ÇUKUROVA UNIVERSTY

INSTITUTE OF NATURAL AND APPLIED SCIENCES

M.Sc. THESIS

Çağdaş SARIGÜL

DESIGN OF A FULLY AUTOMATED FLEXIBLE PCBA REWORK SYSTEM USING SYSTEMATIC DESIGN TECHNIQUES

DEPARTMENT OF MECHANICAL ENGINEERING

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ÇUKUROVA ÜNİVERSİTESİ

FEN BİLİMLERİ ENSTİTÜSÜ

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YÜKSEK LİSANS TEZİ

MAKİNA MÜHENDİSLİĞ ANABİLİMDALI

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ABSTRACT

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Many various electronic products having different sizes are currently produced by the use of printed circuit board assemblies (PCBAs) that are assembled using surface mount IC packages and printed circuit boards. As with bigger products which are assembled with the use of PCBAs with bigger IC packages and printed circuit boards, the rework process that is carried out manually or with the use of semi-automated devices can be successful. Smaller electronic products such as mobile phones, computers, watch modules, smart cards, etc which involve PCBA with miniaturized advanced type surface mount components (SMCs) and high density boards, the rework process is not easily carried out manually or with the use of semi-automated devices and is prone to unsuccess. The rework of such SMCs can only be possible with fully automated flexible rework system. The design of such a system must be achieved by the systematic design methods or tools, taking into account all phases of a design process.

Development of such a fully automated flexible PCBA rework system using systematic design techniques was found to be technically and economically possible.

Keywords: Automated PCBA Rework, Advanced SMCs, Robotic Rework.

ÖZ

YÜKSEK LİSANS TEZİ

SİSTEMATİK DİZAYN TEKNİKLERİ KULLANARAK TAM OTOMOTİK, ESNEK DEVRE KARTI TAMİR SİSTEMİ TASARIMI

Çağdaş SARIGÜL

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Farklı boyutlardaki çok değişik elektronik ürünler, yüzeye yapışık ileri düzey elektronik devre elemanları ile devre kartlarının birleşiminden oluşan baskı devre kartlarının ürünlere bütünleşmesiyle tasarlanır. Büyük devre kartlarına ve yüzeye yapışık elemanlara sahip olan kartların el veya yarı otomatik tamir aletleriyle tamiri başarılı sonuçlar vermektedir. İleri seviyede yüzeye yapışık elemanlar ve yüksek yoğunluktaktaki kartlardan oluşan daha küçük ürünlerin el veya yarı otomatik aletlerle tamiri kolayca gerçekleştirilemiyor olup başarısızlığa mahkûmdur. İleri düzeyde yüzeye yapışık elemanlar barındıran baskılı devre kartlarının tamiri ancak tam otomatik ve esnek tamir sistemleriyle mümkün olabilir. Bu sistemin tasarımı sistematik tasarım tekniklerini kullanılarak yapılmalıdır.

Sistematik tasarım tekniklerini kullanılarak böyle bir tam otomatik esnek deve kartı tamir sistemin geliştirilmesi teknik ve ekonomik olarak mümkün görüldü.

Anahtar Kelimeler: Otomatik Olarak Gerçekleştirilen Baskılı Devre Kartı Tamiri, İleri Düzey Elektronik Devre Elemanları, Robotik Tamir.

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1. INTRODUCTION

1.1. Printed Circuit Board Technology (PCB)

The printed circuit or wiring board is a substrate on which electronic components are mounted for electrical interconnection and mechanical support. Printed circuit boards are used in wide range applications such as handheld consumer electronic products, sophisticated electronic tools of military and space industry. This variety of application areas results in complex PCBAs of different types (Geren and Çakırca, 2004).

1.1.1. Printed Circuit Boards (PCBs)

PCBs can be classified according to the method of manufacturing and the type of substrate. According to the method of manufacturing there are three types of PCBs: single sided, double sided and multilayer boards. According to the type of substrate there are different types of PCBs available such as: rigid boards, flexible and rigid-flex boards, metal-core boards, and injection molded boards.

PCBs are made of different types of base materials some of which are FR-4 epoxy glass, poly-functional FR-4, multifunctional FR-4, polyimide-glass, BT epoxy, cyanate ester-glass, PPO epoxy, PTFE-glass and alumina. Of these FR-4 (fire resisted) epoxy glass is commonly used in electronic industry (Geren and Çakırca, 2004).

1.1.2. Surface Mount Components (SMCs)

Capacitors, resistors, transistors, diodes, inductors, integrated circuits, and connectors are called surface mount components (SMCs). Of these integrated circuits (ICs) become overwhelming because of that they are well suited for miniaturized PCBs.

IC packages are classified according to package constructions. There are three types of packages according to constructions. These are ceramic, plastic and metal packages. Packages of plastic and ceramic types are widely used in electronics.
Ceramic packages are classified into two groups one of which is ceramic leaded chip carriers (CLCCs) and the other of that is leadless ceramic chip carriers (LCCCs). Plastic packages are also broken down into three groups which are dual row, quad row and array row.

The array row packages which are also called advanced type SMCs have many advantages over the others because of that they are faster, lighter, smaller and less expensive. The array row packages are divided into three groups: ball grid arrays (BGAs), chip scale packages (CSPs) and flip chips (FCs). These packages are commonly used in electronic industry because of their overwhelming advantages over the other packages (Geren and Çakırca, 2004).

1.1.3. Mounting Technologies in Electronics Assembly

To assemble electronic components there are two technologies one of which is through hole technology (THT) and the other is surface mount technology (SMT). SMT has many advantages over THT such as improved performance, savings in space at the PCB and system levels, reduction at the PCB costs, reduction in PCB size, weight and number of layers, etc. Nowadays SMT is preferred to THT because of these advantages. This study is mainly focus on PCBAs with surface mounted components.

SMCs in SMT are placed on PCB either by the use of underfill or without underfill. The underfill reinforces the physical and mechanical properties of the solder joints by compensating stresses which occur during thermal cycling and dynamic loading conditions. Therefore the underfilling method is intensively used in electronic industry. Underfilling is executed by the help of two techniques: one is capillary flow undefilling and the other is no flow underfilling. Due to high level of product reliability underfilling process is currently preferred in the electronics manufacturing cell (Geren and Çakırca, 2004).

1.1.4. Solder Types Used in Electronics Industry

Electronic components are attached to PCB by solder. There are two types of solder used in electronics. These are Sn/Pb and SnAgCu solder alloys. Sn/Pb solder alloys include lead which is not environmentally friendly and bears a health threat risk to human beings. Therefore electronic industry has a tendency to use lead free solder alloys such as SnAgCu (Geren and Çakırca, 2004).

1.2. Flexible Manufacturing Systems (FMSs)

FMS may be defined as a reprogrammable manufacturing system in its broadest sense, dealing with high level distributed data processing and automated material flow, using highly flexible, computer controlled (and in some cases manually operated) material and information processors within an integrated, multilayered feedback control architecture (Ranky P. G., 1990).

A flexible manufacturing system has an ability to take up different positions and to adopt a range of states. But the range of states which the flexible manufacturing system can adopt does not completely describe its flexibility. The ease, with which it moves from one state to another, in terms of cost or organizational disruption, is also important. A production system which moves smoothly and cheaply from State A to State B should presumably be considered more flexible than a system which can only achieve the same change at a great cost and/or organizational disruption.

A production system which is flexible must utilize highly automated and programmable cells. These manufacturing cells must take care of themselves with the help of powerful controllers and self diagnostic systems and have the ability to change their tools and parts. They must be controlled by a computer or a controller in which all necessary data such as the production plan, the part programs, etc is found, and must be linked into a system by the use of direct access or random material handling systems (AGV) between them.

In addition to the features which the FMS must conform, it must create a part tool and pallet storage facility, provide high level computer control inside and outside the system by the aid of distributed processing subsystems and local networks, and dynamically reroute and reschedule production in case of that any workshop breaks down.

Briefly, the subsystems, methods and technology that a flexible manufacturing system must have are as follows:

- Machining, assembly, etc.
- Materials handling and storage
- Production control (loading sequencing, scheduling, balancing, capacity planning)
- Real-time and off-line quality control, contact and non-contact inspection

The FMS involves the operations and activities that occur within complex manufacturing and other types of systems that are being designed. System modeling techniques are used to describe such a complex system and to aid the design of new complex system. These techniques are touched upon in later steps.

The flexible manufacturing system that has the features above provides many benefits to company. These are as follows:

- It increases productivity by a factor of 2 to 3.5
- It decreases production costs often by 50%
- It decreases inventory and work-in-progress to a level lower than ever before
- It offers a batch size of one
- It provides 100% inspection thus increasing the quality of the product
- It decreases repetitive physical work

Flexibility of the system is very important for a PCBA rework process, especially as the PCBAs of various sizes and board densities are available. Hence, manufacturing cells which are to be designed for PCBA rework must be designed as flexible as possible. However, the design process more important than ever before as the design of the flexible systems are becoming more complex and demanding. This can be met if systematic design techniques are used.

1.3. Systematic Design Process

According to Pahl and Beitz (2005), in order to overcome difficulties relating to the complex nature of modern technology harboring so many scientific fields such as engineering, economics, etc., and have probability of success of new design increase, design process must be planned carefully and implemented systematically. To accomplish the aims above systematic design process which includes some design methods or tools must be followed.

Systematic design process encourages a problem-directed approach, fosters inventiveness and understanding, is compatible with the concepts, methods and findings of other disciplines, does not rely on finding solutions by chance, facilitates the application of known solutions to related tasks, is compatible with electronic data processing, is easily taught and learned, reduces workload, saves time and prevents human error.

A design process can be divided into four main phases which are as follows:

- Product planning and clarifying the task
- Conceptual design
- Embodiment design
- Detail design

Now, these design phases will be explained in more detail.

1.3.1. Product Planning and Clarifying the Task

A product idea is generated during *product planning phase* either by listening the customer or by a product design process which takes into account the market, the company and the economy. Product planning, based on company's goals, is the systematic search for, and the selection and development of, promising product ideas with the help of some useful tools. On the other hand product planning, based on clients, formed directly with the desire of customer.

As soon as a product idea is generated, the design task must be clarified as fully and clearly as possible. In order to clarify the task relating to product idea, necessary information about the requirements that have to be fulfilled by the product and about the existing constraints and their importance is collected during this phase. There are some very useful methods and tools, which will be touched upon later in more detail, available to assist the designer in this phase.

1.3.2. Conceptual Design

Conceptual design phase is the vital part of the design process and follows the clarification of the task. This phase determines the principle solution for the task with the help of some solution finding methods, selection and evaluation charts and other auxiliary tools.

Auxiliary tools are used to divide the task (overall function) into subtasks (sub functions) which can be easily handled by designers. Promising solutions for every sub functions are found by the help of solution finding methods. Then these promising solutions are evaluated to determine the most promising solution by the aid of selection and evaluation methods. More detail about these methods and tools will be given later.

1.3.3. Embodiment Design

During this phase, designers, starting from a concept (principle solution), determine the construction structure (overall layout) of a technical system in line with technical and economic criteria. Embodiment design results in the specification of layout.

The definitive layout provides a check of function, strength, spatial compatibility etc, and it is also at this stage, at the very latest, that the financial viability of the project must be assessed.

1.3.4. Detail Design

This is the phase of the design process in which the arrangement, forms, dimensions and surface properties of all the individual parts finally laid down, the materials specified, production possibilities assessed, cost estimated and all the drawings and other production documents produced. The result of the detail design phase is the specification of production.

1.4. PCBA Rework

Due to the miniaturization in the PCBAs as a result of the use of the advanced SMCs some defects are possible in PCBA. The PCBA with defective component or components are not scrapped off easily because of the fact that PCBs include heavy metals which are hazardous waste for environment and especially they are of high value and have a complex structure. Therefore the PCBAs with defective SMCs should be reworked accordingly.

The rework process is commonly carried out in electronics industry manually or with the use of semi-automated equipments by skilled operators. The steps of the rework process are generally as follows:

- Determining the defective SMC
- Removal of the defective SMC
- Site cleaning application
- Application of solder paste or flux
- Replacement of new component
- Reflow soldering

The defective PCBA is reworked by following the procedure above. After determining the defective SMC, it is heated up to solder reflow temperatures without overheating the board, the adjacent components or the solder joints of adjacent components. So that it can be removed from PCB easily. The remnants of solder or underfill, after removal of the SMC, are cleaned without giving any damage to board substrate or wiring. After the application of the solder paste or flux to PCB site, new component is replaced accurately. Finally new component is heated to reflow temperatures to form solder joint between PCB and new component.

