbox.com). Compressed air is assumed to behave ideally and there are no leakages. The compressed air delivery system is assumed to deliver at a constant flow rate consistently, i.e. variation in mass flow rate during the production cycle is insignificant. Therefore by using the ideal gas law, the mass flow rate of the compressed air in the inlet is determined.

$$\dot{m}^{n}_{A,i} = \frac{P^{n}_{A,i} \cdot \dot{V}^{n}_{A,i}}{R^{n}_{A,i} \cdot T^{n}_{A,i}} \tag{2.02}$$

Under assumption of steady state conditions, the mass flow rates in and out are equal. i.e.: $\dot{m}^{n}_{A,i} = \dot{m}^{n}_{A,j}$.

Nitrogen gas is supplied for the reflow and selective soldering ovens at a pressure of 552 kN/m^2 (80 Psig) in a 15 mm (½") diameter pipe. For calculation of mass flow rates, it is assumed that the leakage is also insignificant and the system is efficiently air tight. The reflow oven has a flow meter at the entry and from that it is observed that oven consumes ($\dot{V}^4_{N,i}$) at 540 Normal l/min (0.009 m^3/s). Using the density of nitrogen at N.T.P (1.165 kg/m^3), the mass flow rate is determined as 10.5 g/s.

$$\dot{m}^4_{N,i} = \rho^4_{N,i} \cdot \dot{V}^4_{N,i} \tag{2.03}$$

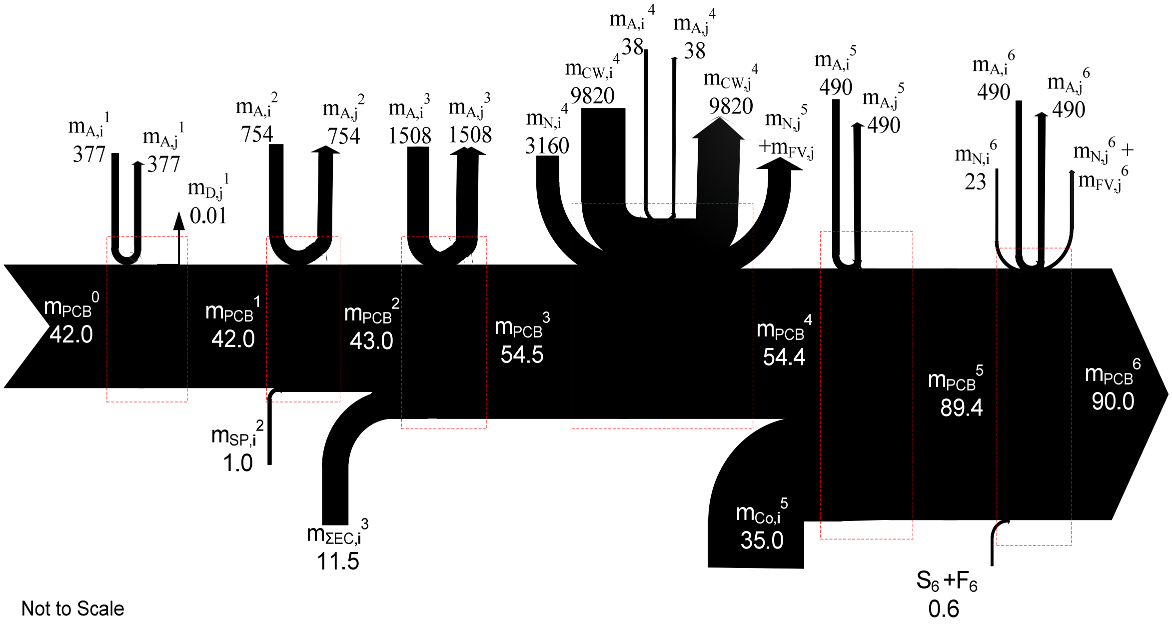
In case of selective soldering unit, the pressure gauge and flow velocity meter is available at the exhaust pipe of 100mm (4") diameter. The flux added in this stage is considered very minimal and the exhaust predominantly contains nitrogen gas and traces of other vapors. The exhaust pressure($P^6_{N,j}$), velocity($v^6_{N,j}$) and temperature ($T^6_{N,j}$) were at 0.3 kN/m^2, 22.86 m/s (4500 fpm) and 55°C respectively. Using these conditions, the flow rate of nitrogen is determined as 0.57g/s.

$$\dot{m}^6_{N,j} = \rho^6_{N,j} \cdot v^6_{N,j} \cdot A^6_{N,j} \tag{2.04}$$

Both these ovens are run continuously during the production time. For estimation of the mass consumed per unit board, consumption per shift (10 hours) is calculated. Using the productivity per shift (average: 900 boards/shift), the mass of nitrogen gas consumption per unit PCB assembly can be determined. Using this, nitrogen consumption per unit PCB in reflow and selective soldering processes ovens 420 g and 23 g. The figures of merit for these values are subjected to the limitations of the above described assumption. For evaluation purpose, these uncertainties are neglected.

Water is supplied in a 25 mm (1”) pipe to the reflow oven, which typically enters at a temperature 6°C and exits at 15°C. By a rule of thumb in piping designs, the maximum delivery flow velocity in a 1” pipe is considered as 1 m/s (engineeringtoolbox.com). For a nominal system under the given conditions, velocity of the water flow in this reflow oven is assumed to be at 0.5 m/s. From the density and pipe diameter, applying equation 2.04, the mass flow rate is estimated to be at 245 g/s. From productivity achieved per shift, it is calculated that reflow oven consumes 9.8 kg water for unit PCB assembly. In comparison with the estimated values, the uncertainties associated with the above described assumptions were considered to be negligible.

The stage by stage mass addition to the product is pictorially represented with help of the mass flow diagram (Fig. 2.3). As shown in Table 2.1 and in Appendix 2 & 3, the values are scattered in a wide range. So the thicknesses of the arrows were not scaled to the mass quantities of the respective material flows.



Not to Scale
Mass quantities associated for unit PCB

Units: grams (g)

Fig 2.3 Mass flow per unit PCB assembly

2.3.2 Enthalpy Flows

As explained in section 1.3.2, for the material flows that are considered as simple solids or incompressible liquids or ideal gases, their enthalpies can be calculated from specific heat values corresponding to the physical state of the constituent materials. . The specific heat values for various constituent elements and compounds identified with the product (PCB assembly) and auxiliary material flows are referred from standard sources for physical properties of materials (NIST webbook, Kaye & Laby online, Goldsmith, A., et al. and Perry, R.H.).

The enthalpies carried by the minor constituents, whose mass were less than 0.01 g the etched dust, flux were expected to carry negligible quantities and were not included. All the sub-components are made up of various metals, alloys, polymers and organic compounds. From the manufacturers of these components, the precise percentage mass of individual constituents were collected. Because of proprietary concerns, many critical compositions of were not available. In that case, the most simple or closest possible composition materials were considered for the evaluation purpose.

But in the case of electronic components like resistors, capacitors etc., there exact types of associations between the constituent elements or compounds are not known. So it is assumed that electronic components are lumped together as a physical assembly or mixture of various constituent elements and compounds, which do not interact with each other. But in reality it may not be the case. When materials of various kinds, like in the case of electronic components made of plastics, semiconductors, metals and chemical compounds, it could be obvious that constituent materials as a package are tend to behave differently. With limitations on data availability, it may be believed that the above assumption can be the easy direction to proceed. Moreover, the electronic components constitute only 11.5 g (see Table 2.1), which about 12% of the mass of the product. Compared to the enthalpies possessed by other material flows, this uncertainty can be considered to have minimal impact, which can be neglected.

The total enthalpy (H) carried by a component 'D' consisting of 'k' constituent at materials at inlet condition i, will be sum of the individual contributions of all the constituent materials (k).

$$\boldsymbol{H_D = \sum_k m_k \cdot h_k = \sum_k m_{k,i} \cdot C_{k,i} \cdot T_{D,i}} \tag{2.05}$$

Where

H_B – Enthalpy carried by the component 'D'

$T_{D,I}$ – Temperature of component 'D' (assuming uniform temp. is maintained)

m_k – mass of individual constituent material 'k'

C_k – Specific heat of constituent material 'k'

There were about 64 different compounds and alloys. Out of that only, 29 major constituents were taken for calculation and others whose contribution is less than 0.01% by mass can be considered as insignificant quantities (Appendix 3).

The specific heat values of the elements vary with their physical state and temperature. Knowing the state and temperature of the constituent materials, the specific heats were estimated from the standard physical property tables. (NIST webbook, Kaye & Laby online, and Perry, R.H.). The temperatures of the all these material flows were measured at entry and exit of each system using Omega HH11A digital thermometer with k-type thermocouple. This is a handheld device with a resolution of 0.1°C in a range of -50°C to 1000°C. It is assumed that the temperature is uniform throughout the body.

Illustration: Enthalpy carried by PCB wiring board ($H_{PCB,}$ 0)

The mass fractions of printed circuit board (m_{PCB}^0) is made up of copper (37%), epoxy resin (26%), silica (17%), fiber glass (6%) and other undisclosed constituents (14%). The contributions of fiber glass and undisclosed constituents were considered insignificant.

$$\boldsymbol{H_{PCB} = \sum_k m_{PCB}^0 \cdot h_{PCB}^0 = m_{Cu} \cdot C_{Cu} \cdot (T_{PCB}^0) + m_{ER} \cdot C_{ER} \cdot (T_{PCB}^0) + m_{SiO2} \cdot C_{SiO2} \cdot (T_{PCB}^0)} \tag{2.06}$$

Table 2.2 Enthalpies carried by the major product material flows

Material Flow	Mass, m_i	Tempe-rapture, T_i	$\sum_k(m_k . Cp_k)$	Enthalpy H_i
(Units)	(g)	(K)	(J/K)	(J)
PCB (m_{PCB}^0)	42.0	291.15	24.7	7188.7
Solder paste (SP)	1.0	289.15	0.14	39.1
Elec. Components (∑ EC)	11.5	291.65	6.43	2320.7
PCB +SP +∑ EC ($m_{PCB,3}$)	54.5	296.15	31.34	9733.2
Reflowed PCB ($m_{PCB,4}$)	54.4	333.15	31.34	10946.5
Connector	35.0	293.15	42.54	12146.1
Final PCB Assy ($m_{PCB,6}$)	90.0	348.15	61.67	25898.8

Similarly the enthalpies carried by the process materials are also calculated (See Appendix 4).

2.3.3 Electrical Work Flow

Electrical energy resources are the primary source of the work rate input given to the manufacturing systems. Electric energy is continuously drawn (may be small quantities) from the power source by the machine throughout the time for which the machine is kept on. On the basis of the activity state, the consumption pattern of cyclic machines can be categorized in active and passive (idle) states. The duration for which the machine works on the product (PCB) can be considered as active state. If otherwise, the machine is said to be in passive (idle) state. This is the period for which the machine is kept waiting for the next job. Current consumption pattern during these two states were observed and recorded. Based on these values, the power and work required were calculated.

Active energy consumed is the electrical power drawn during active processing time (cycle time of the machine). The fully automatic assembly line is often forced to have stoppages because of technical reasons. These stoppages contribute to the idle times and their durations vary with the severity of the issue. As the assembly line is designed to have only a maximum inventory as explained in section 2.1.2, stopping one machine may enforce a line stoppage. As these line stoppages are frequent and erratic, it is cumbersome to exactly measure the average idle time for each machine in the line. In order to quantify the idle times, all calculations were made with reference to the production output achieved during one shift of operation (10 hours). On an average, this particular assembly line delivers 900 PCB assemblies (450 panels) per shift. The total time per board is about 40s. The idle time per board (t_{aux}) is calculated from the actual processing time per assembly (t_{nec}).

$$\boldsymbol{t_{aux}} = \frac{\mathbf{36000}}{\mathbf{900}} - \boldsymbol{t_{nec}} = \mathbf{40} - \boldsymbol{t_{nec}} \tag{2.07}$$

Measurement methods

The best suggested method is to monitor and record the current and voltage while the regular running of the machines. Namely, there is a phase shift that impacts the power otherwise calculated from the current and voltage. Current clamps and voltage probes were used for measuring the current flow used. Fluke 33 600V CAT III clamp meter with operating range of 0.3 A – 400 A is used to record the true RMS value of the current. For 0.3 A – 40 A range, it has a resolution of 0.01A at an accuracy of ± (2%+20). This device also has features to capture the maximum, minimum and average reading during the monitoring period. It also has features to get the three seconds running average when the variations are very rapid. Voltage is monitored with probes on Fluke 73 multi-meter 600V maximum, with a resolution of 1mV at 2% accuracy. Using these probes, the voltage and current flow values were monitored at the electrical panel of the machines. For three phase machines, considering a balanced supply with unit power factor ($\mathbf{Cos}\ \boldsymbol{\varphi}$ =1), the total electrical work input is calculated from phase, voltage and current supply details (Appendix 5).