1.5. Scope of the Study

Many various electronic products from different sizes are currently designed by the integration of PCBAs that are structured from surface mount IC packages and PCBs into the products. As with bigger products which are assembled with the use of PCBAs with bigger IC packages and PCBs the rework process that is carried out manually or with the use of semi-automated devices can be successful. Smaller electronic products such as mobile phones, computers, watch modules, smart cards, etc which involve PCBA with miniaturized advanced type SMCs and high density boards the rework process is not easily carried out manually or with the use of semi-automated devices and is prone to unsuccess. The density of boards and miniaturization of SMCs results in many problems associated with heat application, handling of components, solder dispensing and accessibility to the defective component in the rework process.

The rework of PCBAs of different sizes and different types of SMCs, regardless of standard, fine or advanced types of SMCs, can only be possible with fully automated flexible manufacturing and rework system. This system must have all features of a flexible manufacturing system. The design of such a system must be achieved by the systematic design methods or tools, taking into account all phases of a design process. So that optimum and creative solutions for the problems can be found during the design of the system.

According to the results of the literature search, the first flexible manufacturing and rework system for standard and fine pitch SMCs was developed in the University of Salford, England, based on iris-focused IR reflow soldering method by Geren et al. (1992). This system is capable of reworking both the components which are mounted on PCB with through hole technology (THT) and surface mount technology (SMT) based on the batch size of one, and also capable of reworking double sides of PCBA.

Two rework systems then were developed in Rensselaer Polytechnic Institute, in USA, by Merrick (1994) and third Fidan (1996). Both of them are a laser based remanufacturing cell system that has been designed and developed for fully automated rework of fine pitch SMCs. Again, a flexible manufacturing and rework system has been proposed in the Cukurova University, in Turkey, by Geren and Çakırca et al. (2004). This system has the ability to rework the advanced SMCs, as the other developed systems have not.

This study will be carried out as an extension of the Master thesis which has been carried out by Çakırca (2004). Therefore, the results of Çakırca (2004) will be used as an input to this study.

The aim of this study is to design a flexible fully automated PCBA rework system by the use of systematic design techniques and FMS modeling techniques taking the results of Çakırca (2004) as an input. This system must be capable of reworking advanced type SMCs and must have features of a FMS. For this purpose design process is followed step by step and a flexible fully automated PCBA rework system is developed by the use of design tools and FMS modeling techniques.

2. PREVIOUS STUDIES

In this chapter, PCBA rework systems that have been used currently, systematic design techniques, and FMS system are explained in more detail. Now, PCBA rework systems will be explained as below.

2.1. PCBA Rework Systems

Manual and semi-automated rework systems are currently used in electronic industry to rework PCBA which have different physical properties and different types of SMC. In addition to manual and semi-automated rework systems, a few fully automated flexible PCBA rework systems were developed in the worldwide by few researchers.

Fully automated flexible PCBA rework system has numerous advantages over manual or semi-automated rework systems. It is more suitable for reworking miniaturized, high lead count, fine pitch SMCs and densely populated multilayer PCBs which are extremely difficult and time consuming with manual or semi-automated rework systems. Also, the automation provides consistent, flawless, high quality repairs by continuous control of all rework steps. Additionally, it eliminates human errors. So that more accurate, reliable and cost effective rework process is achieved by these systems. (Geren, 2001). Now, these fully automated systems will be run through below.

2.2. Fully Automated PCBA Rework Systems

An autonomous and fully automated printed circuit board assembly (PCBA) robotic rework cell has been developed, implemented, and manufactured based on system modeling techniques at the Aeronautical and Mechanical Engineering Department of Salford University in the U.K by Geren in 1993. This cell was capable of performing assembly, rework, and in-process inspection of both through-hole (TH) and surface mount (SM) electronic components with a cell controller coordinating in-process inspections and robot/tool operations. A computer integrated the rework cell had ability to study the generic problems associated with the removal, replacement, and fastening of pre- and post-soldered SM and TH components. This cell had maximum flexibility and was also capable of identifying and locating faulty components based on automatic test equipment (ATE) and CAD/CAM data, planning appropriate rework operations according to inspection results, and formulating the robot program (Geren, 2001).

A fully automated electronics remanufacturing system was designed and implemented by Fidan in 1996 in USA. This flexible system was only capable of reworking the fine pitch surface mount components.

Finally, a fully automated PCBA rework system was proposed by Çakırca in 2004. This system was capable of performing rework of advanced SMCs such as FCs, CSPs and BGAs. A cell controller was proposed to control robot/tool operations and in-process inspection in fully automated manner during rework process. This system was proposed to be highly flexible.

Now, the general rework procedure that a rework system should follow will be given in more detail as followings.

2.3. General Rework Procedure

Whether rework is carried out by manually, semi-automated or fully automated, rework procedure for defective PCBA that has underfilled SMCs is mainly as in figure 2.1 and 2.2.

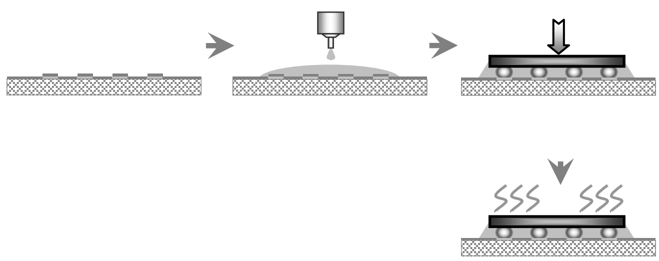


Figure 2.1. Novel No Flow Underfilling Process Steps

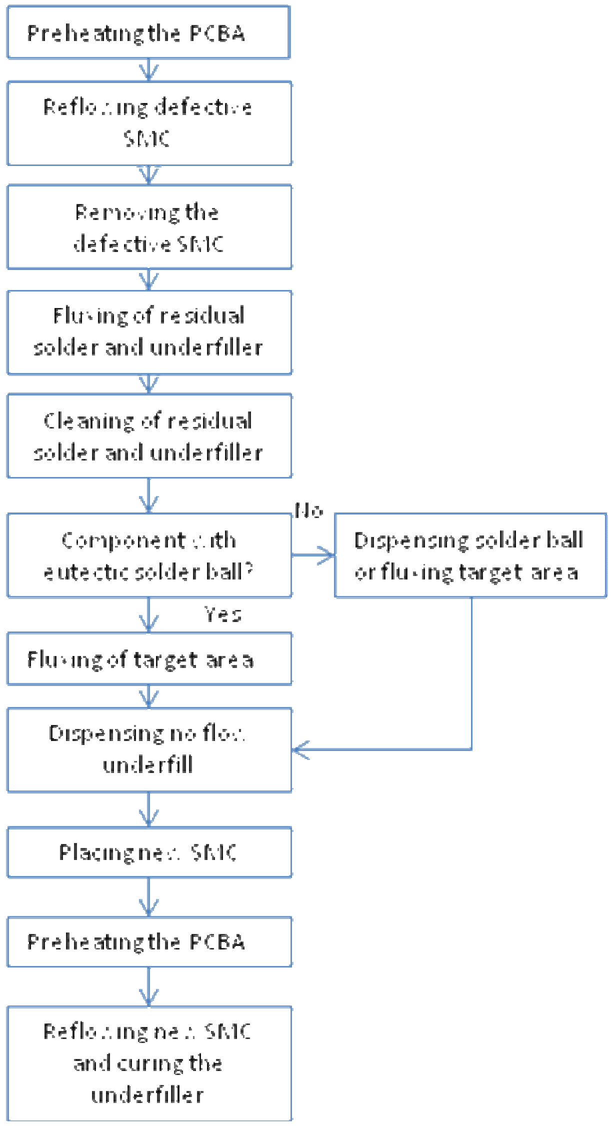


Figure 2.2. General PCBA rework procedure.

In addition to the main rework steps in figure 2.2, a fully automated flexible rework system should also carry out some necessary functions such as inspecting the results after the related rework step, aligning new SMC during replacement, temperature measurement and control during preheating and reflow, and replacement force measurement and control during replacement. Now, these are explained briefly below, before introducing the rework steps in figure 2.2.

Some rework steps should be inspected during rework process by the use of advanced inspection systems. Especially, for the identification of defective SMC advanced inspection techniques such as real-time transmission x-ray or acoustic microscopy are needed to identify solder faults such as bridging, lack ofsolder, etc. Besides, site cleaning, solder/underfiller dispensing and component removal results should be inspected and fed to control equipments which will analyze them and then control the rework system.

A heat control mechanism during preheating and reflow also measure and control temperature of the board and SMC. Also, SMC replacement force is to be measured and controlled during replacement in order to avoid any damage to PCB. As for alignment system, it is also needed to accurately place new component on the target area on the board. Some other auxiliary facilities such as tool parking place, SMC storing and feeding, defective component storing, etc should be provided by a fully automated flexible PCBA rework system.

Now, it is beneficial to give more information about general specifications of PCB, SMC, solder and underfiller that build PCBA, before examining the rework steps in figure 2.2.

As mentioned in chapter 1, *PCBs* are commonly made of FR-4 (fire resisted) epoxy glass. The glass transition temperature range of this material is between 125 ^{0}C and 180 ^{0}C. This temperature range should be considered during reflow process.

As for advanced *SMCs*, they are divided into three groups, as stated in chapter 1. These are BGAs, CSPs and FCs. Their dimensional specifications and accuracy requirements needed during their replacement on the board are shown in table 2.1 and 2.2. Their maximum allowable temperatures range for SMCs is between 240 ^{0}C and 260 ^{0}C. During reflow the maximum reflow peak temperature should be kept below this temperature range. Also, the temperature ramp rate during preheating should be 2 ^{0}C/s for plastic SMCs and 1 ^{0}C/s for ceramic SMCs.

Table 2.1. Dimensional Specifications of Advanced SMCs

Component type	**Body size (mm)**	**Pitch (mm)**	**D_{ball} (mm)**	**D_{pad} (mm)**
BGA	7*7 to 50*50	1.5 - 0.5	0.75 – 0.3	0.55 – 0.25
CSP	4*4 to 22*22	1.0 – 0.4	0.5 – 0.25	0.4 – 0.2
FC	3.81*3.81 to 12.7*12.7	0.75 – 0.1	0.2 – 0.08	0.15 - 006

Table 2.2. Summary of Essential Accuracy Requirements of Advanced SMCs

Component type	Required Accuracy	
	Linear offset (mm)	Rotational offset (^{0})
BGA	≤0.0167	≤0.0138
CSP	≤0.013	≤0.0255
FC	≤0.04	≤0.013

As mentioned in chapter 1, *the underfiller* is a key material that enhances the thermal-mechanical strength of the area array component solder joints (Wang and Wong, 2001; Liu, 2001; Gowda, 2002; Stoyanov, 2002). The underfill is a polymeric material that fills the gap between component and PCB, and encapsulates the solder joint interconnects (Wang, 2000; Tu, 2001; Kuerbis, 2003). The underfiller that is reworkable is mostly preferred in electronic industry.

There are two underfilling process that are used in electronic industry as mentioned in chapter 1. These are capillary flow underfilling and no flow underfilling. Of these methods, no flow underfilling is mostly preferred due to its numerous advantages over capillary flow underfilling such as reduced tendency for incomplete filling and void formation, good wetting, low complexity, its suitability to advanced SMCs, possibility to combine the solder joint reflow and underfill cure into a single step, relatively low cost, no requirement for additional filleting process, etc. To achieve good underfiller dispensing and cleaning results the thermal conditions below should be provided by the system during rework process.

In order to avoid void formation and incomplete filling, and provide good wetting, board temperature should be 90 ^{0}C. Board temperature range for cleaning off the underfiller during site scavenging should be 120 ^{0}C – 150 ^{0}C. Also, bottom side heating range of PCB for cleaning off the underfiller during site scavenging should be 85 ^{0}C - 100 ^{0}C. In order to easily remove underfilled defective SMC, defective FC should be left on reflow temperature for 30-90 seconds and defective CSP/BGA should be left on reflow temperature for 60-90 seconds. Underfiller curing temperature range after component placement should be 150 ^{0}C – 160 ^{0}C.

As for *solder alloys*, in surface mount assembly, a key step in producing finished assemblies is the reflow soldering process which consists of remelting solder material previously applied onto a PCB pad sites (Blackwell, 2000; Cluff and Pecht, 2001). Solder paste manufacturers supply a recommended reflow thermal profile for use with their specific solder paste. These generic profiles offer a convenient starting place for setting up a reflow profile (Scheiner, 2003). Therefore the reflow profile of the solder paste used is becoming very important for the designer in order to achieve a successful rework process.

As explained in chapter 1, there are two types of solder alloy. These are SnPb or SnPbAg and SnAgCu or SnAG solders alloys. They each have a reflow profile supplied by their manufacturers as in figure 2.3 and 2.4. Melting point of SnPb or SnPbAg solder alloy is 183 ^{0}C. SnAgCu or SnAg solder alloy has a melting point of 217 ^{0}C.

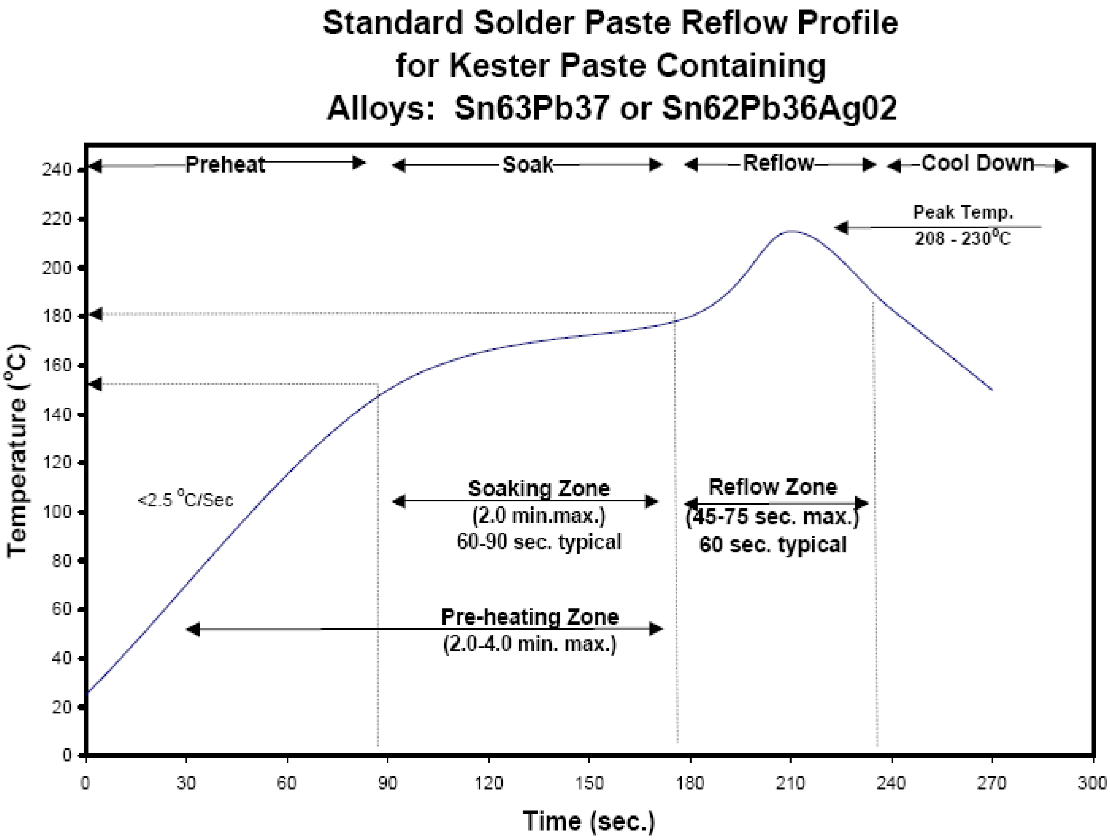


Figure 2.3. Generic Reflow Profile for Eutectic Sn/Pb Solder Alloy (http://www.kester.com, 2007)

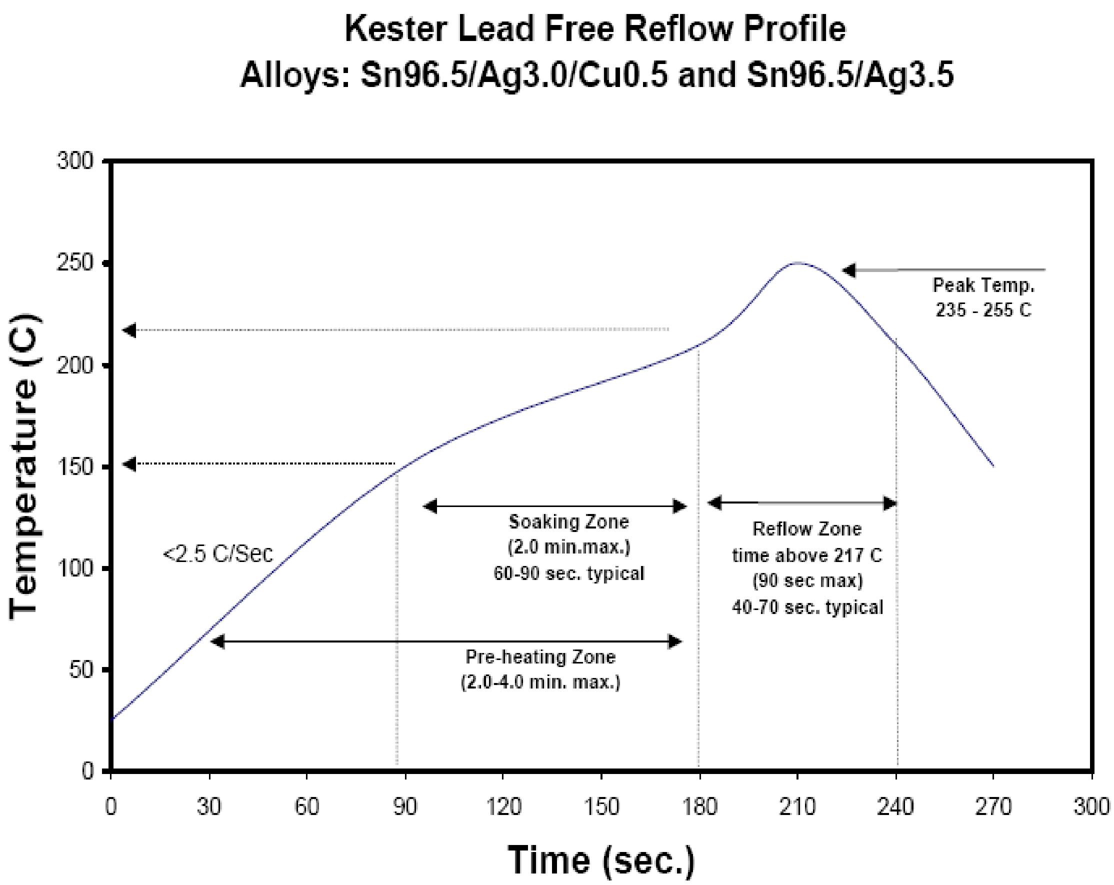


Figure 2.4. Generic Reflow Profile for Eutectic Sn96.5/Ag3.0/u0.5 and Sn96.5/Ag3.5 Solder Alloys (http://www.kester.com, 2007)

As can be see in figure 2.3 and 2.4, the thermal profiles consist of four stages. These stages are preheat, soak, reflow and cool down. Now these stages together with the other rework steps will be explained in more detail as followings.

Preheating PCBA: The purpose of this stage is to quickly bring the assembly from room temperature up to a temperature where solder paste can become chemically active (http://www.kester.com, 2007). Due to the localized heat application during rework process destructive differential stresses may occur both within the component body and PCB. This is especially critical on high density multilayer circuit boards (Blackwell, 2000; Geren, 2001; Alander, 2002). Not only does the preheating prevents warping and thermal stresses to the board, but also brings the assembly up to a temperature that expedite component removal and contribute to reduce reflow time (Blackwell, 2000; McCall, 2000; Prasad, 2001; Naugler, 2002; Primavera, 2003). In addition to these, preheating also provides to achieve more uniform heating profiles and to minimize adjacent components disturbance.

Preheating temperature during preheating should be kept below the glass transition temperature of the PCBA material ((Blackwell, 2000). Moreover, it was stated that any part of the PCBA over 160 ^{0}C – 170 ^{0}C is close to the solder melting temperature of 183 ^{0}C and risks damaging the solder joint integrity of adjacent components on the board (Ward, 1999; Geren, 2001). Therefore, for Sn/Pb and SnAgCu or SnAg solder alloys preheating temperature range should be between 100 ^{0}C and 150 ^{0}C (Ward, 1999; Wood, 1999; Cluff and Pecht, 2001). In addition to that the rate of preheating temperature, as stated earlier, should be limited to 2 ^{0}C/s for plastic SMCs and 1 ^{0}C/s for ceramics (Geren, 1997). Also, it is recommended that 75% of the total heat should be applied from bottom side and just 25% of the heat should be applied from top side (http://www.pdrsmt, 2007).

Reflowing Defective SMC: As stated earlier, reflowing the solder alloy is a key step in rework process. Since during reflow process component delamination, overheating of adjacent components and board warpage are possible (Primavera, 2003). To prevent these defects, while strictly following the reflow profiles of solder alloys in figure 2.3 and 2.4, thermal properties of SMCs and PCB should also be considered by designer.

Reflow profile of solder alloys consists of four stages. These are preheat, soak, reflow and cool down stages. Of these stages, preheat stage is already carried out by ‘’preheating PCBA’’ step. Now, the other stages will be run through briefly.

The purpose of *the soaking stage* is to bring the temperature of the assembly up to a uniform temperature so that a very small differential between the hottest and coldest soldering locations on the assembly (i.e. minimizing temperature gradients) (http://www.kester.com, 2007). Furthermore, in this stage the temperature of the assembly is raised slowly to the solder melting point. At this temperature, the flux in the solder paste becomes more active and removes oxides and contaminants from the surfaces of the metals to be joined and evaporates (Blackwell, 2000; Cluff and Pecht, 2001).

For Sn/Pb solder alloy, the maximum soak temperature is 180 ^{0}C and the board temperature could be ramped up to soaking temperature at a rate in the range of 0.3 ^{0}C/s – 0.8 ^{0}C/s, resulting in a soak time of approximately 40 to 100 seconds (Scheiner, 2003). For SnAgCu or SnAg solder alloys, the maximum soak temperature is 215 ^{0}C and temperature ramp rate up to this temperature should be 1 ^{0}C/s to 2 ^{0}C/s.

It is important to maintain thermal uniformity across the PCB and within a component being reworked. High thermal gradients (>25 ^{0}C) can be damaging at excessive temperatures resulting thermal shock leading to board and component package warpage, component cracking and also results cold solder joints (Russell, 1999; Primavera, 1999; Prasad, 2001; Nguyen, 2003). In general, for area array devices, a good rule of thumb is to maintain a temperature gradient of 10 ^{0}C or less so as to prevent warpage of the package an to ensure all joints reflow properly (Primavera, 1999; McCall, 2000; Wood, 2003). Also, temperature gradient between solder balls at the center of the package, and the top surface side of the package should be 5 ^{0}C or less than the solder balls on the corners (Nguyen, 2003).

The purpose of *reflow stage* is to rapidly heat the assembly just above the melting (liquidus) temperature of the solder (http://www.kester.com, 2007). When the solder melts, it replaces the liquid flux formed in the previous step and subsequently complete wetting of solder onto conductor pads occurs (Blackwell, 2000; Cluff and Pecht, 2001).

As can be seen in figure 2.3 and 2.4, maximum peak temperature range for SnAgCu or SnAg solder alloys recommended by its manufacturers is between 235 ^{o}C and 255 ^{0}C. Additionally, most SMCs are designed to withstand to 240 ^{0}C and 250 ^{0}C, as stated earlier, so the maximum reflow heating temperature is preferred closer to 235 ^{0}C in order not to damage new SMC during SMC replacement. For Sn/Pb solder alloy the recommended reflow peak temperature is 220 ^{0}C, since higher temperatures increase the risk of die cracking, adhesive degradation, and internal package delamination (http://www.intel.com, 2007).

Further, to avoid submitting sensitive components to a thermal shock, board warping and excessively drying the solder paste, area array components must be heated gradually and maximum rise of the temperature of the component body and interconnects should be below 3 ^{0}C/s for Sn/Pb solder alloys and below 3.5 ^{0}C/s for SnAgCu or SnAg solder alloys during reflow. For all solder alloy types reflow atmosphere should be nitrogen. Nitrogen atmosphere has a significant positive affect on component alignment capability and solder joint integrity, reliability, and quality (Hill, 1997; Wu et al., 1998; Casey, 1999; Bell and Kampfert, 2002). Moreover, it was revealed that nitrogen atmosphere provide smaller temperature differential across the rework site. In addition, the residual solder would be more uniform with a nitrogen atmosphere which facilities the site cleaning (Primavera, 2003).