The Electrical work (W_E) consumed is calculated from the observed time (t) and the electrical power ($\dot{\boldsymbol{W}}_{\boldsymbol{E}}$) supplied. Power is quantified from the current and voltage flows measured in the line. The assembly equipment is either single or three phased ($\boldsymbol{\varphi}$) machines in the line, and so the power is calculated accordingly (eqn. 2.09, TRANSCAT, 2010). For calculation purpose, the conveyors were accounted as part of the work stations prior to their locations.

$$W_{E,i}^{n} = \dot{W}_E \cdot t \tag{2.08}$$

$$\dot{W}_E = V \cdot I.Cos\,\varphi \tag{2.09}$$

The total electrical work (W) consumed by the cyclic processes is the sum of active (W_a) and passive (W_b) work consumed per board, which is quantified in the units of joules.

$$W_{E,i} = W_{E,nec} + W_{E,aux} = \varphi \cdot V \cdot (I_{nec} \cdot t_{nec} + I_{aux} \cdot t_{aux}) \tag{2.10}$$

In case of the ovens, where the current is continuously consumed for maintaining the temperature, the cycle time of the process is considered as the active time per board.

Many of the transport conveyors and laser etch machine at idle state draw less than 0.3 A. These current values are negligible compared to the scale of the other major flows in the stream. So they are assumed to be at a minimum value, which is assigned as 0.01 A for calculations. During the laser etching process, while initiating the laser, the machine draws a maximum current of 0.5A for couple of seconds and then maintains a constant rate of 0.38A during the processing cycle. The rotary conveyor machines also draw different current values during different stages of the processing cycle. Those current values and their respective durations were recorded as observed. In Reflow oven, the current flow variations were very instantaneous, and the range was like 5A - 40A. And hence three seconds running average values were recorded for active and passive stages were 16A and 20A respectively. Similarly during the selective soldering, the passive (idle) current was varying from 6 - 12 A, so the running average value of 8 A is recorded as the passive current consumed.

3. Evaluation of Resources Utilized

3.1 Balance of Energy Flows

With the quantified values, the energy flows are balanced across each subsystem. The energy balance equation for the PCB assembly line is derived on the basis of all resources identified. From equation 1.07, with ‘i' and ‘j’ denoting in and out interaction ports respectively, the energy balance equation for the PCB assembly line is derived.

$$\frac{\boldsymbol{dE}}{\boldsymbol{dt}} = \sum_{n=1}^{6} \dot{Q}_i^n - \sum_{n=1}^{6} \dot{Q}_j^n + \sum_{n=1}^{6} \dot{W}_i^n - \sum_{n=1}^{6} \dot{W}_j^n + \sum_{n=1}^{6} \dot{H}_i^n - \sum_{n=1}^{6} \dot{H}_j^n \tag{3.01}$$

In the chosen PCB manufacturing line, there is no well-defined heat energy stream that is crossing the defined system boundary. ($\dot{Q}_i^n = 0; \dot{Q}_j^n = 0$; excluding heat losses). Like in any typical manufacturing system, no work is extracted out of the system ($\dot{W}_j^n = 0$). In these systems, the work supplied is in the form of electrical work ($\dot{W}_{E,i}^n$The enthalpy crossing the system boundary is the aggregate of the enthalpies carried by all individual bulk mass flow interactions ($\sum_k \dot{H}_{k,i}^n$).

Apart from the energy resource carried by the material flows, in this case the enthalpies, there are many other energy out-streams from the system. These processing centers are fully automatic and have many electro-mechanical and pneumatic units that help to control the system performance. Apart from heat dissipation losses, work-transfer losses may also be experienced in the systems. Frictional losses are expected between mechanical moving parts. Display devices use electricity and give out heat and light radiations. In other words, these are the energy streams exhausted by the auxiliary components of the system, which assist in production process. Apart from these, heat losses in the form of convection and radiation are inherent in the soldering ovens. And there will also be some uncertainties in the measurement methods. Due to technical difficulties, direct measurement of these individual out streams was avoided. Instead they are lumped together as unaccounted energy streams ($\dot{\boldsymbol{\lambda}}_j^n$), which effectively includes all uncertainties in accomplishing the energy balance.

In a steady state process, the net energy balance is zero, i.e. total energy flowing in is equal to the total energy flowing out of the boundary layer ($\frac{dE}{dt} = \mathbf{0}$). The energy balance for the assembly line can be redrawn as the following.

$$\mathbf{0} = \sum_{n=1}^{6} \dot{W}_{E,i}^{n} - \sum_{n=1}^{6} \dot{\lambda}_j^{n} + \sum_{n=1}^{6}\sum_{k} \dot{H}_{k,i}^{n} - \sum_{n=1}^{6}\sum_{k} \dot{H}_{k,j}^{n} \tag{3.02}$$

Then the unaccounted energy streams in each system can be calculated from the relationship derived from equation 3.02.

$$\dot{\lambda}_j^{n} = \dot{W}_{E,i}^{n} + \sum_{k} \dot{H}_{k,i}^{n} - \sum_{j} \dot{H}_{k,j}^{n} \tag{3.03}$$

Table 3.1 Unaccounted energy streams in each subsystem (Appendix 5B and 7)

Process (Units)	Electrical work $W_{E,i}^{n}$ (kJ)	Total Enthalpies in $\sum_k H_{k,i}^{n}$ (kJ)	Total Enthalpies out $\sum_k H_{k,j}^{n}$ (kJ)	Unaccounted Energy streams λ_j^{n} (kJ/kg)
Bar code etching	4.50	21.24	21.43	4.31
Solderpaste printing	14.97	35.38	35.63	14.72
Component stacking	433.62	65.77	66.54	432.86
Reflow Soldering	1027.05	11575.07	11962.88	639.25
Connector stacking	18.25	41.36	42.32	17.30
Selective soldering	347.48	48.96	52.00	344.44
Total	1845.86	11787.78	12180.80	1452.85

With the above quantified energy streams are represented with a Sankey diagram.

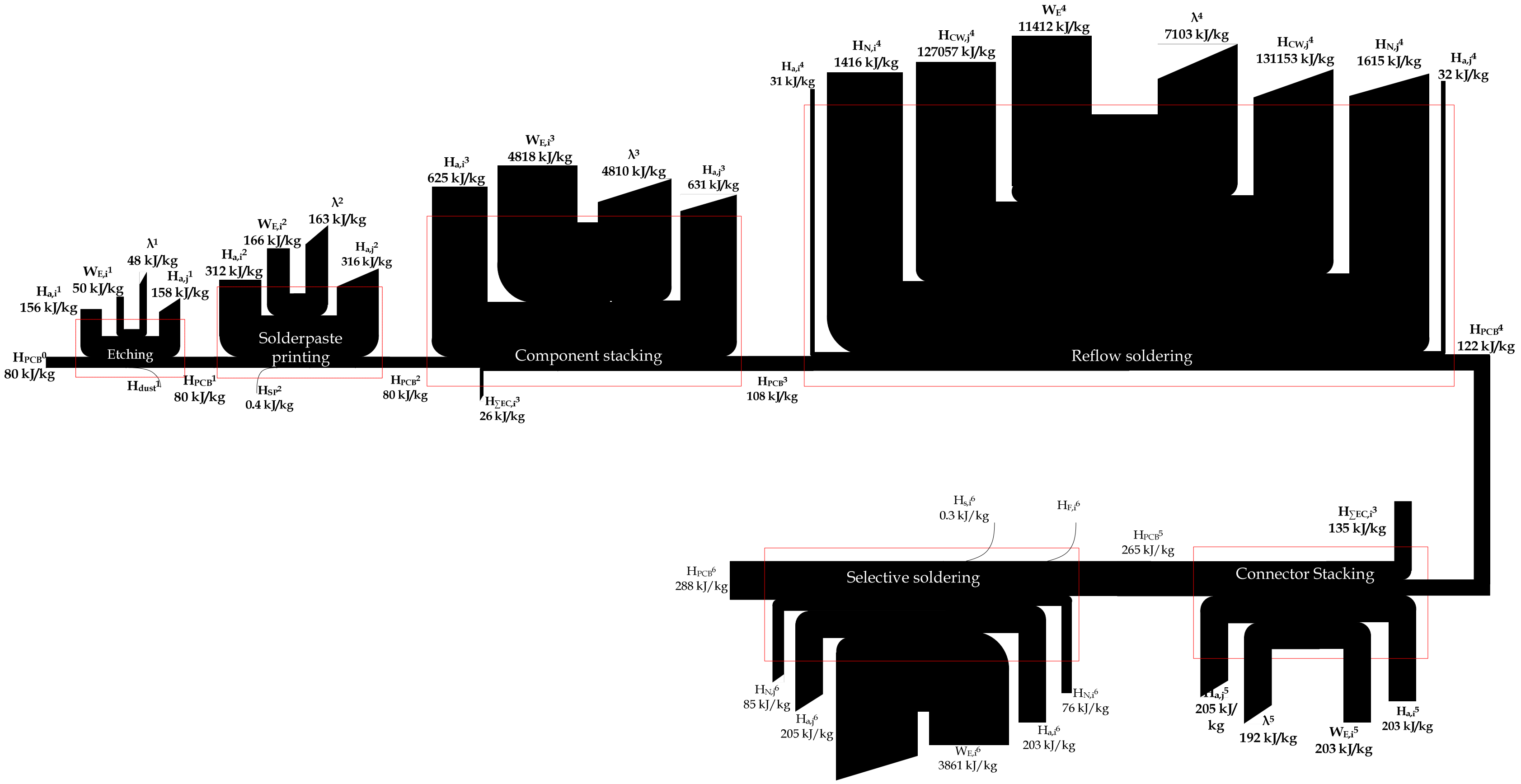


Fig. 3.1 Sankey representation of Energy flows per unit mass of PCB assembly (as tabled in Table 3.1 and Appendix 5A).

3.2 Balance of Exergy Flows

The exergy carried by the resources are to be evaluated and balanced for the assembly line. While balancing the energy flows, it is noted that there are only three kinds of resources associated with PCB assembly line. They are electrical work (W_E), enthalpy flows (H_i) and unaccounted energy flows (λ). There is no specific heat flow into the system.

$$\dot{\varepsilon}_{Q}^{n,in} = 0 \qquad (3.04)$$

In line with the energy balance (eqn. 3.02), the exergy balance equation for the PCB assembly line was deduced for steady state conditions.

$$\frac{d\varepsilon}{dt} = \sum_{n} \dot{\varepsilon}_{W,i}^{n} - \sum_{n=1}^{6} \dot{\varepsilon}_{\lambda,j}^{n} + \sum_{n=1}^{6}\sum_{k} \dot{\varepsilon}_{k,i}^{n} - \sum_{n=1}^{6}\sum_{k} \dot{\varepsilon}_{k,i}^{n} - \sum_{n=1}^{6} \delta\dot{\varepsilon}_{loss}^{n} = 0 \qquad (3.05)$$

3.2.1 Heat and Work exergies

The potential of the electrical work (W_E) is fully available for further potential and so its exergy is equivalent to its work quantity. The calculated electrical works are directly taken as the electrical exergy associated.

$$\varepsilon_{E}^{n,in} = W_{E}^{n,in} \qquad (3.06)$$

As explained in Sec 3.1, the unaccounted energy flows (λ) are not in a single definite form. It accounts for different forms of energy transfer which were not exactly verified for their proportions. But this stream of energy is not available for any further exploitation. It is mostly consumed by the system for performing auxiliary functions or dumped into the environment. For evaluation purpose, it can be logically considered as the low temperature loss in form of a heat released from the processing centers at room temperature. Then using the equation 1.09, their exergy content can be calculated.

$$\varepsilon_{\lambda=Q} = Q\left(1 - \frac{T}{T_0}\right) = Q\left(1 - \frac{T_0}{T_0}\right) = 0\,J \qquad (3.07)$$

Then unaccounted energy streams are considered to carry no exergy (i.e., all this exergy is lost).