The purpose of *cooling stage* is to cool the assembly down quickly to solidify the solder. To do this, the temperature of the assembly is dropped below the solder liquidus point, forming acceptable (shiny and appropriate volume) solder joints (Blckwell, 2000; Cluff and Pecht, 2001).

The cooling rate of the solder joint after reflow is important because the faster the cooling rate the smaller the grain size of the solder, and therefore this means enhanced fatigue fatigue resistance of solder (Su, 1997; Prasad, 2001). However, too rapid cooling should be avoided because rapidly cooling down not only creates an undesired temperature gradient between the component body and solder balls which may lead to package warpage but also cause excessive board warpage (http://www.ibm.com, 2007). As a consequence of above, based on the main IC component manufacturers' recommendations, typical cooling rate should be lower than 6 ^{0}C/s for Sn/Pb solder alloys (http://www.amd.com/usen/, 2007). Cool down rates for SnAgCu or SnAg solder alloys should be between 2 ^{0}C/s and 4 ^{0}C/s.

Removing the Defective SMC: SMC removal should be done with as small a force applied to the component as possible to avoid applying excessive pressure to the component because this may bring about solder joint collapse and adherence to the board surface, complicating the PCB site cleaning process (Russell, 1999; Dalrymple and Milkovic, 2000; Wood, 2002; Naugher, 2002; Primavera, 2003). Besides, removing tool should be highly flexible to be able to handle different types of SMC and should let manipulator be able to twist the defective SMC.

Cleaning Residual Solder and Underfiller: PCB reworked sites should be made as uniform as possible prior to reattachment of the new component. In its simplest form, site cleaning comprises applying a source of heat to the PCB and removing the residual solder by some means. The aim is to effectively remove the residual solder without adversely affecting PCB quality (McCall, 2000; Nguty, 2000; Naugler, 2002).

Besides, an appropriate flux should be applied during cleaning. During applying flux bottom side temperature of the board should be between 85 ^{0}C and 100 ^{0}C. Flux expedites the cleaning and bottom side heating decreases top and bottom temperature gradients, reduce the thermal shock to the board, further eliminating any accidental pulling of fragile pads (Wood, 1998; Primavera, 2003).

Additionally, once all residual solder has been removed from the lands, they should be cleaned with an approved solvent, preferably one prescribed by the solder manufacturer (Tazi and Bergman, 1999; Ward, 1999; Blackwell, 2000).

Fluxing Target Area: After the PCB site cleaning, flux is applied to the pad site. Fluxing can be achieved by dipping the component into a flux film deposit, dispensing, spraying, and brush methods (Ward, 1999; Primavera, 1999; Lee, 2002). In order to minimize the flu residue left on the PCB following reflow, it should be precise in terms of exactly where flux is applied and how much put down, and no flux can be deposited beyond the intended target area (Primavera, 1999; Naugler, 2002; Berger, 2003).

Dispensing Solder Ball: After the PCB site cleaning, new solder paste is applied to the pad site. The solder paste deposit should have both adequate thickness and volume to compensate flatness defects due to the board warpage and/or poor component coplanarity (Saint-Martin, 1996; Bird, 1999). Besides, solder dispensing method should offer both flexibility and a faster cycle time.

Dispensing No Flow Underfill: As said earlier, *the underfiller* is a key material that enhances the thermal-mechanical strength of the area array component solder joints (Wang and Wong, 2001; Liu et al., 2001; Gowda et al., 2002; Stoyanov et al., 2002). When working with no flow underfill materials, the goal is to place the underfill in a pattern that will flow to fill the gap evenly in all directions (Babiarz, 2000).

According to no flow underfill manufacturer's data sheets, no flow underfill should be dispensed in a single dot/glop pattern over the over the center of component attachment site at room temperature to avoid air entrapment and shorten the dispensing time. Then the component should be placed in to the no flow underfill encapsulant spread evenly underneath the component (http://www. kester.com, 2007). The requirement from the dispense step is the formation of a single glob of material, of the appropriate volume and shape, which allow the fluxing of all the bumps during reflow and form proper fillets afterwards, with the minimum number and size f voids (Kuerbis, 2003; Kondos and Borgesen, 2004).

Besides, no flow underfill should have the shape like a glop or dome with is highest point in the middle (Debarros and Katze, 2000; Kuerbis, 2003; Kondos and Borgesen, 2004).

Placing New SMC: After dispensing underfiller, new SMC is placed on the underfiller. Placement force should be fine tuned so as not to deflect the board or damage the tiny CSPs or FC (Russell, 1999; Primavera, 2003). Placement tool should be highly flexible to be able to handle different types of SMCs. Manipulator that positions new SMC should accomplish the accuracy requirements in table 2.2. Besides, alignment between individual pad site and bottom of the component should be provided very precisely by an alignment system.

After explained main rework steps in detail, it is time to give some information about the system tools that were used in these developed and proposed fully automated PCBA rework systems to carry out the rework steps.

2.4. System Tools Used in the Fully Automated PCBA Rework Systems

Now, tooling specifications of the fully automated PCBA rework systems that were developed by Geren and were proposed by Çakırca (2004) will be given under subtitles below:

2.4.1. Prime Reflow Methods

Prime reflow methods has been investigated by Geren (2001). Investigations have indicated that infrared reflow, hot air/gas reflow and laser reflow systems are superior to others when automation of PCBA rework process are considered. All three methods are capable of desoldering and resolderig of all SMCs and capable of breaking down underfill bond. Speed of reflow is fast for all methods and double sided repair possible again for all three reflow methods. Also, closed loop control is possible for these methods (Geren, 2001). Other features of these reflow methods will be explained below:

Hot Air/Gas Reflow: In hot air/gas reflow soldering systems, convective energy is used for thermal processing of electronic assemblies. The air or inert gas is heated to reflow temperatures and directing it via specifically designed nozzles to accurately concentrate heat on the component and solder joints (Primavera, 2003).

Main problems with this method are the risk of reflowing surrounding component and the requirement of sufficient interpackage spacing to accommodate hot air nozzles (Prasad, 2001). In addition to these, for each component type specifically designed interchangeable nozzles are required for reflow (Wood, 1998; Geren, 2001). Another problem with this method temperature ramp rate control possibility is low. However, its cost is low and closed loop control is possible. Temperature uniformity degree range for this reflow method is ±2ºC to ±10ºC.

Laser Reflow: Laser soldering process utilizes a focused high-power density laser beam to deliver highly concentrated energy to the components to be soldered and to the solder for a short period (Becker, 1997; Beckett, 2002). The demand of laser applications is significantly increased due to the growing the growing applications of expensive, moisture sensitive fine pitch and advanced SMCs on densely populated PCBAs and also due to the impending use of lead-free solders (Prasad, 2004).

Main advantage of laser reflow is its ability to precisely and accurately apply required heating energy to a specific component or target area without overheating surrounding components (Becker, 1997; Beckett, 2002). In laser flow any interchangeable part is not needed as component type changes. In addition to these, extreme compactness, almost completely eliminated maintenance requirement, high reliability, real time power control, ease of integration/automation, markedly enhanced lifetime and no dedicated tooling requirement are also other attractive properties (Hoult and Apter, 2001; Hoult, 2002; Bachman, 2003). However, laser flow is not without drawbacks, as its cost is very high.

There are four different types of laser system available. These are CO_2, Nd:YAG, DPSS Nd:YAG and HPDL (high-power diode laser). Main differences between laser types for soldering applications are associated with the wavelength of the emitted energy, the level of energy absorption by the soldering materials, the energy delivery medium, the efficiency, and the ease of the energy control (Beckett, 1997). For all laser types temperature uniformity degree is ±5ºC. A comparison of lasers has been made by Çakırca (2004) and a summary of the comparison is provided in table 2.3.

Infrared Reflow: Infrared refers to that part of the electromagnetic spectrum having wavelengths lying between the visible and microwave regions, with 0.75 to 2.5 μm being near-IR, 2.5 to 25 μm middle-IR, and over 25 μm far-IR (http://www.thermometrics.com, 2007).

In IR reflow systems, either lamp emitters are used to generate IR radiation energy in a concentrated wavelength at the near end of the spectrum called non-focused IR or emitter panels are used to produce the IR radiation energy in the mid to far wavelength regions of the spectrum called focused IR (Conway et al. 1990).

Geren and Redford (1994) has indicated that non-focused IR method is promising to be well suited to automated rework system for the standard SMCs with respect to costs, adaptability, suitability, flexibility, and reliability reasons. In addition, they have also successfully designed and implemented the proposed no-focused IR based system in a fully robotized manner which verifies the viability of the proposal.

Table 2.3. Comparison of Lasers Used Soldering

	CO_2	Nd:YAG	DPSS Nd:YAG	HPDL
Wavelength	10.6 µm	1.06 µm	0.8~1.06 µm	0.8~0.98 µm
Delivery system	Free space	Fiber optics	Fiber optics	Fiber optics
Laser Efficiency	Inferior (10-15%)	Poor (1-5%)	Very Good (25~30%)	Excellent (≥50%)
Beam quality	Good	Good	Better	Moderate
Investment and Running Cost	High	High	Moderate	Low
Size and Weight of the laser system	Inferior	Inferior	Good	Excellent
Controllability	Inferior	Good	Very Good	Very Good
Adaptability and Integration for a system	Moderate	Moderate	Good	Excellent
Wavelength suitability for soldering	Inferior	Good	Very good	Very good
Adaptability for future trends in electronics	Inferior	Inferior	Good	Excellent
Maintenance requirement (service life time)	Frequent	Frequent	No or Least Frequent	No or Least Frequent

With non-focused infrared (IR) very good rework results can be achieved and soldered joint quality is good. It is also suitable for future SMCs. In addition to this temperature uniformity degree range is ±5ºC to ±10 ºC. However, it has some drawbacks such as possibility of adjacent component reflow during reflow, high cost of the equipment and dedicated tooling requirement (http://www.intel.com, 2007).

2.4.2. Closed Loop Heat Control Mechanism

Closed loop heat control mechanism consists of a heat sensor, a controller and interfacing devices. Pyrometer is a kind of a radiation thermometer that measures the radiation energy being emitted from a body or surface in fractions of a second. Because of its speed, accuracy, economy and specific advantages pyrometers are very suitable candidates for the reflow and preheating process. Its temperature measurement range is also sensitive from about 20ºC to the solder reflow temperature. Two proportional integral derivative (PID) controller and interfacing devices are also the other necessary tooling of closed loop heat control system (Geren, 2001).

2.4.3. Manipulating Devices

Two manipulating devices which are open frame X-Y positioning table and robot have been identified as main requirements for positioning PCBA, SMC and tooling during rework. As open frame X-Y positioning table is needed to transfer PCBA to different work point locations, a robot will perform top-side rework operations. The robot accomplishes linear and rotational requirements of SMCs in table 2.2.

There are two candidates for SMC and necessary tooling: one is SCARA robot and the other is Gantry robot.

Of these, SCARA (Selectively Compliant Assembly Robot Arm) robot is a direct drive, four axes assembly robot. First two joints of a SCARA robot enable the robot to move its end arm in a horizontal planar workspace defined by two concentric circles. As third joint enables the end arm to move in vertical axis, the fourth joint enables the robot to twist its end arm in its own axis (Lasky, 2000; Rehg, 2000). A SCARA robot configuration is shown in figure 2.5.

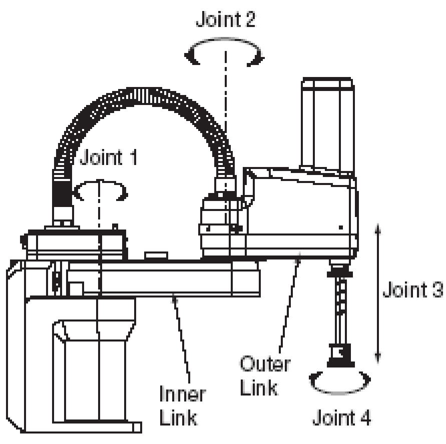


Figure 2.5. SCARA robot (www.adept.com, 2007).

The Gantry configuration, figure 2.6, is geometrically equivalent to the Cartesian configuration. Gantry robots have an elevated bridge structure and consist of three orthogonal prismatic joints and so that the robot moves in X,Y and Z directions in the joint space (Lewis, 1999; Lasky, 2000). In addition to three orthogonal joints a revolute joint can be added to the end arm of the robot to enable its end arm to rotate in its own axis. Main advantages and disadvantages Gantry and SCARA robots are given in table 2.4.

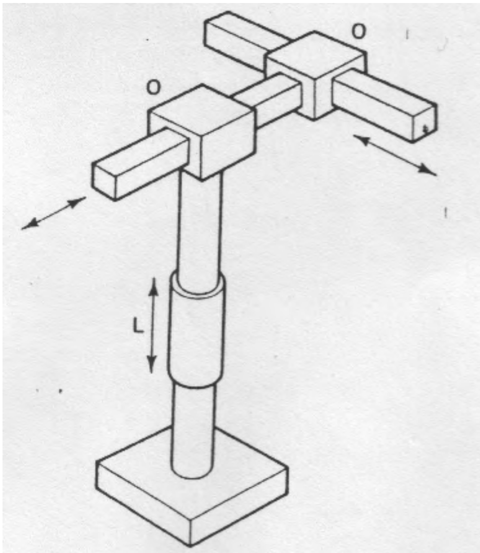


Figure 2.6. Gantry robot configuration (www.adept.com, 2007).

Table 2.4. Advantages and disadvantages of SCARA and Gantry Robots

Type	*Advantages*	*Disadvantages*
Scara	• Stiffness in Z axis • Large work area for floor space (efficient space utilization) • Long horizontal reach • Horizontal compliance • High speed • No gravity effect on positioning • High positional repeatability	• Two ways to reach a point • Complex kinematics • Variable resolution and accuracy • Difficult to program off-line • Medium to low payloads
Gantry	• Linear motion in X-Y-Z axes • Rotational motion in end arm • Simple kinematics • Rigid structure • Inherently better accuracy and resolution • Very high repeatability • Easy to visualize • Easy to program off-line • Easy position control • No position dependency on gravity and inertia • Constant resolution and accuracy • Highly configurable • High payloads are possible	• Occupies large floor space for size of work envelope (poor space utilization) • Workspace is smaller than robot volume • Guiding surfaces of prismatic joints must be covered to prevent ingress of dust (all axes exposed to environment) • Low speed

One of these robot types will be selected for manipulating necessary tooling and SMCs according to their advantages and disadvantages in table 2.4 in following chapter.

2.4.4. Component Removal/Replacement Tool

Two types of removal tools are found to be essential for rework. These are vacuum suction tool and a gripper. Of these, the vacuum tool has not ability to apply sufficient twisting action to break down the underfill bond during component removal. Therefore, this tool is insufficient to remove an underfilled SMC. However, with this tool component removal or placement process can be achieved without damaging the component. Besides, all types of SMCs can be handled with the use of this tool and this tool has feature which enables it to mount on the robot end arm.

On the contrary to the vacuum tool, gripper provides sufficient twisting action during component removal. Beside, gripper are have feature which enables it to mount on the robot end arm. On the other hand, SMC damage can be possible during component placement and with this tool to handle all types of SMCs is not possible (Çakırca, 2004).

2.4.5. Solder Dispensing Tools

There are three candidates for this purpose. These are time/pressure valve, rotary positive displacement pump and linear positive displacement pump. Their features will be explained below.

Time Pressure Valve: It consists of a reservoir of material that is pressurized to extrude material through a needle or nozzle. The amount of material is controlled by controlling the time of the air pulse and the air pressure (Wedekin, 2001; Peek, 2001; Pracci, 2000).

Time/pressure valve is relatively simple and inexpensive. On the other hand, fluid viscosity changes are possible over time because of heat generation during high pressure cycling, resulting in inconsistent dispensing. Besides high pressure air pulsing can cause separation of solder particles from light flux/binder system and clogging all of which negatively effects the precise dispensing (Wedekin, 2001; Peek, 2001; Pracci, 2000). In addition to these, pressurization time change which leads to the dot inconsistency and less repeatable dispensing is possible (Çakırca, 2004).

Rotary positive displacement pump: Its primary component is an *auger* feed screw that can be turned on and off by a DC servo motor. The motor is turned on for a set time, causing the auger screw to move a precise distance. As the screw turns, it shears the fluid material, forcing the material down the thread and out the needle, producing a very precise and consistent dot deposition (Piracci, 2000). It is less sensitive to viscosity changes. So much more repeatable dispensing at a higher rate is possible with this method. Besides it less prone to clogging and can dispense a very small, accurate amount of solder dot in a controlled manner.

Linear Positive Displacement Pump: In linear positive displacement pump a piston is used to change the volume of an auxiliary shot reservoir that is fed from the main syringe. Therefore material flow rate is a function of the piston speed and diameter. Changes in viscosity, needle size and supply pressure have no effect on the material flow rate. The linear positive displacement pump has drawbacks such as possibility of separation of solder particles and possibility of clogging due to viscosity changes in solder (http://www.asymtek.com, 2007).

2.4.6. Flux Dispensing Tools

There are two applicable tools for this purpose. These are spray valve and jetting valve. Comparison of these two techniques is given in table 2.5.

Spray Valve: In spray fluxing, flux is forced through a nozzle to spray it on the planar surface of the circuit board. The flux is atomized into fine droplets (http://www.techconsystems.com, 2007; http://www.ijfisnar.com, 2007).

Jetting Valve: In this method, flux is dispensed via a non-atomizing high pressure jet in specific quantities with extremely thin film builds (<10 µm) and weights with excellent edge definition. Flux can be jetted either in dot or line pattern at prefixed dispense gaps from the board surface (Lewis, 2003).

In jetting there is no need precise positioning in vertical axis. Therefore this gives a significant savings in time and an increase in dispense cycle time from 10 % to 50 % over the rotary and linear piston pumps with equal or better consistency (up to two times) (Piracci, 2000).

Table 2.5. Comparison of Flux Dispensing Methods

	Spraying	Jetting
Atomization	Possible	No
Wetting	Fair	Good
Speed	High	Can be very high
Edge definition	Poor	Excellent (speed dependent)
Film Thickness	Good control	Very good control
Over spray	No	No
Area of coverage	> 6 mm	> 5 mm
Cost	Low	High
Dispensing Cycle	Fast	Fast

2.4.7. Underfiller Dispensing Tools

Four possible solutions are available for this purpose: time/pressure valve, rotary positive displacement pump, linear positive displacement pump, and jetting about which were mentioned above.

Of these, in time/pressure valve and rotary positive displacement pump viscosity changes are possible, as the underfill dispense tool have to be independent of the viscosity of the material (http://www.asymtek.com, 2007). Therefore accurate repeatable underfill dispensing is difficult for these methods.

As it is explained previously, in linear positive displacement pump changes in viscosity, needle size and supply pressure has no effect on the material flow rate. So this specification of this tool provides accurate repeatable underfill dispensing. However, it has drawback. It requires precise positioning in vertical axis to provide consistent dispensing gap. This drawback increases cycle time and complicates the process control methodology (Pracci, 2000).

In jetting there is no need precise positioning in vertical axis. Therefore this gives a significant savings in time and a decrease in dispense cycle time. Comparison of jet dispenser and linear positive displacement pump is provided in table 2.6.

Table 2.6. Main features, advantages and disadvantages of jet dispenser and linear positive displacement pump

	Linear Positive Displacement Pump	**Jet Dispenser**
Flow rate	< 1 mg/s to >500 mg/sec	120 mg/sec
Shot size	0.002 to 2 ml	> 0.012 µl
Repeatability	Typically ± 1% except for very small dispense volumes (< 20 µl)	±3% for dot volume ±10% for dot diameter
Dispense cycle	90 msec/dot	8 to 15 msec/dot
Advantages	• Fast, efficient priming with minimal material waste. • Dispense volume proportional to piston travel, so one time calibration establishes accuracy for long production runs. • Lower initial investment cost compared to jet • Lower cost of ownership. • Tool-free disassembly and assembly for quick and easy cleaning	• Threefold improvement in consistency over needle-based method. • Low cost of ownership: easy and quick to clean in 10 min or less; maintenance is tool-free; less waste of material due to small wetted path; consumable parts are lower cost. • Outperforms needle based method with regard to speed, flexibility and process simplification
Disadvantages	• Requires periodic cleaning with limited pot life materials. • Sensitive to air in the fluid	• Requires periodic cleaning. • One dot size per jet (multiple shots for larger dot size). • High initial investment cost

2.4.8. Site Cleaning Tools

There is one tool for this purpose: vacuum desoldering tool. Vacuum desoldering tool combines highly focused hot air jet and vacuum nozzle. Hot air jet melts the remnant and vacuum nozzle draws the molten solder away from the PCB as in figure 2.7 (Fidan, 1999).

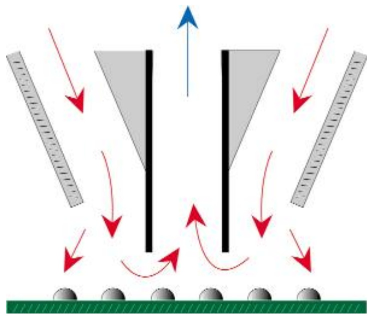


Figure 2.7. Working principle of site cleaning tool.

2.4.9. Inspection System

X-ray inspection system was proposed by Çakırca to inspect dispensing results, site cleaning results, fiducials, defective and good SMCs, board warpage and rework results. It consists of a X-ray camera, X-ray tube, a vision camera and auxiliary tools. Images captured by X-ray inspection system are enhanced, analyzed and prepared for display on a monitor by the vision controller (Rowland, 2002).

2.4.10. SMC Alignment System

Double imaging vision alignment system was proposed by Çakırca (2004) to replace new SMC precisely on the board. Double imaging vision alignment system consists of two cameras one of which images the under side of the component and one of which images the surface of the board and vision controller which analyses images coming from this system and inspection system.

2.4.11. Possible Solutions for Force Measurement

Force control during replacement and component removal is necessary in order not to damage to new SMC during replacement or PCB during replacement or removal. Therefore force during SMC removal and replacement must be controlled. Force control during replacement and removal is provided by two force sensors and cell controller.

2.4.12. Auxiliary Tools

Few more tools are also needed to increase the flexibility of he system. These are robot end effectors, AGV (automated guided vehicle) SMC feeder, tool parking station and junk bin stores. Of these, robot end effectors provide enabling the robot to handle necessary tooling during rework process. AGV (automated guided vehicle) feeds PCBA to the rework system. SMC feeder feeds new SMCs to the rework system. Junk bin stores defective SMCs, Finally, tool parking station stores necessary tools for rework process. These tools contribute to increase the flexibility of the system and are necessary to carry out the rework process in fully automated manner.

2.5. Systematic Design Techniques

As mentioned in chapter 1, the design process consists of four stages. These are product planning and clarifying the task, conceptual design, embodiment design and detail design. This study aims to propose a flexible PCBA rework system by the help of first two phases (product planning and clarifying the task, and conceptual design). Therefore, now, the techniques that are currently used at these phases will be examined closely step by step as below.

2.5.1. Quality Function Deployment (QFD)

This method are used in first phase (product planning and clarifying the task) of the design process. Quality function deployment is a method that supports the process from problem identification to design specification (Roozenburg and Eekels, 1991). Design specifications can be defined as a list of objectives (or a requirements list). According to Roozenurg and Eekels (1991), the QFD method consists of some nine-odd steps.

- *Product attributes:* this step involves defining product attributes which are based on costumer wishes and demands and specifying relative importance of these attributes.
- *Product evaluation:* the performance of the product is compared with that of the competitive products (better, similar or worse)
- *Project objectives:* combining the relative importance of product attributes with the performance of product results in project objectives. Product improvement is also possible at this step.
- *Engineering characteristics:* engineering characteristics or technical parameters of the new product are described at this step. These parameters can be derived either from the specifications of former products which are similar with the new product or by operationalization of the product attributes.
- *Interaction matrix:* interaction matrix determines whether there are relationships between technical parameters and product attributes, if there are, how strongly these are related with each other, and also the priority of technical parameters, taking into account the project objectives.
- *Interactions between parameters:* with changing of one parameter how other parameters are influenced is important to generate solutions in order to improve one or more specific parameters of the product. So a second matrix, called 'roof of the House of the Quality', is constructed at this step to lay down the interactions between parameters.
- *Technical analysis and target values:* to set target values and increase the possibility for improvement of the product the current product and competitive products are analyzed and a comparison between these products is made at this step.
- *Feasibility:* during the feasibility of an improvement designer considers the knowledge and skills of the people in organization, the available development capacity, the available production processes and the costs of the improvement.

- *Development plan:* finally target values for technical parameters are laid down in a development plan which is tailored to the development capacity for the project.

As mentioned above, this method leads the designer to design specifications, or requirements list, or a list of objectives. Then these design specifications can be used in conceptual design phase.

2.5.2. The Requirements List (Design Specifications) and Abstraction

This tool is used in ‘’product planning and clarifying the task’’ phase. In order to clarify the task, which is given by customer or a product planning process, in more detail it is necessary to formulate the requirements list. The purpose of this clarification of the task is to collect information about the requirements that have to be fulfilled by the product, and about the existing constrains and their importance (Pahl and Beitz, 2005).