3.2.2 Physical and Chemical Exergies

The exergy potential available with the materials entering or leaving the system is also called as flow exergy. As explained in Sec 1.3, the exergy consists of two parts, namely, physical and chemical exergies. Like explained in section 2.3.2, the potential and kinetic energy carried by the material streams are insignificant. As the list of the individual constituent elements in the product are considered in their simplified forms, knowing their thermodynamic state (like temperature and pressure along the assembly line) enthalpy and entropy values can be estimated. Enthalpy and entropy values for various chemical compounds are available in many scientific resources (NIST web book, Kaye & Laby online and Perry, R.H.). If else, approximate values of enthalpies and entropies were calculated from their pressure, temperature and specific heats. As explained in section 1.3.2 (equation 1.12), the physical exergy calculation for any material stream require to know the thermodynamic properties (enthalpy and entropy) both at the given state and at the state of thermodynamic equilibrium with the surroundings (at the surrounding temperature (also called as restricted dead state).

The physical exergies carried by different material streams can be calculated from the exergies carried by the individual constituent elements. It is taken into account that exergy although non conserved quantity does possess the additive property. In soldering processes, although higher temperatures are reached inside the system, the out streams were relatively at lower temperatures. The hottest material stream crossing the system boundary is the final product ($m_{PCB,6}$) coming out of the selective soldering oven at a temperature of 75°C. The corresponding heat carried by the PCB is dissipated to surroundings by slow cooling along the subsequent inspections stages. Since the temperatures of individual material streams at entry and exit of the systems are near room temperature (20°C), their physical exergies are very small and hence in most cases negligible.

Chemical exergy per mole of the substance is derived from the chemical potential of the material. It can also be calculated from the Gibbs free energy of the formation reaction. An elaborate database about the chemical exergy of various engineering materials is available in Dr. Szargut's Text Book on Exergy (Szargut, J., 2005). This data is referred for calculation of chemical exergies. For example, the printed wiring board contains about 15.5 g of copper. The chemical exergy is carried by this copper is calculated from the reference value of 132.5 kJ/mol at atmospheric conditions (1.01 bar and 25°C). Using the Molecular weight of copper (63.5 g/mol), chemical exergy carried per unit mass (g) can be calculated. Then using the mass of copper, chemical exergy can be represented as extensive property.

$$\boldsymbol{\varepsilon_{Cu,PCB}^{che} = m_{Cu} \times \varepsilon_{Cu,Ref}^{che} = 15.5 \times 2.11 = 32.82\ kJ} \tag{3.08}$$

Similarly exergy carried by all individual constituent is calculated. It is assumed that each material stream (including the PCB assembly) is a mixture of individual chemicals and elements, which do not interact or react with each other. But in a reality, it may not be the case. They can react with each other and form intermetallic or intermediate compounds at the regions of contact. Moreover, details about the kind and intensities of the interactions possible within the stream (inside components or PCB assembly) were not available. Considering the quantity of the chemicals/substances involved, which is in few milligrams or even less, the impact of these quantities in total exergy can be considered negligible. Hence the total exergy content in a stream is considered as the sum of individual exergies. The net exergy carried by the stream calculated as the sum of all individual chemical exergies.

Chemical exergy carried by unit PCB at the entry of the assembly line

$$\boldsymbol{m_{PCB,i}.\,\varepsilon^{che}_{PCB,i} = m^{0}_{Cu,i}.\,\varepsilon^{che}_{Cu,PCB} + m^{0}_{EP.R,i}.\,\varepsilon^{che}_{Ep.R} + m^{0}_{SiO_2,i}\,\varepsilon^{che}_{SiO_2,i}} \tag{3.09}$$

$$\boldsymbol{= 32.82 + 384.3 + 0.26 = 417.4\ kJ}$$

Chemical exergy of chemical compound can also be calculated using Gibbs free energies associated with their formation reaction. For example, the oxidation of Zirconium (Zr) produces Zirconium oxide (ZrO_2). The Gibbs free energy with this zirconium oxide formation reaction is -1023 kJ/mol (Perry,R.H., et al., 2008).

$$\boldsymbol{Zr + O_2 \xrightarrow{\Delta_f G^o = -1023\ kJ/mol} ZrO_2} \tag{3.10}$$

Then from Gibbs free energy of the reaction and chemical exergies of reactants, (Zirconium and Oxygen) the chemical exergy of the Zirconium oxide can be calculated (Szargut, J., 2005).

$$\boldsymbol{\varepsilon^{che}_{ZrO_2} = \Delta_f G^o + \varepsilon^{che}_{Zr} + \varepsilon^{che}_{O_2}} \tag{3.11}$$

$$= -1023 + 1083.4 + 3.97 = 63.96\ \text{kJ/mol}$$

The chemical exergy of the pure organic compounds can be calculated from the structure of the constituent elements, using *group contribution method* (Szargut, J., 2005). According to this method, for pure organic compounds, the chemical exergies carried by the compound is some of the standard chemical exergy of individual carbon/chemical groups. Using this method, the chemical exergy of organic substances in the PCB assembly can be calculated.

In case of polymers, the chemical exergy can be calculated from the exergies of monomer molecules using the Gibbs free energy of polymerization (as explained in eqn. 3.11). Since exact details about the polymerization reactions were not available, the Gibbs free energy of polymerization reaction data cannot be gathered. But it was observed that Gibbs free energy of polymerization for common polymers were within the range of 100 - 300 kJ/mol. Considering the chemical exergies possessed by monomers, which was 2000-10000 kJ/mol (see appendix 9), simply the Gibbs free energy of polymerization can be considered insignificant. A detailed list of associated chemical compounds with all their chemical exergy is available (Appendix 9).

With physical and chemical exergies calculated, the total exergy carried by each stream can be calculated as the sum of their physical and chemical exergies (Appendices 7 and 8). Using these total exergy quantities, the exergy balance can be completed.

3.2.3 Net Exergy Balance

As all mapped resource flows were assessed in terms of exergies flowing in and out of the system, they can be represented in Grassmann diagram (Grassmann P., 1959). In the Fig. 3.3, the exergy flows are represented in kilojoules per unit mass of the PCB assembly. This representation clearly shows the magnitude of various exergies with respect to the mass of PCB assembly. It could be noticed that for assembling a unit PCB, a total of about 2.5 MJ of exergy is fed to the assembly line in the form of work(W) and auxiliary flow($\sum_{P} \boldsymbol{\varepsilon}_{P,i}^{n}$) exergies (see appendix 12). Apart from the electrical exergy supplied to the system, the various auxiliary materials take in exergies of about 690 kJ per PCB assembly. In that 690 kJ, of about 538 kJ of exergy is carried out as waste streams which are dumped unutilized. These values enumerate the resource intensity of the assembling process.

Each product at the end of the assembly line not only carries a weight of 90g but also has an exergy content of about 1.4 MJ (See appendix 8). Most of it is in the form of chemical exergy which shows the resource intensity of the product. This high value could be attributed to the richness of chemical composition and their resource intense states. It is clear that to meet the designed function the PCB assembly needs these high quality resources. But this raises questions about the sustainability of the product design in terms of resources utilization. It should be noted that assessment of sustainability represents a complex matter, which may not be represented by a single (physical) metric. But in this case, we are presenting a metric that considers only the resource utilization aspect. In terms of mass quantities these appear as small entities (less than 100 g). But apparently their corresponding resource intensities may be significant.

It could be observed that there is a difference in the net exergy flowing in and out of each system. This difference is proportional to the exergy destroyed or lost inside the system during the process. This will be relevant for measuring the efficiency of the manufacturing in terms of resources used, expressed by exergy flows. With that objective, the net exergy flow diagram is drawn for the manufacturing line.

It should be noted that unaccounted streams which were lumped to form rest of the balance in the energy balance, were considered as low temperature heat dissipations. As explained in earlier (equation 3.07), these exergy streams $\dot{\varepsilon}^{n}_{\lambda,j}$ were accounted to carry no valuable exergy. But in reality, they may possess small quantities of exergy, which is not utilized. In calculation of exergy loss associated with the system, these unaccounted streams can be lumped with the exergy losses ($\dot{\delta\varepsilon}^{n}_{loss}$).

The exergy losses identified at each sub-system, as well as for the overall manufacturing line, are the attributes of the associated thermodynamic irreversibility, i.e., entropy generation in each sub-system of the manufacturing (assembly) line. From the exergy balance (eqn. 3.05) the rate of exergy lost ($\dot{\delta\varepsilon}^{n}_{loss}$) in each system in the PCB assembly line is derived.

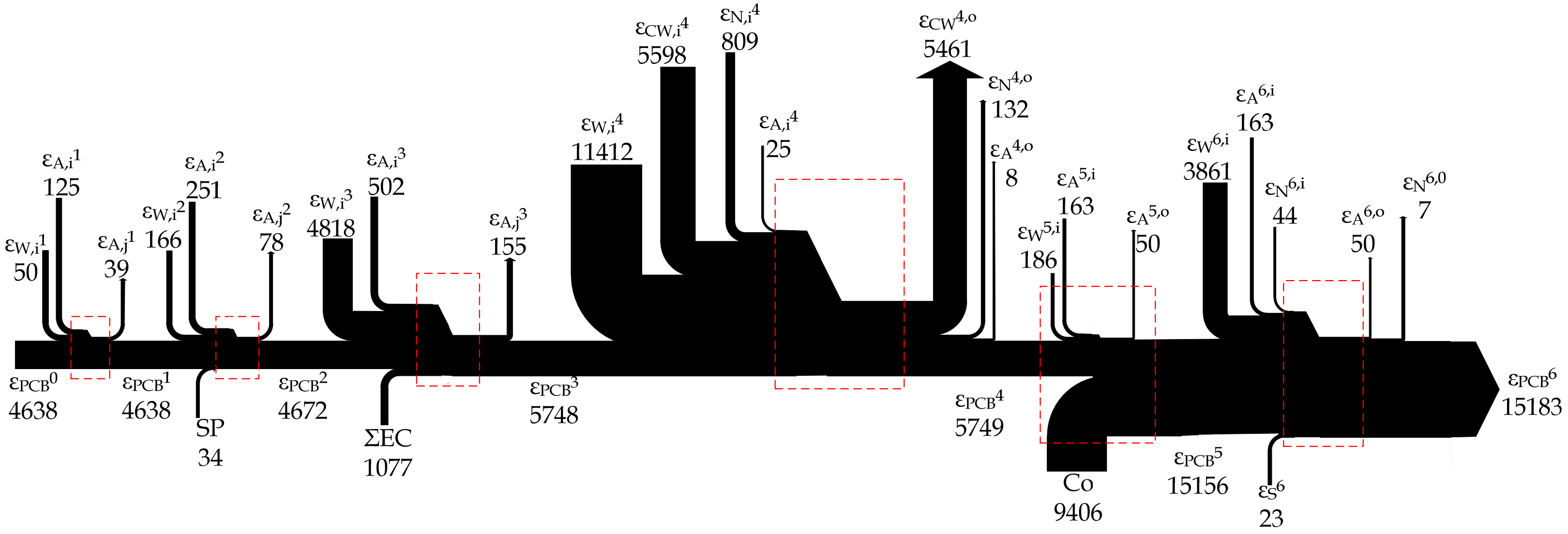
$$\dot{\delta\varepsilon}^{n}_{loss} = \dot{\varepsilon}^{n,in}_{W} - \sum_{k} \dot{\varepsilon}^{n,in}_{k,i} - \sum_{k} \dot{\varepsilon}^{n,out}_{k,j} \tag{3.12}$$

This shows in the PCB assembly line, the exergy is destroyed at a rate of 22MJ/kg of the product (PCB assembly).

From table 3.3, it can be noticed that there is an exergy loss of about 2 MJ in the making of unit PCB assembly. When the trend of the exergy destroyed (Fig 3.3) in the assembly line is analyzed, it is noticed that maximum of the exergy lost, about 56% is in the reflow soldering process. It could also be noted that compared to other processes, the reflow soldering processes requires more energy resources (Refer Table 3.1, particularly $\sum_{k} H^{4}_{k,i}$ and$W^{4}_{E,i}$). But this is also the process more which involves controlled heating of the entire board with components to about 230°C. Whereas in case of selective soldering, most of the energy consumed is spent on maintaining the solder pot temperature, to keep the solder molten. Moreover, only one connector unit is selectively soldered to the board. So this heating activity is limited and concentrated only on the solder pot. That may be the reason for less exergy loss in selective soldering than reflow soldering, in spite of reaching higher temperature of about 380°C.

Table 3.2 Net Exergy flows in the PCB assembly line per unit PCB Assembly (see appendix 11)

	Processing station / System (n)	Total (Work + Flow) Exergies in $\boldsymbol{\varepsilon^{n}_{W,i} + \sum_{H} \varepsilon^{n}_{H,i}}$		Total (Flow) Exergies out $\boldsymbol{\sum_{H} \varepsilon^{n}_{H,j}}$		Net Exergy Destroyed (Total in – Total out) $\boldsymbol{\delta\varepsilon^{n}_{loss}}$	
		kJ/kg	*kJ*	*kJ/kg*	*kJ*	*kJ/kg*	*kJ*
1	Barcode Etching	4811	433	4678	421	144	13
2	Solder paste printing	5100	459	4744	427	344	31
3	Components Stacking	11067	996	5900	531	5167	465
4	Reflow Soldering	23589	2123	11344	1021	12244	1102
5	Connector Stacking	15400	1386	15200	1368	200	18
6	Selective Soldering	19244	1732	15233	1371	4011	361
	Total	79211	7129	57100	5139	22111	1990



All units are in kJ/kg

Fig 3.2: Grassmann Representation of Exergy flows per unit mass of PCB Assembly

(All relevant data see appendix 9 and 10)

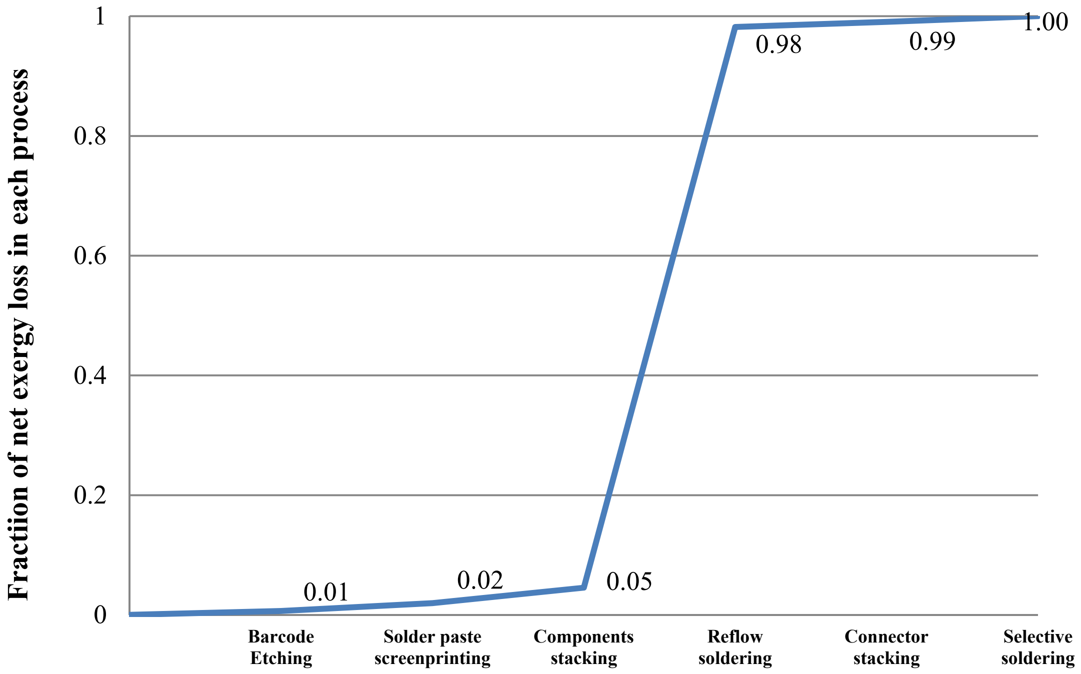


Fig 3.3: Fractions of exergy lost along the PCB assembly line

3.3 Exergetic Efficiencies

3.3.1 Net Use Efficiency

A process can be evaluated on the basis of the exergy utilized and destroyed during the manufacturing process. Efficiency of a process can be defined using the net exergies flowing in and out of the process. The maximum exergetic efficiency of the system can be defined as the ratio of total exergy output to the total exergy supplied to the system. In other way, this ratio is proportional to the exergy destruction inside the system, which is inherent in the system.

Maximum exergetic efficiency of a system

$$\eta_{\varepsilon}^{n,\max} = \frac{\sum \varepsilon_j^{n,}}{\sum \varepsilon_i^{n,}} \tag{3.13}$$

Where,

$\sum \varepsilon_j^{n,}$ - Sum of all exergies flowing out of subsystem ‘n’.

$\sum \varepsilon_i^{n,}$ - Sum of all exergies flowing in to subsystem ‘n’.

But in a conventional manufacturing setup, not all the output exergies are utilized. In many cases, the exergies carried by the wastes are dumped unutilized. In this assembly line also, large quantities of exergy are dumped into environment. Of the various output exergy flows, only the product is utilized in next station. The perception in this analyzes is that the efficiency carried by the PCB assembly is fully required in the next station of the assembly line. With this viewpoint, the efficiencies can be redefined with the product achieved at the station. Then the ratio of the exergy carried by the product (PCB assy.) to the total exergy invested in that system can be termed as the actual exergetic efficiency. This is also termed as rational efficiency or effectiveness (Szargut, J, 2005).

Actual exergetic efficiency of the system,

$$\eta_\varepsilon^{\mathrm{n,\,Act}} = \frac{\varepsilon_{PCB,j}^{n,out}}{\sum \varepsilon_i^{n}} \tag{3.14}$$

Where,

$\varepsilon_{PCB,j}^{n,out}$ - Total exergy carried by the product at the exit of the substation.

$\sum \varepsilon_i^{n}$ - Total exergy fed to the subsystem through various flows.

But for evaluation of manufacturing process, it is disputed to use only a selected exergy flow quantity (product exergy) as the objective function or purpose of the process. It may vary case to case. For example in drilling a small hole in a large mass of material, the output (product) exergy can be the exergy carried by the large mass or the small hole (removed material). Then, the exergetic efficiencies depend on the perspective of the analyzer. Relevance of these exergy efficiencies (equation 3.14), as the ultimate metric for assessing the manufacturing process sustainability should be weighed carefully (Gutowski, T.G. et al, 2009).

Using the above equations (3.13 and 3.14), the efficiencies of the individual stations (processes) were determined. Similarly the maximum and actual exergetic efficiency of the assembly line was also determined and tabled (See appendix 13).

Maximum exergetic efficiency of the assembly line,

$$\eta_{\varepsilon}^{\mathrm{L,\,max}} = \frac{\sum_{n=1}^{6}\sum_{j}\varepsilon_{j}^{n,}}{\sum_{n=1}^{6}\sum_{i}\varepsilon_{i}^{n,}} \tag{3.15}$$

Actual exergetic efficiency of the assembly line,

$$\eta_{\varepsilon}^{\mathrm{L,\,act}} = \frac{\sum_{n}\varepsilon_{PCB}^{n,out}}{\sum_{n=1}^{6}\sum_{i}\varepsilon_{i}^{n,}} \tag{3.16}$$

Where,

$\sum_{n}\sum_{j}\varepsilon_{j}^{n,}$ - Sum of all exergy flowing out of the subsystems

$\sum_{n=1}^{6}\sum_{i}\varepsilon_{i}^{n,}$ - Sum of all exergies flowing in to the subsystems

$\sum_{n}\varepsilon_{PCB}^{n,out}$ - Sum of exergy carried by the PCB assembly after processing.

Using these efficiencies (see appendix 13) a comparative study of the individual subsystems for their exergy destruction and exergy utilization was carried out. Like explained, the maximum exergetic efficiency (equation 3.13) is proportional to the exergy destroyed inside the subsystem. The actual exergetic efficiency (equation 3.14), can be considered to signify the proportions of the outflowing exergies which is utilized in subsequent operations. In Fig 3.4, these efficiencies of the subsystems are pictorially compared.

From Fig. 3.4, it could be concluded that most of the processes use maximum of the output exergies and their actual efficiencies are close to the maximum possible efficiency. But Reflow soldering process is an exception in which the gap between the actual and maximum is widest. The actual efficiency of reflow soldering process is about 24 %, which is half of the maximum efficiency (48%). These values are very lower than the overall line efficiencies, which has a maximum efficiency of 72% and actual efficiency of 65%. To understand the reasons for this drop, the contribution of various exergy flows are to be studied in detail.

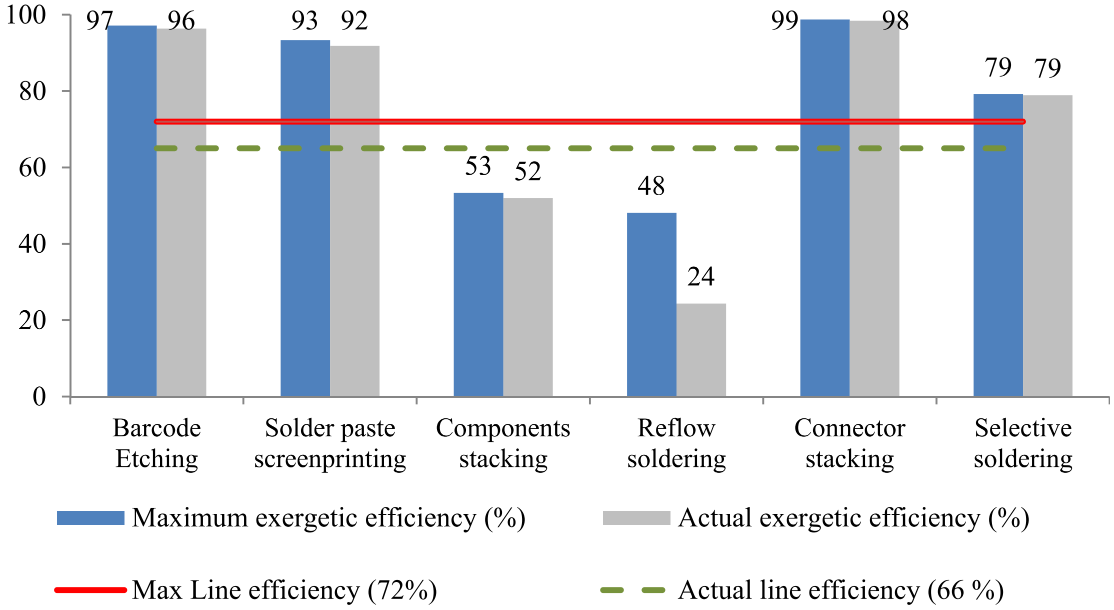


Fig 3.4: Comparison of Exergetic Efficiencies of the processes in the assembly line

A comparative analysis of various exergy flows in the assembly line helps to reason the low efficiencies in the assembly line. So exergies flows in each subsystem are grouped into three categories, namely total work exergies in ($\boldsymbol{\varepsilon}^{n}_{W,i}$), total flow exergies in ($\sum_{H} \boldsymbol{\varepsilon}^{n}_{H,i}$) and total flow exergies out ($\sum_{H} \boldsymbol{\varepsilon}^{n}_{H,j\mathrm{j}}$). These lumped quantities were stacked against the actual exergetic efficiency ($\eta_{\varepsilon}^{\mathrm{n,\,Act}}$) of each subsystem. In Fig. 3.5, in each subsystem, the above lumped categorizes were compared with one another with the exergy fractions against the total value ($\sum_{H} \boldsymbol{\varepsilon}^{n}_{H,i} + \sum_{H} \boldsymbol{\varepsilon}^{n}_{H,j} + \boldsymbol{\varepsilon}^{n}_{W,i}$) in that subsystem. And the exergetic efficiency is plotted with line connecting the efficiency values in each subsystem.