According to Pahl and Beitz, when preparing a detailed requirements list it is essential to state whether the individual items are demands or wishes. *Demands* are requirements that must be met under all circumstances, in other words, requirements without whose fulfillment the solution is not acceptable. *Wishes* are requirements that should be taken into consideration whenever possible, perhaps with the stipulation that they only warrant limited increases in cost, for example central locking, less maintenance etc. Layout of a requirements list and main headings which should be included in a requirements list are shown table 2.7 and 2.8.

According Pahl and Beitz (2005), after preparation of a requirement list, abstraction based on this requirements list can be very useful to designer. Abstraction is used to solve the problem of fixation and sticking with conventional ideas. This means ignoring what is particular or incidental and emphasizing what is general and essential. With abstraction the problem was defined in more general terms and such a generalization leads us to the crux of the task. Abstraction will be used in later chapter, if necessary.

Table 2.7. Check List for Drawing a Requirements List

Main headings	Examples
Geometry	Size, height, breadth, length, diameter, space requirement, number, arrangement, connection, extension.
Kinematics	Type of motion, direction of motion, velocity, acceleration.
Forces	Direction of force, magnitude of force, frequency, weight, load, deformation, stiffness, elasticity, stability, resonance.
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage capacity, conversion.
Material	Physical and chemical properties of the initial and final product, auxiliary materials, prescribed materials (load regulations etc)
Signals	Inputs and outputs, form, display, control equipment.
Safety	Direct safety principles, protective systems, operational, operator and environmental safety.
Ergonomics	Man-machine relationship, type of operation, clearness of layout, lighting, aesthetcs.
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances.
Quality control	Possibilities of testing and measuring, application of special regulations and standards.
Assembly	Special regulations, installation, siting, foundations.
Transport	Limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of dispatch.
Operation	Quietness, wear, special uses, marketing area, destination (for example, sulphurous atmosphere, tropical conditions)
Maintenance	Servicing intervals (if any), inspection, exchange and repair, painting, cleaning.
Recycling	Reuse, reprocessing, waste disposal, storage.
Costs	Maximum permissible manufacturing costs, cost of tooling, investment and depreciation.
Schedules	End date of development, project planning and control, delivery date.

Table 2.8. Layout of a requirements list.

User	Requirement list For project, product		Identification Classification Page:
Changes	D W	Requirements	Responsible
Date of change	Specify whether item is **D** or **W**	Objective or property with quantitative and qualitative data If necessary split into sub-systems (functions or assemblies) or based on checklist headings	Design group responsible
		Replaces issue of	

This document, if chosen to be used, will be used in conceptual design phase and designer must consider all design specifications in this document.

2.5.3. Objectives Tree (Design Specifications)

Objectives tree is used in the conceptual design phase as the function structure. The objectives tree is derived from design specifications or the requirements list and is used by designer in later steps as an auxiliary tool. Main objective which is main design specification is broken down into sub-objectives (see figure 2.8).

In objectives tree the individual objectives are arranged in hierarchical order. The sub-objectives are arranged vertically into levels of decreasing complexity, and horizontally into objective areas – for instance, technical, economic –or even into major and minor objectives (Pahl and Beitz, 2005).

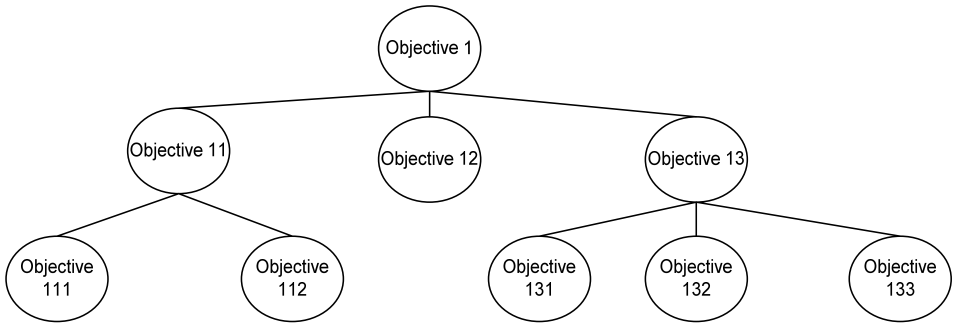


Figure 2.8. Objectives Tree

During design process all objectives must be accomplished and this tool easies designer's job in conceptual design phase.

2.5.4. Function Structure

Function structure is used in the conceptual design phase. According to Pahl and Beitz, design specifications or requirements determine the function, that is, the relationship between the inputs and outputs of a plant, machine or assembly. An overall function based on design specifications (the requirements list) which are prepared in first design phase can be established and then the overall function is broken down into sub-functions of lower-complexity. So that overall function together with sub-functions constitutes the function structure (see fig. 2.9).

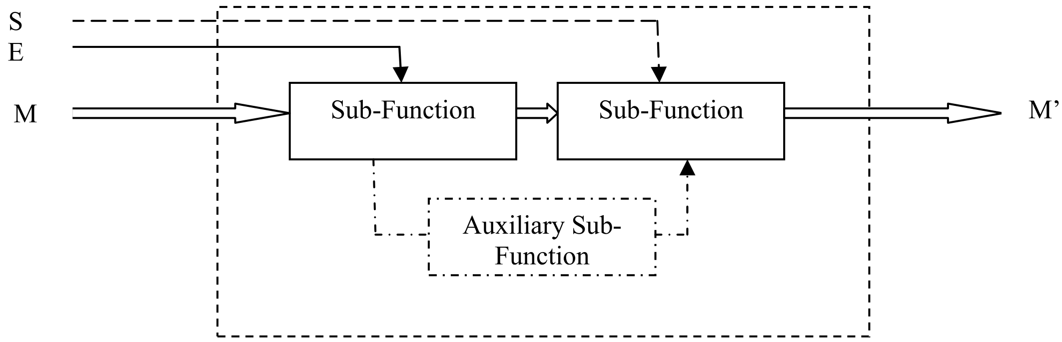
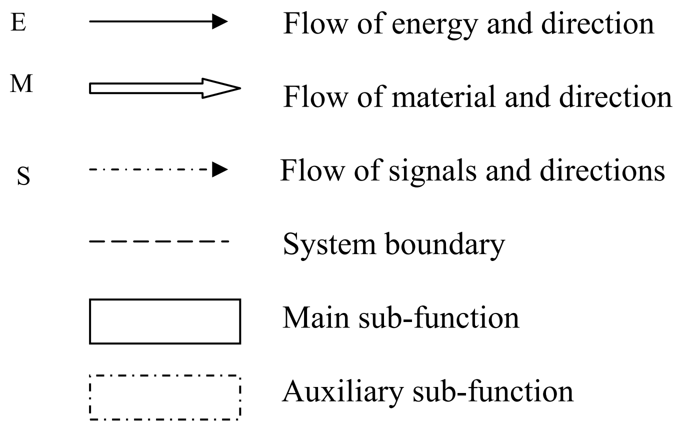


Figure 2.9. Overall function and its sub-functions with its inputs and outputs.

Symbols in figure above, which are representing overall function, sub-functions, inputs and outputs are as follows:



Energy (E) can be mechanical, thermal, electrical, chemical, optical, nuclear, force, current, heat energy, etc.

Material (M) can be gas, liquid, solid, dust, raw material, test sample, workpiece, end product, component, etc.

Signals (S) can be magnitude, display, control impulse, data, information, etc.

2.5.5. Solution Finding Methods

Solution finding methods are used in the conceptual design phase. Conceptual design phase mostly relies on these methods. According to Pahl and Beitz, they can be divided into three groups: conventional methods, intuitive methods and discursive methods.

Intuitive methods such as brainstorming, method 635, gallery method, delphi method, synectics and many others involve group dynamics to generate the widest possible range of ideas. One of the effects of group dynamics is the uninhibited exchange of associated ideas between the members. Most of these techniques were originally devised for the solution of non-technical problems. They are, however, applicable to any field that demands new, unconventional ideas.

Conventional methods are literature search, analysis of natural systems, analysis of existing technical systems, analogies, measurements and model tests. Conventional methods will be run through briefly as followings:

Literature Search: For designers, up-to-date technological data provide a wealth of important information. Such data can be found in textbooks and technical journals, in patent files and in brochures published by competitors. They provide a most useful survey of known solution possibilities.

Analysis of Natural Systems: The study of natural forms, structures, organisms and processes can lead to very useful and novel technical solutions. For example, light weight structures can be achieved by the use of honeycombs.

Analysis of Existing Technical Systems: The analysis of existing technical systems is one of the most important means of generating new or improved solution variants step-by-step.

This analysis involves the mental or even physical dissection of finished products. It may be considered a form of structure analysis aimed at discovery of related logical, physical and embodiment design features. Sub-functions can be derived from the function structure of existing system. From them, further analysis can lead to the identification of the physical effects involved which, in turn, might have suggested new solution principles for corresponding sub-functions. It is also possible to adopt solution principles discovered during the analysis.

It will prove particularly helpful in finding a first solution concept as a starting point for further variations. It must, however, be said that this approach carries the danger of causing designers to stick with known solutions instead of pursuing new paths.

Analogies: In the search for solutions and in the analysis of system properties, it is often useful to substitute an analogous problem (or system) for the one under consideration, and to treat it as a model.

Besides helping in the search for solutions, analogies are also helpful in the study of the behavior of a system during the early stages of its development by means of simulation and model techniques, and in the subsequent identification of essential new sub-solutions and the introduction of early optimizations.

Measurements and Model Tests: Measurements on existing systems, model tests supported by similarity analyses and other experimental studies are among the most important sources of information. In precision engineering and mass production industries, including the development of micro-mechanisms and electronic products, experimental investigations are an important and established means of arriving at solutions.

As for *discursive methods,* discursive methods such as systematic study of physical processes, systematic search with the help of classification schemes and use of design catalogues provide solutions in a deliberate step-by step approach that can be influenced and communicated. Discursive methods do not exclude intuition, which can make its influence felt during individual steps and in the solution of individual problems, but not in the direct implementation of the overall task. Discursive methods will be run through briefly as followings:

Systematic Study of Physical Processes: One way of this method includes a known physical effect (chemical or biological) which has independent and dependent variables and has relationships between these variables. Good solutions for a function can be derived from the analysis of their interrelationships. Another way of obtaining new or improved solutions by the analysis of physical equations is the resolution of known physical effects into their individual components.

Classification Schemes: All possible solutions for a function are shown on the classification scheme. The classification schemes contribute to designer in many ways. They can be regarded as design catalogues for the designer during solution finding process and can also help in the combination of sub-solutions into overall solutions. They can be called as *morphological matrices.* General structure of a classification scheme is as in table 2.9.

Table 2.9. General Structure of Classification Schemes

Classifying criterion for labelling the columns		Column parameters				
Classifying criterion for labelling the rows		C1	C2	C3	C4	
Row parameters	R1					
	R2					
	R3					
	R4					
	R5					

According to Pahl and Beitz, the choice of *classifying criteria* or of their parameters is of crucial importance. In establishing a classification scheme it is best to use the following step-by-step procedure:

Step 1: Solution proposals are entered in the rows in random order.

Step 2: These proposals are analyzed in the light of the headings (characteristics) (see table 2.10 and 2.11) such as type of energy, type of motion etc.

Step 3: They are classified in accordance with these headings.

Table 2.10. Classifying Criteria and Headings (Characeristics) for Variation in the Form Design Search Area

Classifying criteria: Working surfaces, working motions and basic material properties	
Working geometry	
Headings:	*Examples:*
Type	Point, line, surface, body
Shape	Curve, circle, ellipse, hyperbola, parabola Triangle, square, rectangle, pentagon, hexagon, octagon Cylinder, cone, rhomb, cube, sphere Symmetrical, asymmetrical
Position	Axial, radial, tangential, vertical, horizontal Parallel, seqential
Size	Small, large, narrow, broad, tall, low
Number	Undivided, divided Simple, double, multiple
Working motions	
Headings:	*Examples:*
Type	Stationary, translational, rotational
Nature	Uniform, non-uniform, oscillating Plane or three dimensional
Direction	In x,y,z direction and/or about x,y,z axis
Magnitude	Velocity
Number	One, several, composite movements
Basic material properties	
Headings:	*Examples:*
State	Solid, liquid, gaseous
Behavior	Rigid, elastic, plastic, viscous
Form	Solid body, grains, powder, dust

Table 2.11. Classifying Criteria and Headings (Characteristics) for Variation in the Physical Search Area

Classifying criteria: Types of energy, physical effects and outward appearance	
Headings:	*Examples:*
Mechanical	Gravitation, inertia, centrifugal force
Hydraulic	Hydrostatic, hydrodynamic
Pneumatic	Aerostatic, aerodynamic
Electrical	Electrostatic, electrodynamics, inductive, capactative piezo-electric, transformation, rectification
Magneic	Ferromagnetic, electromagnetic
Optical	Reflection, refraction, diffraction, interference, polarization, infra-red, visible, ultra violet
Thermal	Expansion, bimetal effect, heat storage, heat transfer heat conduction, heat insulation
Chemical	Combustion, oxidation, reduction, dissolution, combination transformation, electrolysis, exothermic and endothermic reaction
Nuclear	Radiation, isotopes, source of energy
Biological	Fermentation putrefaction, decomposition

These characteristics or classifying criteria can also be obtained from an earlier use of intuitive methods to analyze known solutions or solution ideas.