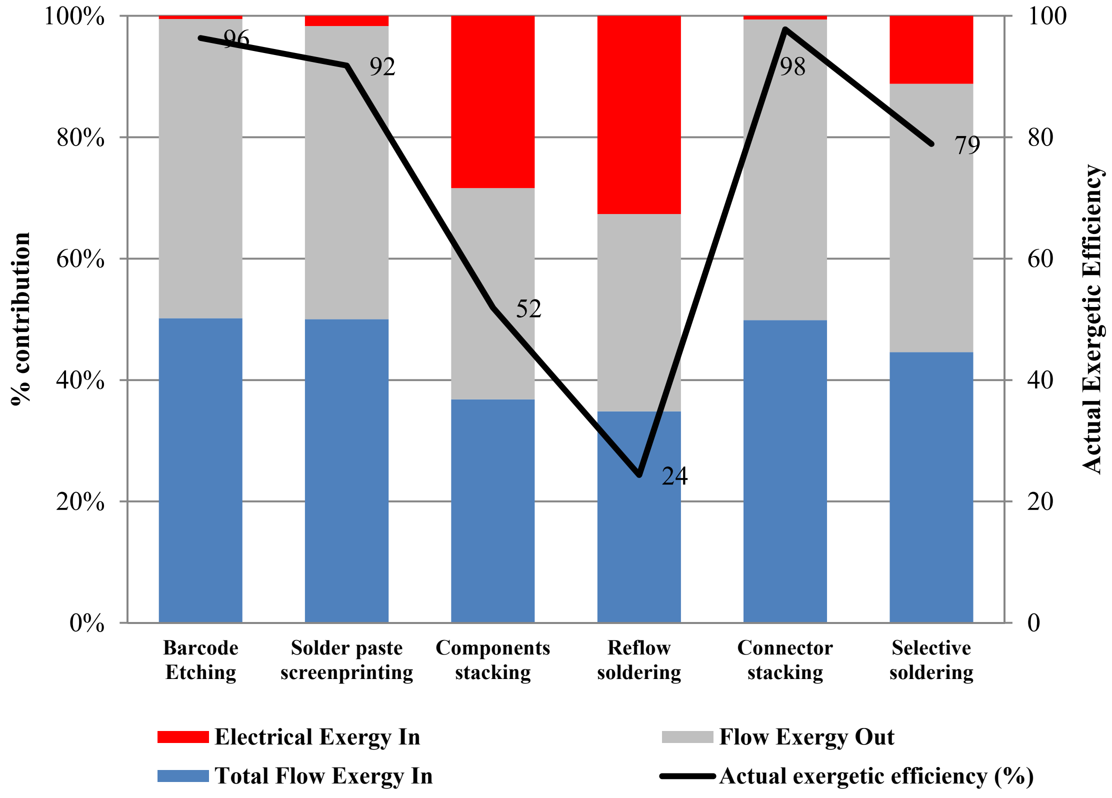


Fig. 3.5: Comparative Analyzes of various exergy flows through the PCB assembly

From Fig 3.5, it could appear that the materials flowing out of the subsystems carry about 80% of their original exergy with which they enter the system. But this can vary case to case. For example, let us consider two auxiliary flow exergies flows, say exergy carried by water and the nitrogen gas in reflow soldering process (See appendix 9). For a unit PCB assembly, the exergy carried by the nitrogen gas, which enter the subsystem with 72.8 kJ of exergy, is reduced to 11.8 kJ after utilization in reflow soldering. But in the case of water, the exergy content remains almost intact, with a small exergy loss ($\boldsymbol{\varepsilon_{CW,i}^{4}} - \boldsymbol{\varepsilon_{CW,j}^{4}}$) of about 12 kJ per PCB assembly only. This rich content is because the chemical exergy content of water remain intact (based on the adopted assumptions), and only their physical exergies are changed during the assembling process. This also means, the quality of water is remains good which encourages recycling of water.

From Fig. 3.5, the exergetic efficiencies are observed to be low for processes which consume more electrical exergy. This electrical exergy provided to the process gets converted primarily into heat or mechanical work. It is in this energy transfer process that lot of useful exergy is wasted (heat dissipation, friction). Utilization of electrical exergy in the system plays a vital role in determining the net exergetic efficiency of the system.

3.3.2 Electrical Exergy use efficiency

Among various exergy streams, electrical exergy is predominant and it is consumed at a rate of about 1.85 MJ per PCB assembly (see appendix 7). In mechanical assembling process under the prevailing condition (As explained chapter 2), exergy lost in product material is insignificant (as observed from Appendix 8 and Fig. 3.2). On observing exergy of auxiliary flows (See appendix 12), it could be observed that for a unit PCB assembly, the auxiliary materials (air, water and compressed air) lose only about 22% of the exergy content inside the system. So the majority of the lost exergy should be from the electrical exergy. This value cannot be fully attributed for the unaccounted exergy out-streams ($\varepsilon_{\lambda q}$), which is assumed to carry zero exergy (as explained in section 3.2.1). This invokes interest to study the utilization pattern of electrical exergy.

From observing the consumption pattern, it is noticed that the maximum electrical work was consumed while material is processed. But there are many occurrences in which the machines were running idle during the production time. To evaluate this passive consumption, one typical production shift was studied in detail. In an assembly line where the provision for work-in-progress inventory is to be maintained at minimum level (about 10 panels, as explained in chapter 2), the stoppage of one machine forces the entire line to stop. But as long as the machines are plugged to an electrical power source, machines continue to absorb some quantities of electrical work. This may be acceptable for small users and high efficiency electrical devices but may not applicable for the ovens. Due to high startup times, the ovens are made to maintain their temperatures throughout the production shift.

The efficiency of a system in terms of it electrical exergy utilization is derived with their necessary and auxiliary use quantities as defined in section 2. The electricity use efficiency ($\boldsymbol{\eta^{n}_{E\varepsilon}}$) of the subsystem can be calculated as the ratio of necessary electrical exergy (Work) to the total electrical exergy consumed by the subsystem for a unit PCB assembly.

$$\boldsymbol{\eta^{n}_{E\varepsilon} = \frac{W^{n}_{E,nec}}{W^{n}_{E,i}}} \tag{3.17}$$

Where,

$\boldsymbol{W^{n}_{E,nec}}$ - Electrical work consumed during the active phase in the subsystem ‘n’.

$\boldsymbol{W^{n}_{E,i}}$ - Total Electrical work consumed by the subsystem ‘n’.

Similarly the Electricity use efficiency for the whole assembly line ($\boldsymbol{\eta^L_{E\varepsilon}}$) can be derived as

$$\boldsymbol{\eta^L_{E\varepsilon}} = \frac{\sum_n \boldsymbol{W^n_{E,nec}}}{\sum_n \boldsymbol{W^n_{E,i}}} \tag{3.18}$$

Where,

$\sum_n \mathbf{W^n_{E,nec}}$ - Sum of the active electrical work consumption in individual subsystems.

$\sum_n \mathbf{W^n_{E,i}}$ – Total electrical exergy invested in the manufacturing line.

Electrical use efficiency of the assembly line is just about 55%, which denotes that rest of the energy consumed is not contributing for the assembling process.

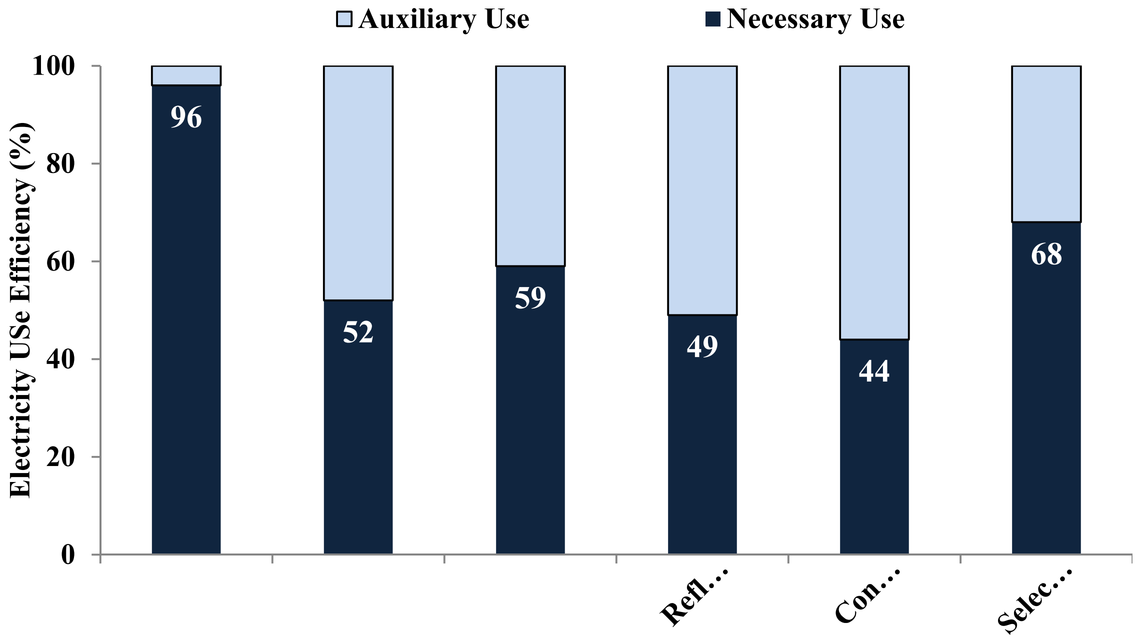
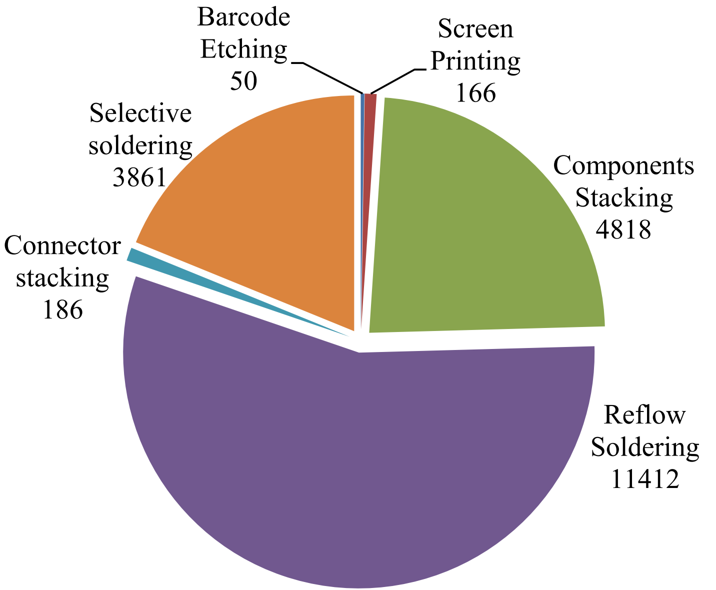


Fig 3.6: Efficiency of Electrical Exergy Utilization in PCB assembly line

From the Fig. 3.6, it could be evidenced that except for laser etching, the other machines operate at nearly the same electricity use efficiency, around 50%. But the actual magnitudes of the energy consumed ($\boldsymbol{W^n_{E,i}}$) are not the same. For example, though reflow soldering and connector stacking operation run at a nearly same efficiency, their actual intensities are very different. As evidenced in Fig. 3.7, the reflow soldering process consumes at least sixty times more energy than that of connector stacking. Unlike other machines, the ovens are designed to run continuously to maintain the set point temperatures. So the power consumption is almost uniform during the shift, resulting in poor utilization.



All values are in kJ/kg

Fig 3.7: Electrical Exergy Consumed for various process in the assembly line

4. Discussion

4.1 Evaluation of Resource utilization aspect of Sustainability

4.1.1 Exergy based sustainability metric

As discussed earlier (Chapter 1), the scientific and industrial communities invest a significant effort in a search of a universal, unambiguous metric to assess the sustainable development in different domains as well as globally. Manufacturing products and processes must be the part of such assessments and proper selection of sustainability metrics is an important direction of related efforts. Like demonstrated in this exercise so far, any manufacturing product and process can be assessed in terms of exergy, to study the resource utilization aspect. For developing optimized designs, the exergies of the associated resources indicate their resource intensities without any ambiguity. Moreover, the same metric may be used for various kinds of energy and material resources (otherwise considered as physical entities, as mass and energy). So during the product/process development, inclusion of exergy analysis helps to evaluate some aspects of the resources sustainability of a product/process.

The exergy carried by the product is a physical indicator that may demonstrates the resource intensity of the product through exergy balances and efficiency definitions. The exergy content at the given thermodynamic state of a resource also reveals the potential available with the resource to pursue on the secondary and/or subsequent lifecycles. At the end of a lifecycle, the discarded products also carry significant quantity of exergy potential.

The exergy indicates the resource "intensity," a difference of a potential between the existing (current) state, and an ultimate dead state (characterized with the presence of equilibrium between a system and its surroundings). Continuous utilization in secondary lifecycles extracts these available potentials, which may be devised with the reuse, remanufacturing and recycling options. On this basis, comparative studies can be carried out between two products or resource options, which can help to judge the sustainability of the product.

In this exercise, it was observed that the resource intensity of the 90g PCB is about 1360 kJ of exergy ($\boldsymbol{\varepsilon_{PCB,j}^{6}}$) at the end of manufacturing (assembling) process. This is carried in the form of chemical exergies possessed by the product materials associated with the PCB. After the utilization phase in the automobile, at the end of life the PCB dumped in the landfill may possess nearly the same quantity of exergy. However, not only that actual, physically present resource quantity is available, rather the product has an "imbedded" energy resource acquired during manufacturing that may be revealed only if a LCA in exergy terms is performed. To optimally reclaim the actual hidden potential, the PCB may have to undergo second lifecycle after reuse/ remanufacturing/recycling options as explained earlier (Sec. 1.2). On the other hand, the existing PCB can be redesigned to use optimal resources with an alternate more sustainable design. That could mean that one may perform design optimization with exergy as one of the constraints.

Similarly from the sustainability viewpoint, the process may be assessed on the basis of exergetic efficiencies. Like explained earlier (Sec 3.3), the exergetic efficiency of the process directly indicates the effectiveness of a resource utilization and the exergy loss is the indicator of resource destruction happening inside the system. The low value of 24% in reflow soldering (see appendix 13), precisely enumerates the limitations of the existing reflow soldering technology. With replacement of lead solders with lead-free alternatives, within the confines of the same manufacturing technology, requires reaching higher temperatures for soldering. This will increase the resource consumption, particularly electrical exergy. This can further worsen current situation and lower efficiencies. So, the trade-offs must be considered between the environmental impact and resources use within the given technology, or a transformational technology must be developed (Sekulic, D.P., 2011)

Moreover the exergies of the outgoing streams carry their resource intensities, which may cause local disturbances when dumped into the environment. In the case considered, water is continuously recycled for few more cycles and only its physical exergy is transferred to the environment. Since physical exergy of water constitutes a small value, the most of their exergy would be reutilized. But the exergy of the exhaust gases are transferred to the surroundings often without any use. The exergies of the compressed air out may include some physical exergy (chemical exergy will not significantly differ at the exit from the value at the inlet) which may indicate a measure of a resource spent (availability of compressed air used for the process). The practical step for reducing this exergy loss would be to minimize the compressed air requirement and effective utilize the available compressed air.

Considering the exergy investments in different production phases, the analyses of exergetic efficiencies may point out the directions for further development. Like in this case study, the comparative analysis of electrical exergy investments between active and passive production regimes indicate the exergy potential lost during passive (idle) phases of production. In this assembly line about 45% of the electricity invested is not productive due to maintaining the furnace temperature continuously. There is a need to develop alternate production methods featuring the resource consumption that is comparatively less than the existing state-of-the-art processes. To replace conventional soldering techniques with new transformational, developing technologies (like laser soldering, conductive adhesives etc.) is usually a big leap forward which may demand more support from the engineering communities, and may impact in diverse domains of sustainability (economic impact, social impact etc.).

One of the tenets of sustainability is to earn economic benefits. To understand the economics, the costs associated with exergies are to be evaluated. This kind of studies has been developed in energy field and is called 'Thermo-economics' or 'Exergonomics'. This methodology is virtually never implemented for energy using manufacturing systems (except for large petrochemical and process industry plants (Bejan, A., et al., 1996) The cost of a unit exergy in a resource depends on the availability and market value of the resource. On this basis, the exergies can be represented in terms of their monetary values. On further extension, the cost associated with the rate of exergy destruction inside a process can also be evaluated.

4.1.2 Limitations of Exergy metrics

Like demonstrated, the exergy analyzes can help to evaluate different types of resources in same units without compromises or ambiguities. For an extensive application, the analysis method is needed to be simple to use. But the intricacies of exergy analysis impede the wide spread application. At present, concept of exergy analysis for non-energy systems are in developing stage. Although the significance of such an analysis looks promising, the full potential of it needs to be explored.

Optimum use of exergy, followed with a minimum exergy loss can be the premise for designing products, processes and systems for sustainable development. But relevant exergy data for the concerned processes and associated resources may not be available before hand, during the design phase. Many advanced polymers and chemical compounds, which are effectively used in recently developed products and production systems, may need further characterization. So a precise tracking of their associated exergies can be cumbersome. An elaborate database, which could serve as a guide book is to be developed. For a complete evaluation of a product, exergy analysis needs to be done for all stages of a product lifecycle. But in many cases, design features of the product may not be considered as relevant beyond the quality standards of raw materials procured. So this means, a holistic approach involving the entire lifecycle chain is necessary.

Like explained, the economics of exergy can be developed. But to consider it as early as the design phase, information on cost per unit of exergy for different resources is needed. Till a versatile and widely verified data bases are secured, a precise evaluation of the cost benefits at the design stage may not be possible.

In this exercise, although the usability of the exergy method was demonstrated, there are certain limitations in regard to the exergy metric values generated. The exergy values calculated where subject to assumptions during the identification and quantification stages (explained in Chap. 2). Due to data insufficiencies and propriety concerns, only 90% material content of the product was considered for the analysis (Appendix 3). The contribution of the remaining 10% by mass was assumed to be insignificant. There were also limitations in the precision of the electricity and chemical exergies data collected ((explained in sections 2.3.3 and 3.2.2 respectively). The results obtained on exergy loss and exergetic efficiencies (in sections 3.2.3 and 3.3 respectively) are precise within the limitations of the assumptions (as explained in chapters 2 and 3).

4.2 Limitations of traditional energy intensive practices

Traditional manufacturing processes are designed to deliver quality products with the resource use as a factor of cost for product performance. Resources and process parameters are optimized for the best quality and its associated economics. But in sustainable manufacturing, minimization of resource use and elimination of wastes and harmful concerns should be included in an objective function. The challenge for sustainable development lies in designing profitable products and processes, which must satisfy much more complex objective functions – as a rule not explicitly formulated. In the pursuit for minimization of resource use and elimination of wastes, a full exploitation of potentials hidden in the resources is necessary. The exergy approach brings more than the energy approach. The additional aspect addressed is the quality of an energy resource (included through thermodynamic irreversibility and expressed through exergy losses). So, the resource use efficiencies of manufacturing processes are to be assessed to identify the critical factors which essentially affect both (i) quantity, and (ii) quality of resources use for the product sustainability.

Lead free soldering is the most significant industrial initiative that improves the sustainability rating of the PCB assembly and electronic products. This study was, however, conducted only for a lead containing soldering assembly line. This traditional process consumes resources (both material and energy) at a rate of about 28MJ/kg of PCB assembly (see appendix 12). As explained earlier (see Section1.3), the lead free alternatives demand more process resources than the existing lead soldering method.

Since the technology would not be altered (except for material change and operating parameters change – with the sequence the same), the switch to lead free solders is expected to have higher resource intensities. This may create reservations regarding the resources effectiveness of the new lead-free processing. However, the new approach is mandated by the requirement that is beyond the energy/material resource use, in the domain of environmental and human (societal) protection. This is an excellent example of a complex trade-off situation imposed by a sustainable development implementation at the level of a manufacturing process.

During a soldering process, the solder alloy is melted and let to make joint, driven by surface tension between the connectors/leads, substrate and liquid solder alloy made of Sn-Pb. In this 90g PCB assembly, the quantity of eutectic Sn-Pb alloy solder is about 1.5g. Theoretical calculations show that the energy requirement for a complete melting 1.5g of Sn-37Pb solder alloy is only about 50 J. But in this assembly, the soldering processes together demand an electrical exergy of about 1.4 MJ for each PCB assembly!

The difference between the theoretical minimum resource use and an industrial manufacturing process is about O (10^5)! (See appendix 15). Although an idle running of the ovens and other losses associated with the manufacturing system could cause this high value, a fundamental reason is the necessity to use a large quantity of exergy to heat the other material flows (including some auxiliary flows, and surroundings). More precisely, this large need is because in a traditional soldering technology, along with the solder alloy, the components, and the entire chamber are to be heated to a temperature as high as 230°C, and subsequently cooled without utilizing the invested energy resources. The energy invested in heating is dumped into the environment by the subsequent cooling processes. Moreover, a lack of instantaneous heat generation in any such conventional method, costs more resources for processes to maintain the required thermal state inside the system. IN the context of sustainability, this limits the performance of the soldering process dramatically.

Since the resource use margin between the existing technology and the assessed minimum resource use is too wide, it cannot be overcome within the present technology solutions. This demands an alternate non-intensive (resource conserving) technology (if other trade-offs permit such a change), which must be commercially viable and industrially efficient. Few techniques under development are the electrically conductive adhesives (ACA), laser soldering, ultrasonic soldering, solder jet printing etc. Only a limited heating is required in these techniques, the losses are expected to be minimum. But as of now, there are reservations about the applicability of these techniques for a mass production of dense circuit boards.

5. Conclusion

5.1 Summary

It appears that sustainable development will be the only option for the society in the twenty first century. But to navigate and monitor the progress, metrics for measuring sustainability are needed. One of the aspects for such a development is the optimal use of appropriate materials and energy resources, as imposed by the requirements of sustainable development. The universal metric for assessment of resources use may be offered by thermodynamics. The metric evaluates at a given state of the system, the level of available energy used or obtained by the system. This available energy is also called exergy. Potency and versatility of such a metric, so far has been demonstrated and extensively used in energy systems. There are challenges in using it in non-energy systems, such as manufacturing systems. One such exercise was carried out in this work and it is applied in manufacturing of PCB assembly by soldering process.

Like every resource is quantified in mass and energy quantities, it can be in measured in terms of exergies associated with the resources. The exergy analysis can enumerate both the resource quantity and its hidden quality. In the case of this study, each PCB is weighing 90 g and carries about 1.4MJ of exergy. It was estimated that for each PCB assembly, about 2MJ of exergy is destroyed along the path of product manufacturing by the adopted technique, which involves soldering. This value adds to the overall resource requirement that can (and should) be determined for a PCB assembly during its lifecycle. This relatively high value (i.e., about 22 MJ/kg of the product) signifies limitations of a traditional (although the state of the art) soldering process, one of the traditional manufacturing techniques.

In the existing soldering technology, apart from the required solder quantity, the energy resources are invested for inevitable heating of the significant mass of associated materials, which increases the resource consumption. The difference between the theoretical minimum energy requirement and the existing practice is $^{\text{for}}$ multiple orders of magnitude, i.e. O (10^4). It is assessed that no appreciable investments of capital, energy and material resources and time can bring the existing technology closer to the theoretical minimum values – unless novel, transformational technologies are introduced. This, for example, signifies a need for developing alternate joining technologies and/or netshape assembly procedures that may operate closer to the idealized conditions.

5.2 Future Areas of Interests

Viabilities of exergy analysis for non-energy (manufacturing) systems analysis were demonstrated on the identified PCB assembling process. In the current work, exergies associated with the identified product and the associated assembly line were quantified and analyzed. This analysis can be further extended into a thermo-economic analysis for evaluating economic significance by appropriately identifying the cost value of a unit of exergy, hence converting an exergy balance into a monetary objective function. Similarly, the exergy flows may be pondered to express the environmental impact associated with the products, auxiliary by-products and released effluents,

To have the full assessment of a product, in this case the chosen PCB assembly, the analysis has to be performed along its lifecycle. Moreover, such effort may be performed for any subsequent life cycle as well. The main premise is that these material/energy resources can be recovered in part from the process/product and or effluents and put back into another lifecycle, through reuse/remanufacturing/recycling options.

In evaluation of the process exergies, it was found that 45% of the net energy consumed is used in passive phase of production. Effective counter measures can be developed to improve the active utilization phase over the passive phase. This can be done by improving the productivity and by reducing the line stoppages. Methods can be developed to maintain an optimal temperature in the ovens during the passive phases of operation and hike the temperatures to the required values during the active phase of production. This variable consumption pattern can reduce the passive phase electricity consumption. But these remedies within the given technologies, most likely would not lead to significant reductions of resources use. The solution has to be uncovered in developing and implementing entirely new process technologies, the so-called transformational technologies.

A detailed study the exergy destruction in the soldering ovens can be carried out. Similar studies as conducted for lead solders, should be carried out for lead-free alternatives, which are of the current interests in a search for sustainable development alternatives in a PCB assembling process (for example, reduction of the ecological footprint). Such studies will offer a margin of difference between the existing (less energy intensive!) soldering technologies and lead-free alternatives (most likely more energy intensive but with a smaller ecological footprint).