This procedure not only helps with the identification of compatible combinations but, more importantly, encourages the opening up of the widest possible solution fields.

Design Catalogues: Design catalogues, table 2.12, are collections of known and proven solutions to design problems. They contain data of various types and solutions of distinct levels of embodiment. Thus they may cover physical effects, working principles, principle solutions, machine elements, standard parts, materials, bought-out components etc. Design catalogues should provide:

- Quicker, more problem-oriented access to the accumulated solutions or data;
- The most comprehensive range of solutions possible, or, at the very least, the most essential ones, which can be extended later;
- Applications independent of specific company or discipline; and
- Data for conventional design procedures as well as for computer-aided methods.

Table 2.12. Basic Construction of a Design Catalogue.

Classifying criteria			Solutions			Solution characteristics					Remarks		
1	2	3	1	2	Nr.	1	2	3	4	5	1	2	3
					1				X				
					2				X	X			
					3	X	X						
					4								
					5								

The *classifying criteria* determine the structure of the catalogue. They influence the ease with which catalogues can be handled and reflect the level of complexity of particular solutions, and also their degree of embodiment. In the conceptual design phase it is advisable to select as classifying criteria the functions to be fulfilled by the solutions. This is because the conceptual design is based on the underlying sub-functions. For classifying characteristics it is best to choose generally valid functions, which help to elicit the most product-independent solutions. Available design catalogues are introduced in table 2.13.

In addition to the methods above, some currently used methods such as TRIZ (Theory of Inventive Problem Solving), ASIT (Advanced Systematic Inventive Thinking) are available to overcome some contradictions in the problem world. TRIZ/ASIT methods are explained below.

TRIZ and ASIT Methods: TRIZ is a problem solving method based on logic and data, not intuition, which accelerates the project team's ability to solve these problems creatively. TRIZ also provides repeatability, predictability, and reliability due to its structure and algorithmic approach (Katie Barry, Ellen Domb and Michael S. Slocum, 2006).

Table 2.13. Available design catalogues.

Application	Object	Author
General	Construction of catalogues	Roth
	List of available catalogues and solutions	Roth
Principle solutions	Physical effects	Roth
	Solutions to functions	Koller
Connections	Types of connections	Roth
	Connections	Ewald
	Fixed connections	Roth
	Welded joints for steel profiles	Wölse and Kastner
	Riveted joints	Roth Kopowski Grandt
	Adhesive joints	Fuhrmann and Hinterwalder
	Clamping elements	Ersoy
	Principles of threaded joints	Kopowski
	Threaded fasteners	Kopowski
	Elimination of backlash in threaded joints	Ewald
	Elastic joints	Giessner
	Shaft-hub-connections	Roth, Diekhöner
Guides and bearings	Linear guides	Roth
	Rotational guides	Roth
	Plain and roller bearings	Diekhöner
	Bearings and guides	Ewald
Power generation, power transmission	Electric motors (small)	Jung and Schneider
	Drivers (general)	Schneider
	Power generators (mechanical)	Roth
	Effects to generate power	Roth
	Single stage power multiplication	Roth
	Lifting mechanisms	Raab and Schneider
	Screw drivers	Kopowski
	Function systems	Roth
Kinematics, mechanics	Solving motion problems using mechanisms	VDI 2727
	Chain drives and mechanisms	Roth
	4-bar mechanisms	VDI 2222
	Logical inverse mechanisms	Roth
	Logical conjunctive and disjunctive mechanisms	Roth
	Mechanical flip-flops	Roth
	Mechanical non-return safety devices	Roth
	Lifting mechanisms	Raab ad Schneider
	Uniform –motion transmissions	Roth
	Handling devices	VDI 2740
Gearbox	Spur gear	VDI 2222, Ewald
	Mechanical single-stage gearboxes with constant gear ratio	Diekhöner and Lohkamp
	Elimination of backlash in spur gears	Ewald
Safety technology	Danger stations	Neudörfer
	Protective barriers	Nedörfer
Ergonomics	Indicators, controls	Neudörfer
Production processes	Casting	Ersoy
	Drop forging	Roth
	Press forging	Roth

In the course of solving any one of technical problem, the 40 Principles of Problem Solving are the most accessible "tool" of TRIZ (see table 2.14). These 40 principles involve some general solutions which were found against some contradictions faced by designers in the world, and lead designer to create solutions against these contradictions encountered during problem solving. A contradictions matrix (database) is also other tool of TRIZ with which designers can decide which principles can solve the contradiction and then follow these principles. In addition to 40 principles and contradiction matrix, there are also some other tools in TRIZ: *standard solution and physical effect, evaluation of systems, the little man method and S-field analysis tool.*

Table 2.14. 40 Principles of TRIZ (www.triz-journal.com, 2007)

1. Segmentation	**A.** Divide an object into dependant parts
	B. Make an object sectional-easy to assemble or disassemble
	C. Increase the degree of fragmentation or segmentation
2. Taking out	**A.** Extract the disturbing part or property from an object
	B. Extract the only necessary part (or property) of an object
3. Local quality	**A.** Change of an object's structure from uniform to non-uniform
	B. Change an action or external influence from uniform to non-uniform
	C. Make each part of an object function in conditions most suitable for operations
	D. Make each part of an object fulfil a different and/or complementary useful function
4. Asymmetry	**A.** Change the shape or properties of an object from symmetrical to asymmetrical
	B. Change the shape or properties of an object to suit external asymmetries (i.e. ergonomic features)
	C. If an object is asymmetrical, increase its degree of asymmetry
5. Merging	**A.** Bring closer together (or merge) identical or similar objects or operations in space
	B. Make objects or operations contiguous or parallel; bring them together in time
6. Universality	**A.** Make an object perform multiple functions; eliminate the need for other parts
7. Nested doll	**A.** Place one object inside another
	B. Place multiple objects inside another
	C. Make one part pass (dynamically) through a cavity in the other
8. Anti-weight	**A.** To compensate for the weight of an object, merge it with other objects that provide lift
	B. To compensate for the weight of an object, make it interact with the environment (use aerodynamic, hydrodynamic, buoyancy and others)
9. Prior counteraction	**A.** When it is necessary to perform an action with both harmful and useful effects,

	this should be replaced with counteractions to control harmful effects
	B. Create beforehand stresses in an object that will oppose known undesirable working stresses later on
10. Prior action	**A.** Perform the required change of an object in advance
	B. Pre-arrange objects such that they can come into action from the most convenient place and without losing time for their delivery
11. Cushion in advance	**A.** Prepare emergency means beforehand to compensate for the relatively low reliability of an object ('belt and braces')
12. Equipotentially	**A.** If an object has to be raised or lowered, redesign the object's environment so the need to raise or lower is eliminated or performed by the environment
13. The other way round	**A.** Invert the action used to solve the problem
	B. Make movable parts fixed, and fixed parts movable
	C. Turn the object (or process) upside down
14. Speheroidality-Curvature	**A.** Move from flat surfaces to spherical ones and from parts shaped as a cube (parallel piped) to ball-shaped structures
	B. Use rollers, balls, spirals
	C. Go from linear to rotary motion (or vice versa)
	D. Use centrifugal forces
15. Dynamics	**A.** Change the object (or outside environment) for optimal performance at every stage of operation
	B. Divide an object into parts capable of movement relative to each other
	C. Change from immobile to mobile
	D. Increase the degree of free motion
16. Partial or excessive action	**A.** If 100 percent of an object is hard to achieve using a given solution method then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve
17. Another dimension	**A.** Move into an additional dimension – from one to two – from two three
	B. Go from single storey or layer to multi-storey or multi-layered
	C. Incline an object, lay it on its side
	D. Use the other side
18. Mechanical vibration	**A.** Cause an object to oscillate or vibrate
	B. Increase its frequency (even up to the ultrasonic)
	C. Use an object's resonant frequency
	D. Use piezoelectric vibrators instead of mechanical ones
	E. Use combined ultrasonic and electromagnetic field oscillations

19. Periodic action	**A.** Instead of continuous action, use periodic or pulsating actions
	B. If an action is already periodic, change the periodic magnitude or frequency
	C. Use pauses between actions to perform a different action
20. Continuity of useful action	**A.** Carry on work without a break. All parts of an object operating constantly at full capacity
	B. Eliminate all idle or intermittent motion
21. Rushing through	**A.** Conduct a process, or certain stages of it (i.e. destructible, harmful or hazardous operations) at high speed
22. Blessing in disguise	**A.** Use harmful factors (particularly, harmful or hazardous operations) at high speed
	B. Eliminate the primary harmful action by adding it to another harmful action to resolve the problem
	C. Amplify a harmful factor to such a degree that it is no longer harmful
23. Feedback	**A.** Introduce feedback to improve a process or action
	B. If feedback is already used, change its magnitude or influence in accordance with operating conditions
24. Intermediary	**A.** Use and intermediary carrier article or intermediary process
	B. Merge one object temporarily with another (which can be easily removed)
25. Self-service	**A.** An object must service itself by performing auxiliary helpful functions
	B. Use waste resources, energy or substances
26. Copying	**A.** Replace unavailable, expensive or fragile object with available or inexpensive copies
	B. Replace an object, or process with optical copies
	C. If visible optical copies are used, move to infrared or ultraviolet copies
27. Cheap short-living objects	**A.** Replace an expensive object with a multiple of inexpensive objects, compromising certain qualities, such as service life
28. Replace mechanical system	**A.** Replace a mechanical system with a sensory one
	B. Use electric magnetic and electromagnetic fields to interact with the bject
	C. Replace stationary fields with moving; unstructured fields with structured
	D. Use fields in conjunction with field-activated (e.g. ferromagnetic) particles
29. Pneumatics and hydraulics	**A.** Use gas and liquid parts of an object instead of solid parts (i.e. inflatable, filed with liquids, air cushion, hydrostatic, hydro-reactive)
30. Flexible membranes/thin films	**A.** Use flexile shells and thin films instead of three-dimensional structures
	B. Isolate the object from its external environment using flexible membranes
31. Porous materials	**A.** Make an object porous or add porous elements (inserts, coating, etc.)
	B. If an object is already porous, use the pores to introduce a useful substance or

	function
32. Colour change	**A.** Change the colour of an object or its external environment
	B. Change the transparency of an object or its external environment
	C. In order to improve observability of things that are difficult to see, use coloured additives or luminescent elements
	D. Change the emissivity properties of an object subjected to radiant heating
33. Homogeneity	**A.** Objects interacting with the main object should be of same material (or material with identical properties)
34. Discarding and recovering	**A.** After completing their function (or becoming useless) reject objects, make tem go away, (discard them by dissolving, evaporating, etc) or modify during the process
	B. Restore consumable/used up parts of an object during operation
35. Parameter change	**A.** Change the physical state (e.g. to a gas, liquid, or solid)
	B. Change the concentration or density
	C. Change the degree of flexibility
	D. Change the temperature or volume
	E. Change the pressure
	F. Change other parameters
36. Phase transition	**A.** Use phenomena of phase transitions (e.g. volume changes)
37. Thermal expansion	**A.** Use thermal expansion, or contraction, of materials
	B. Use multiple materials with different coefficients of thermal expansion
38. Accelerated oxidation	**A.** Replace common air with oxygen-enriched air
	B. Replace enriched air with pure oxygen
	C. Expose air or oxygen to ionizing radiation
	D. Use ionized oxygen
	E. Replace ionized oxygen with ozone
39. Inert atmosphere	**A.** Replace a normal environment with an inert one
	B. Add neutral parts, or inert additives to an object
40. Composite materials	**A.** Change from uniform to composite materials

ASIT (Advanced Systematic Inventive Thinking) is a creative thinking method derived from TRIZ. In ASIT method, in contrast to TRIZ, there are two rules (Closed World and Qualitative Change) and five idea-provoking tools (Unification, Multiplication, Division, Breaking Symmetry and Object Removal) which are transformed from the contradiction matrix, 40 principles and the ideal final results rule of TRIZ method.