6. Appendix

List of Appendix

Appendix 1: List of Sub-components on the PCB assembly

S. No.	Component Type	No. of Units
1	PCB	1
2	Connector	1
3	Filter	1
4	Resonator	2
5	Integrated Circuits	7
6	Transistor	7
7	Zener diode	9
8	Diode	15
9	Capacitor	99
10	Resistor	151
	TOTAL	293

Appendix 2: Mass of Product Materials, measured along the assembly line using weighing scale

Instrument: Digital weighing scale

Least count: 0.0001g

S. No.	Product material	Denoted by	Average mass considered for evaluation (g)
1	PCB	$\mathbf{m}_{PCB}^{0}$	42.0
2	Etched PCB	$\mathbf{m}_{PCB}^{1}$	42.0
3	Etched PCB with Solder paste deposited	$\mathbf{m}_{PCB}^{2}$	43.0
4	Etched PCB with Solder paste and components stacked	$\mathbf{m}_{PCB}^{3}$	54.5
5	Reflow soldered PCB assembly	$\mathbf{m}_{PCB}^{4}$	54.4
6	Connector	$\mathbf{m}_{Co}^{5}$	35.0
7	Reflowed PCB with Connector	$\mathbf{m}_{PCB}^{5}$	89.4
8	Selective soldered PCB assembly	$\mathbf{m}_{PCB}^{6}$	90.0

Appendix 3: Auxiliary Materials and their recorded values and quantified masses.

Materials and Intake type and conditions	Process	Mass flow rate (g/s)	Mass consumed per board (g)
Compressed air *Cyclic Consumption* $P_A^i = 100$ *Psig* $= 690$ *kN/m*^{2} $T_A^i = 17^oC = 290.15$ *K* $\varphi_A^i = ¼” = 8$ *mm*	Barcode etching	9.64	48.2
	Solder paste screen-printing	9.64	96.4
	Component stacking	9.64	192.8
	Reflow soldering	9.64	9.64
	Connector stacking	9.64	62.7
	Selective soldering	9.64	62.7
Nitrogen *Continuous Consumption* *Time : 36000 s / shift* *Output: 900 boards*	Reflow soldering $P = 80$ *Psig* $= 552$ *kN/m*^{2} $V = 540$ *n l/min* $= 0.009$ *m*^{3}*/s*	10.5	420
	Selective soldering $P = 0.3$ *kN/m*^{2} $T_N^{5,i} = 55^oC = 338.15$ *K* $v = 4500$ *fpm* $= 22.86$ *m/s*	0.57	23
Water *Continuous Consumption* *Time : 36000 s / shift* *Output: 900 boards*	Reflow soldering $\varphi_{CW} = 25$ *mm* $T_{CW}^{5,i} = 279.15$ *K*	245	9800

Appendix 4: List of Product Materials included for evaluation

S.No	Element	Formula / Structure	Mass (g)	% mass
1	Copper	Cu	27.36	30.40
2	Plastic-bakelite	(C8H9O)n	22.37	24.86
3	Epoxy Resin	(C18H24O)n	11.28	12.53
4	Silica	SiO2	10.15	11.28
5	Zinc	Zn	4.2	4.67
6	Solder alloy	63Sn-37Pb	1.5	1.67
7	Aluminum	Al	1.09	1.21
8	Alumina	Al2O3	0.59	0.66
9	Butyl Rubber	C9H16 (C5H8. C4H8)	0.42	0.47
10	Barium oxide	BaO	0.26	0.29
11	γ-Butyrolactone	C4H6O2	0.22	0.24
12	Cellulose	(C6H10O5)n	0.15	0.17
13	Titanium oxide	TiO2	0.14	0.16
14	Tin	Sn	0.13	0.14
15	Nickel	Ni	0.13	0.14
16	Silicon	Si	0.1	0.11
17	Ferric oxide	Fe2O3	0.09	0.10
18	Iron	Fe	0.08	0.09
19	Talc	3MgO/4SiO2/H2o	0.07	0.08
20	Lead	Pb	0.05	0.06
21	Phenol Formaldehyde Resin	(C8H9O)n	0.04	0.04
22	Epoxy resin bromide	(C8H23O2Br)	0.03	0.03
23	Silver	Ag	0.03	0.03
24	Zinc oxide	ZnO	0.03	0.03
25	Zirconium-dioxide	ZrO2	0.02	0.02
26	Silicone cmpd	(SiC2H6O)n -	0.02	0.02
27	Gold	Au	0.02	0.02
28	carbon black	C	0.01	0.01
29	Nickel-monoxide	NiO	0.01	0.01
30	Others[†]		9.41	10.46

[†] Includes materials that are < 0.01 % by mass and undisclosed proprietary materials.

Appendix 5A: Enthalpy in the auxiliary material flows consumed for unit PCB assembly

Materials	Process		Cycle time	Mol Wt.	Temp., T_i	Mass flow rate	Mass per PCB	Sp. Heat of air	Enthalpy Carried per PCB assembly	
			s	g/ mol	K	g/s	g	kJ/kg.K	J	kJ/kg
Compressed Air	Barcode etching	In	10	28.97	290.15	9.6	48.2	1.005	14055.16	156.17
		Out		28.97	293.15	9.6	48.2	1.005	14200.48	157.78
	Solderpaste screen-printing	In	20	28.97	290.15	9.6	96.4	1.005	28110.31	312.34
		Out		28.97	293.15	9.6	96.4	1.005	28400.96	315.57
	Component stacking – I	In	20	28.97	290.15	9.6	96.4	1.005	28110.31	312.34
		Out		28.97	293.15	9.6	96.4	1.005	28400.96	315.57
	Component stacking – II	In	20	28.97	290.15	9.6	96.4	1.005	28110.31	312.34
		Out		28.97	293.15	9.6	96.4	1.005	28400.96	315.57
	Reflow soldering	In	2	28.97	290.15	9.6	9.6	1.005	2811.03	31.23
		Out		28.97	293.15	9.6	9.6	1.005	2840.10	31.56
	Connector stacking	In	13	28.97	290.15	9.6	62.7	1.005	18271.70	203.02
		Out		28.97	293.15	9.6	62.7	1.005	18460.62	205.12
	Selective soldering	In	13	28.97	290.15	9.6	62.7	1.005	18271.70	203.02
		Out		28.97	293.15	9.6	62.7	1.005	18460.62	205.12
Nitrogen	Reflow soldering	In	40	28.01	292.15	10.5	419.4	1.040	127428.82	1415.88
		Out		28.01	333.15	10.5	419.4	1.040	145312.03	1614.58
	Selective soldering	In	40	28.01	292.15	0.6	22.8	1.040	6805.93	75.62
		Out		28.01	328.15	0.6	22.8	1.040	7644.58	84.94
Water	Reflow soldering	In	40	18.01	279.15	245.0	9800.0	4.180	11435100.60	127056.67
		Out		18.01	288.15	245.0	9800.0	4.180	11803776.60	131153.07

Appendix 5B: Enthapy flow through subsystems per unit PCB assembly

S. no	Process	Energy flow	Symbol	Enthalpy	Hi	Hj
				kJ	kJ	kJ
1	Barcode Etching	PCB in	$H_{pcb,i}^{0}$	7.19	21.24	21.43
		PCB out	$H_{pcb,j}^{1}$	7.23		
		Etched dust out	$H_{ed,j}^{1}$	0.00		
		comp air in	$H_{A,i}^{1}$	14.06		
		comp air, out	$H_{A,j}^{1}$	14.20		
2	Solderpaste printing	PCB in	$H_{pcb,i}^{2}$	7.23	35.38	35.63
		Solder paste, in	$H_{sp,i}^{2}$	0.04		
		PCB out	$H_{pcb,j}^{2}$	7.23		
		comp air in	$H_{A,i}^{2}$	28.11		
		comp air out	$H_{A,j}^{2}$	28.40		
3	Component Stacking	PCB in	$H_{pcb,i}^{3}$	7.23	65.77	66.54
		ΣEC in	$H_{\Sigma C,i}^{3}$	2.32		
		PCB out	$H_{pcb,j}^{3}$	9.73		
		comp air in	$H_{A,i}^{3}$	56.22		
		comp air out	$H_{A,j}^{3}$	56.80		
4	Reflow soldering	PCB in	$H_{pcb,i}^{4}$	9.73	11575.07	11962.88
		PCB out	$H_{pcb,j}^{4}$	10.95		
		comp air in	$H_{A,i}^{4}$	2.81		
		comp air out	$H_{A,j}^{4}$	2.84		
		Nitrogen in	$H_{N,i}^{4}$	127.43		
		Nitrogen out	$H_{N,j}^{4}$	145.31		
		Water in	$H_{CW,i}^{4}$	11435.10		
		Water out	$H_{CW,j}^{4}$	11803.78		
5	Connector stacking	PCB in	$H_{pcb,i}^{5}$	10.95	41.36	42.32
		Connector in	$H_{Co,i}^{5}$	12.15		
		PCB out	$H_{pcb,j}^{5}$	23.86		
		comp air in	$H_{A,i}^{4}$	18.27		
		comp air out	$H_{A,j}^{5}$	18.46		
6	Selective soldering	PCB in	m6	23.86	48.96	52.00
		PCB out	m7	25.90		
		Solder, in	S7	0.03		
		Flux added, in	F7i	0.00		
		Flux vapors out	F7o	0.00		
		comp air in	a7i	18.27		
		comp air out	a7o	18.46		
		Nitrogen in	N7i	6.81		
		Nitrogen out	N7o	7.64		

Appendix 6: Electrical work (W_E) Measurement

Processing Equipment	Ph as e	Voltage	Current per panel		Processing time per panel	Active Work	Total Idle time per shift	Passive work	Total Electrical work	
(Condition)			Idle	Active	Active	per panel	For 450 panels/shift	per panel	per PCB assy	
	ϕ	Vi	I_{aux}	I_{nec}	t_{nec}	$W_{nec,i}$	T_{aux} x 450	$W_{aux,i}$	$W_{E,i}^{n}$	
(Units)	#	(V)	(A)	(A)	(s)	(J)	(s)	(J)	(J)	(kJ/kg)
Barcode etching	3	206	0.01	0.38 / 0.5	33 / 2	8367.72	20250	278.10	4322.91	48.03
Conveyor -1	1	117	0.01	0.44	5	257.40	33750	87.75	172.58	1.92
SP screenprinting	1	117	2.8	3.6	36	15163.20	19800	14414.40	14788.80	164.32
Conveyor -2	1	117	0.01	0.3	8	280.80	32400	84.24	182.52	2.03
Components staking -1	3	208	7	10.5	40	262080.00	18000	174720.00	218400.00	2426.67
Conveyor -3	1	117	0.38	0.5 / 0.7	5 / 5	702.00	31500	3112.20	1907.10	21.19
Components staking-2	3	208	7	10	40	249600.00	18000	174720.00	212160.00	2357.33
Conveyor -4	1	117	0.18	0.4	24	1123.20	25200	1179.36	1151.28	12.79
Reflow soldering	3	480	16	20	35	1008000.00	20250	1036800.00	1022400.00	11360.00
Conveyor -5a	1	117	0.01	0.4	9	421.20	31950	83.07	252.14	2.80
Conveyor -5b	1	117	0.38	0.42	8	393.12	32400	3201.12	1797.12	19.97
Conveyor -5c	1	117	0.01	0.44	8	411.84	32400	84.24	248.04	2.76
Conveyor -5d	1	117	0.44	0.40 / 0.6	8 /8	936.00	28800	3294.72	2115.36	23.50
Conveyor -5e	1	117	0.01	0.33	10	386.10	31500	81.90	234.00	2.60
Connector stacking	1	206	1.8	1.8 / 2	32/3	14955.60	20700	17056.80	16006.20	177.85
Conveyor -6a	1	117	0.42	0.5 /0.34	8/4	627.12	30600	3341.52	1984.32	22.05
Conveyor -6b	1	117	0.01	0.38	10	444.60	31500	81.90	263.25	2.93
Selective soldering	3	205	8	22	35	473550.00	20250	221400.00	347475.00	3860.83

Appendix 7: Electrical Exergy (ε_W) supplied for each process per unit PCB

S. No	Process	Electrical exergy ($\boldsymbol{\varepsilon_{W,i}^{n}}$)	
	(Units)	kJ/kg	kJ
1	Barcode Etching	50	4.50
2	Screen Printing	166	14.97
3	Components Stacking	4818	433.62
4	Reflow Soldering	11412	1027.05
5	Connector stacking	186	18.25
6	Selective soldering	3861	347.48
	Total	20493	1845.86

Appendix 8: Flow Exergy carried by PCB and associated components

Product & symbol	Physical Exergy $(\varepsilon^{phy}{}^{n}_{k})$	Chemical Exergy $(\varepsilon^{che}{}^{n}_{k})$	Total Exergy $(\varepsilon^{n}_{k} = \varepsilon^{phy}{}^{n}_{k} + \varepsilon^{che}{}^{n}_{k})$	
(Units)	(J)	(J)	(J)	(kJ/kg)
PCB (M_{PCB}^{0})	0.2	417411.8	417411.9	4637.91
Etched PCB (M_{PCB}^{1})	0.0	417411.8	417411.8	4637.91
Solder Paste (M_{SP}^{1})	0.0	3050.0	3050.0	33.89
PCB + SP (M_{PCB}^{2})	0.0	420461.8	420461.8	4671.80
Elec. Components (M_{EC}^{3})	0.0	96947.3	96947.4	1077.19
PCB + SP + EC (M_{PCB}^{3})	0.5	517290.8	517291.3	5747.68
Reflowed PCB (M_{PCB}^{4})	82.3	517291.0	517373.2	5748.59
Connector (M_{Co}^{5})	0.0	846524.6	846524.6	9405.83
PCB + Co (M_{PCB}^{5})	93.4	1363971.6	1364065.1	15156.28
Solder alloy (M_{S}^{6})	0.0	2033.3	2033.3	22.59
Final PCB assy. (M_{PCB}^{6})	341.68	1366088.8	1366430.5	15182.56

Appendix 9: Flow Exergies carried by Auxiliary Materials

Material & symbol (k)	Process		Physical Exergy $(\boldsymbol{\varepsilon^{phy}}{}^{n}_{k})$	Chemical Exergy $(\boldsymbol{\varepsilon^{che}}{}^{n}_{k})$	Total Exergy $(\boldsymbol{\varepsilon^{n}_{k} = \varepsilon^{phy}{}^{n}_{k} + \varepsilon^{che}{}^{n}_{k}})$	
			J	J	J	kJ/kg
Compressed Air (A)	Barcode etching	In	7793	3491	11284	125
		Out	0	3491	3491	39
	Solderpaste screenprinting	In	15586	6981	22567	251
		Out	0	6981	6981	78
	Component stacking	In	31173	13963	45136	502
		Out	0	13963	13963	155
	Reflow soldering	In	1559	698	2257	25
		Out	0	698	698	8
	Connector stacking	In	10131	4538	14669	163
		Out	0	4538	4538	50
	Selective soldering	In	10131	4538	14669	163
		Out	0	4538	4538	50
Water (CW)	Reflow soldering	In	14147	489728	503874	5599
		Out	1767	489728	491495	5461
Nitrogen(N)	Reflow soldering	In	62019	10781	72800	809
		Out	1092	10781	11873	132
	Selective soldering	In	3372	586	3958	44
		Out	74	586	661	7

Appendix 10: Chemical Exergy of various constituent compounds

Element/Compouds	Symbol / Formula	Mol. Wt	Specific Chemical Exergy		Source/ Method
		g/mol	kJ/mol	kJ/kg	
Copper	Cu	63.54	134.20	2112	Data table
Silica	SiO2	60.08	2.20	37	Data table
Aluminum	Al	26.98	795.70	29492	Data table
Alumina	Al2O3	101.96	15.00	147	Data table
Butyl Rubber	C_5H_8. C_4H_8	124.22	5043.97	40605	Group Con.*
Epoxy Resin	$(C_{18}H_{24}O)n$	284	9995.37	35195	Group Con.*
Plastic-bakelite	$(C_8H_9O)n$	121	4424.36	36565	Group Con.*
Barium oxide	BaO	153.33	252.00	1644	Data table
gamma-Butyrolactone	$C_4H_6O_2$	86.08	2072.24	24073	Group Con.*
Cellulose	$(C_6H_{10}O_5)n$	162.14	3013.44	18585	Group Con.*
Titanium oxide	TiO_2	79.87	21.70	272	Data table
Tin	Sn	118.71	551.90	4649	Data table
Nickel	Ni	58.69	232.70	3965	Data table
Silicon	Si	28.09	854.90	30434	Data table
Ferric oxide	Fe_2O_3	159.69	12.40	78	Data table
Iron	Fe	55.85	374.30	6702	Data table
Talc	$3MgO/4SiO_2/H_2O$	379.27	14.80	39	Data table
Lead	Pb	207.20	232.80	1124	Data table
Phenol Formaldehyde Resin	$(C_8H_9O)n$	121	4424.36	36565	Group Con.*
Epoxy resin bromide	$(C_8H_{23}O_2Br)$	347	10078.72	29045	Group Con.*
Silver	Ag	107.87	70.20	651	Data table
Zinc oxide	ZnO	81.39	22.90	281	Data table
Zirconium-dioxide	ZrO_2	123.22	63.964	519	Formation†
Silicone cmpd - - Dimethyl silicone	$(SiC_2H_6O)n$	74.14	2271.66	30640	Group Con.*
Gold	Au	196.97	59.9	304	Data table
carbon black	C	12.01	409.87	34127	Data table
Nickel-monoxide	NiO	74.69	23.00	308	Data table
Solder alloy	63Sn-37Pb	140.82	437.11	3104	mole fract.**
Zinc	Zn	65.39	134.20	5187	Data table
Air	$78N_2$-21O20.9Ar0.04CO_2	28.97	2.10	73	mole fract.**
Nitrogen	N_2	28.15	0.72	26	Data table
Water	H_2O	18.01	0.90	50	Data table

Source: Szarguts, J., (2005).

† Calculated from Gibbs free energy of formation reaction.

*Group Contribution method

**Contribution on the basis of mole fraction.

Appendix 11: Exergy Flow through the systems in manufacturing line per unit PCB assembly

S. No (n)	Process	Electrical exergy ($\boldsymbol{\varepsilon^{n}_{W,i}}$)		Total Flow Exergy in ($\sum_H \boldsymbol{\varepsilon^{n}_{H,i}}$)		Total Flow Exergy out ($\sum_H \boldsymbol{\varepsilon^{n}_{H,j}}$)		Net Exergy Destroyed $\boldsymbol{\delta\varepsilon^{n}_{loss}}$	
	(Units)	kJ/kg	kJ	kJ/kg	kJ	kJ/kg	kJ	kJ/kg	kJ
1	Barcode Etching	50	5	4763	429	4677	421	144	13
2	Screen Printing	166	15	4923	443	4749	427	344	31
3	Components Stacking	4818	434	6250	563	5903	531	5167	465
4	Reflow Soldering	11412	1027	12180	1096	11349	1021	12244	1102
5	Connector stacking	186	17	15216	1369	15207	1369	200	18
6	Selective soldering	3861	347	15386	1385	15240	1372	4011	361
	Total	20493	1844	58718	5285	57125	5141	22111	1990

Appendix 12: Work and auxiliary flow exergies through the manufacturing line per unit PCB assembly

S. No (n)	Process	Electrical exergy ($\boldsymbol{\varepsilon^n_{W,i}}$)		Total Auxiliary Flow Exergy in ($\sum_{au}\boldsymbol{\varepsilon^n_{au,i}}$)		Total Auxiliary Flow Exergy out ($\sum_{au}\boldsymbol{\varepsilon^n_{au,j}}$)		Total Product Flow Exergy in ($\sum_{Pr}\boldsymbol{\varepsilon^n_{Pr,i}}$)		Total Product Flow Exergy out ($\sum_{Pr}\boldsymbol{\varepsilon^n_{Pr,j}}$)	
	(Units)	kJ/kg	kJ	kJ/kg	kJ	kJ/kg	kJ	kJ/kg	kJ	kJ/kg	kJ
1	Barcode Etching	50	5	125	11	39	3	4638	417	417	4638
2	Screen Printing	166	15	251	23	78	7	4672	421	4672	421
3	Components Stacking	4818	434	502	45	155	14	5748	517	5748	517
4	Reflow Soldering	11412	1027	6433	579	5601	504	5748	517	5749	517
5	Connector stacking	186	17	163	15	50	5	15154	1364	15154	1364
6	Selective soldering	3861	347	207	19	58	5	15178	1366	15182	1366
	Total ($\sum_n$)	20493	1844	7680	691	5980	538	51133	4602		

Total exergy supplied to the process (in the form of work and auxiliary materials)

$$= \sum_n \boldsymbol{\varepsilon^n_{W,i}} + \sum_{au} \boldsymbol{\varepsilon^n_{au,i}} = 20493 + 7680 = 28173 \text{ kJ/kg}$$

Exergy content of the auxiliary materials destroyed in processing,

$$\sum_{n=1}^{6} \delta\varepsilon_{loss}{}^{n}_{au} = \sum_{au} \varepsilon^n_{au,i} - \sum_{au} \varepsilon^n_{au,i}$$

$$= \mathbf{691 - 538 = \ 153}\ \boldsymbol{kJ}$$

Percentage exergy destroyed in the processing $= \frac{\mathbf{153}}{\mathbf{691}} = 22\%$

Appendix 13: Exergetic efficiency of the subsystems in manufacturing line

S. No (n)	Process	Total Exergy in $(\sum \varepsilon_{i}^{n,})$		Total Exergy out $(\sum \varepsilon_{j}^{n,})$		Total Product Exergy out $(\boldsymbol{\varepsilon_{PCB,j}^{n}})$		Exergetic Efficiencies	
								Maximum $\eta_{\varepsilon}^{n, Max}$	Actual $\eta_{\varepsilon}^{n, Act}$
	(Units)	kJ/kg	kJ	kJ/kg	kJ	kJ/kg	kJ	%	%
1	Barcode Etching	4813	433	4677	421	4638	417	97	96
2	Screen Printing	5089	458	4749	427	4672	420	93	92
3	Components Stacking	11068	996	5903	531	5748	517	53	52
4	Reflow Soldering	23592	2123	11349	1021	5749	517	48	24
5	Connector stacking	15402	1386	15207	1369	15156	1364	99	98
6	Selective soldering	19247	1732	15240	1372	15183	1366	79	79
	Total	79211	7129	57125	5141	51145	4603	72	65

Appendix 14: Electrical Exergy use efficiency of the assembly line for unit PCB assembly

Note: Exergy of electrical work is equal to electrical work ($\boldsymbol{\varepsilon^{n}_{W,i}} = \mathbf{W^{n}_{E,i}}$)

S. No (n)	Process	Total Electrical exergy in ($\varepsilon^{n}_{W,i}$) or ($W^{n}_{E,i}$)		Electrical work for necessary use $W^{n}_{\mathrm{nec},i}$		Electrical work for auxiliary use $W^{n}_{\mathrm{aux},i}$		Electricity Use efficiency
	(Units)	kJ/kg	kJ	kJ/kg	kJ	kJ/kg	kJ	%
1	Barcode Etching	50	5	4.31	48	0.18	2	96
2	Screen Printing	166	15	7.72	86	7.25	81	52
3	Components Stacking	4818	434	256.75	2853	176.87	1965	59
4	Reflow Soldering	11412	1027	505.27	5614	521.77	5797	49
5	Connector stacking	186	17	7.09	79	9.68	108	42
6	Selective soldering	3861	347	236.78	2631	110.70	1230	68
	Total (Σ_n)	20493	1844	1017.92	11310	826.45	9183	55

For relevant data table, see appendix 6.

Appendix 15: Comparing the actual work consumption with the ideal energy requirement.

Quantity of solder (Sn-37Pb) alloy required for unit PCB assembly (from Table 2.1)

$= m_{S,i}^{4} + m_{S,i}^{6}$ =0.9+0.6 =1.5 g

Minimum quantity of heat energy required to completely melt 1.5g of solder alloy

$$Q_{min} = m_{S,i} \cdot C_{S,i} \cdot (T_{melt} - T_0) + m_{S,i} \cdot L_{S,i}$$

Where

m_s – Mass of solder

C – Specific heat of solder (for Sn-37Pb alloy, C = ~ 0.15 kJ/kg)

T_{melt} – Melting point of solder (for Sn-37Pb alloy, T_{melt} = 183°C)

L_s – Specific latent heat (for Sn-37Pb alloy, L=~20 BTU/lb* = 9.5 kJ/kg)

$$Q_{min} = 1.5 * 0.15 * (183 - 20) + (1.5 * 9.5) = 50.93\,J$$

From appendix 14,

Total electrical work invested for unit PCB assembly = 1844 kJ = 18.4 x $10^5\,J$

Electrical work supplied for soldering processes = ($\varepsilon_{W,i}^{4}$ +$\varepsilon_{W,i}^{6}$)

= 1374 kJ =13.7 x $10^5 J$

The difference is in multiple orders of magnitude (O (10^5))

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*Source: http://www.engineersedge.com/properties_of_metals.htm, last referred on 11/15/2010.

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