Instead of 40 principles in TRIZ, five idea-provoking tools are used in ASIT in order to avoid some principles of TRIZ which are very general or very problem-specific. Closed world rule (a solution developed should not involve the addition of a new type of component into problem world) is the most important rule in ASIT. Second rule, which is qualitative change, compensates partly inability of TRIZ in solving contradictions in some problems. Qualitative change can be defined as follows: Look for solutions in which the influence of the main problem factor is either totally eliminated or even reversed. Other rules are below:

1. **Unification**: Solve a problem by assigning a new use to an existing component (the pipe and metal balls problem is solved by Unification - the balls are put to a news use, i.e. protecting the pipe).
2. **Multiplication**: Solve a problem by introducing a slightly modified copy of an existing object into the current system.
3. **Division**: Solve a problem by dividing an object and reorganizing it parts.
4. **Breaking Symmetry**: Solve a problem by turning a symmetrical situation into an asymmetrical one.
5. **Object Removal**: Solve a problem by removing an object from the system and assigning its action to another existing object.

In addition to differences between ASIT and TRIZ which are explained above, ASIT method eliminates other TRIZ elements such as standard solution and physical effect, evaluation of systems, the little man method (www.triz-journal.com, 2007). If necessary, these methods will be used in later section.

2.5.6. Function/Means Tree

The function means tree is used in the conceptual design phase. The function means tree is a well established method for functional decomposition and concept generation. As the function structure, the overall function determined is broken down into sub-functions of lower complexity in hierarchical order (see figure 2.10). Then every function at the lowest steps of the tree is added possible solutions which were determined by the aid of solution finding methods. Then this structure with functions and all possible solutions both helps the designer to handle a complex problem easier and are also used in evaluation process as database.

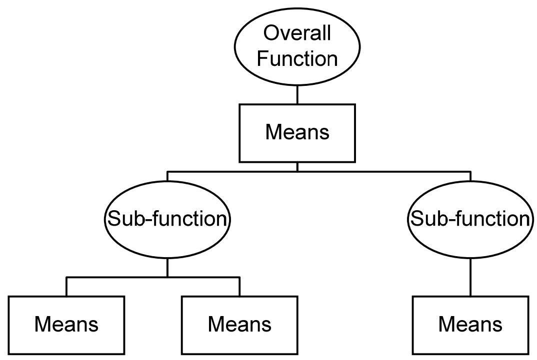


Fig. 2.10. Function/Means Tree

2.5.7. Selection and Evaluation Methods

Selection and evaluation methods are used in the conceptual design phase. Solutions which are developed with the help of methods explained above must now be selected in order to eliminate practically unattainable solutions so that the very great number of solutions is reduced at the earliest possible moment. Then these solutions are evaluated to obtain the most promising solution. This evaluation involves an assessment of technical safety, environmental and economic values. For this purpose some selection and evaluation methods can be used. Now, selection chart will be outlined. After the selection chart, some methods which complete each other and so that form an evaluation procedure will be outlined consequently below.

Selection Chart: At the earliest moment there can be many possible solutions for the designer. Theoretically admissible, but practically unattainable solutions must be eliminated. On the other hand, care must be taken not to eliminate valuable solutions.

This selection procedure involves two steps, namely elimination and preference. First, all totally unsuitable proposals are eliminated. If too many possible solutions still remain, those that are patently better than the rest must be give preference. Only these solutions are further elaborated and evaluated (Pahl and Beitz, 2007).

General structure of a selection chart is shown in table 2.15. As can be seen in table 2.15, in the selection chart there are four design criteria (A, B, C and D) to be used to eliminate unsuitable solutions. Suitable solutions should be compatible with the overall task and with one another (Criterion A), fulfill the demands of the requirements list (Criterion B), be realizable in respect of performance, layout, etc. (Criterion C) and be expected to be within permissible costs (Criterion D).

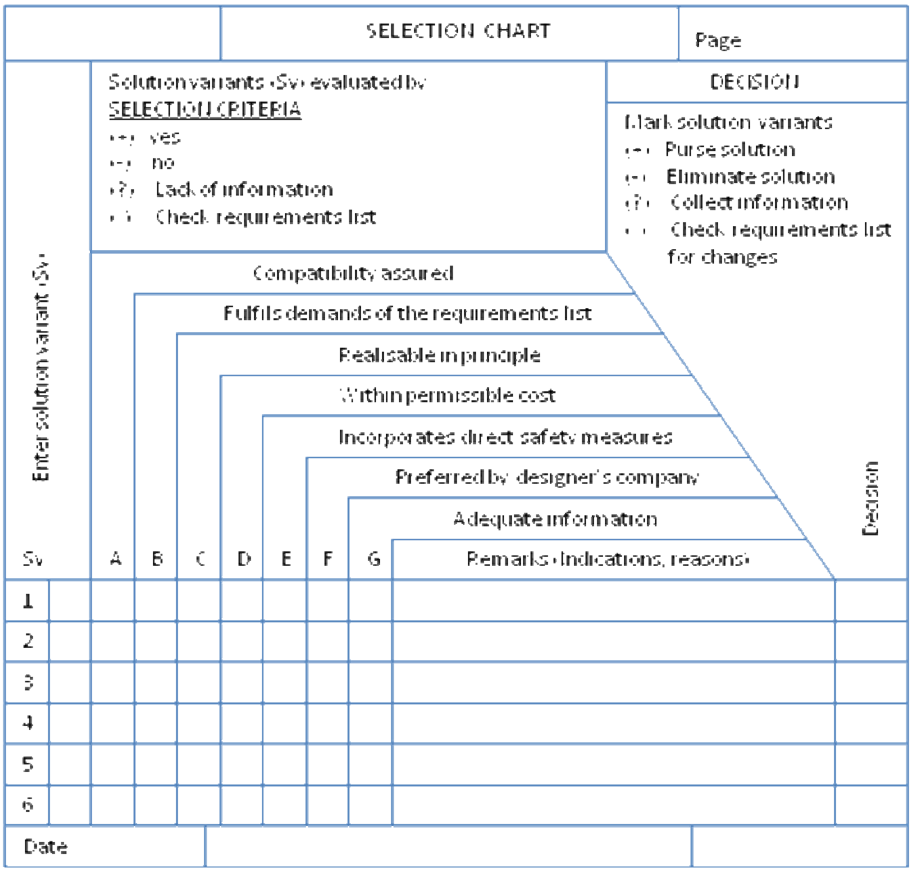
Other criteria are preferential criteria, and are ‘’incorporate direct safety measures’’ (Criterion E) and ‘’preferred by designer’s company’’ (Criterion F). A preference is justified if, among the very large number of possible solutions, there are some those:

- incorporate direct safety measures or introduce favorable ergonomic conditions (Criterion E); or
- are preferred by the designer’s company, that is, can be readily developed with the available know-how, materials, and procedures, and under favorable patent conditions (Criterion F). Additional selection criteria can be used if they are helpful in coming a decision (Pahl and Beitz, 2005).

The solution variants about which the designer has not enough information are not easily passed over. In the case of promising variants that satisfy criteria A and B, the gap will have to be filled by a re-evaluation of the proposal.

Finally, selected solution variants by use of the selection chart should be pursued by the designer. If necessary, this chart will be used in the design of fully automated rework system in following section.

Table 2.15. General structure of a selection chart.



Weighted Objectives Tree: Weighted objectives tree, figure 2.11, is one of the methods which are used in evaluation process. Objectives, which are also called design specifications, are mainly derived from the requirements list and from general constraints. They usually comprise several elements that not only introduce a variety of technical, economic and safety factors, but that also differ greatly in importance.

In figure 2.11, the individual objectives, which are determined from the requirements list, are arranged in hierarchical order. The sub-objectives are arranged vertically into level of decreasing complexity, and horizontally into objective areas such as technical, economic, etc. The values on the right hand side of every objective circle in the weighted objectives tree are given by designer according to the relative importance of the objectives. These values given by designer must be between 0 and 1. And for every objective area such as objective 111 and objective 112 (these objectives forms the objective area) the summation of these values must be 1.

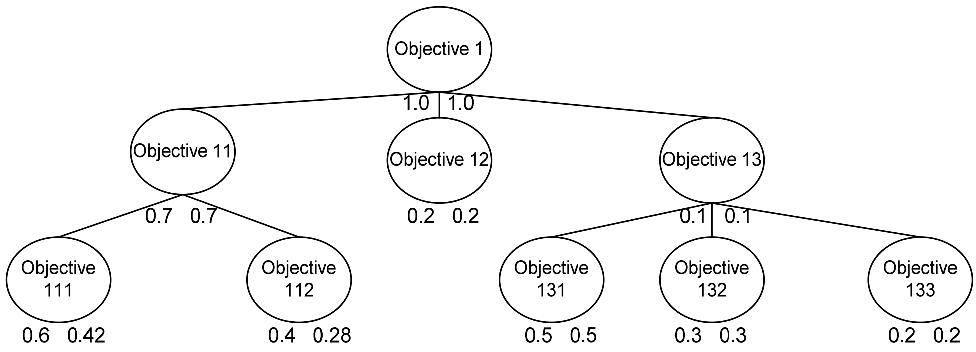


Figure 2.11. Weighted objectives tree.

The weighting factors on the left hand side of every objective are determined by multiplication of the values on the left hand side of the objectives each other in hierarchical manner. For example the value 0.42 for the objective 111 is found by multiplication of 0.6, on the left side of the objective 111, 0.7, on the left side of the objective 11 ,and 1.0, on the left side of the objective 1. The sum of these determined weighting factors must be again 1.

Weighting objectives tree will be used subsequent sections to evaluate optimum solutions for the related functions.

Use-value analysis and guideline VDI 2225: These concepts are used in evaluation process as a continuation of the weighted objectives tree. They are similar to each other in many ways but with minor differences. As soon as weighted objectives tree is prepared, every solution for the objectives is given a number between 1 and 10 for use-value analysis and between 0 and 4 for guideline VDI 2225 (see table 2.16). The number given indicates how the solution reacts to the objective (weak, good, very good, ideal etc.), as can be seen in table 2.16. These numbers then is used for evaluation optimum solution in later methods.

Table 2.16. Points awarded in use-value analysis and guideline VDI 2225.

Value Scale			
Use-value analysis		Guideline VDI 2225	
Points	Meaning	Points	Meaning
0	absolutely useless solution	0	unsatisfactory
1	very inadequate solution		
2	weak solution	1	just tolerable
3	tolerable solution		
4	adequate solution	2	adequate
5	satisfactory solution		
6	good solution with few drawbacks	3	good
7	good solution		
8	very good solution	4	very good (ideal)
9	solution exceeding the requirement		
10	ideal solution		

Evaluation Chart: Then the solutions, objectives (evaluation criteria), weighting factors and the values that get from use-value analysis or guideline VDI 2225 are entered to a chart that is called evaluation chart (see table 2.17).

Table 2.17. General structure of an evaluation chart.

Evaluation Criteria			Objective Parameters		Variant1			Variant2		
No		Wt.		Unit	Magn. (m_{i1})	V_{i1}	Wv_{i1}	Magn. (m_{i2})	V_{i1}	Wv_{i1}
1	Low fuel consumption	0.3	Fuel consumption	g/kWh	240	8	2.4	300	5	1.5
2	-	-	-	-	-	-	-	-	-	-
3	-	-	-	-	-	-	-	-	-	-
4	-	-	-	-	-	-	-	-	-	-
						$\sum v_i=$	$\sum Wv_i=$		$\sum v_i=$	$\sum Wv_{i1}=$

In table 2.17, two variants are evaluated for evaluation criterion ‘’Low fuel consumption’’. The weighting factor taken from the weighted objectives tree for this evaluation criterion, fuel consumption rates of both variants and the number given by the designer using value scale in table 2.16 are all entered into the evaluation chart.

In this chart, ''$\sum v_i$'' is the sum of the given numbers and called as unweighted overall value. ''$\sum Wv_i$'' (overall weighted value) is the sum of weighted values that are determined by multiplication of the given number and the weighting factor. As a result, variant that has the biggest overall weighted value is optimum solution for the related task or function. This chart will be also used in later chapters, where it is needed.

Value Profile: In case of that at the end of evaluation two or more successful solutions, that their overall weighted values determined during evaluation process are almost same, are available, value profiles are used to overcome this difficulty. With value profiles the designer can detect weak points of the solutions. After consideration of value profiles, the most promising solution is determined. General structure of a value profile is as in figure 2.12.

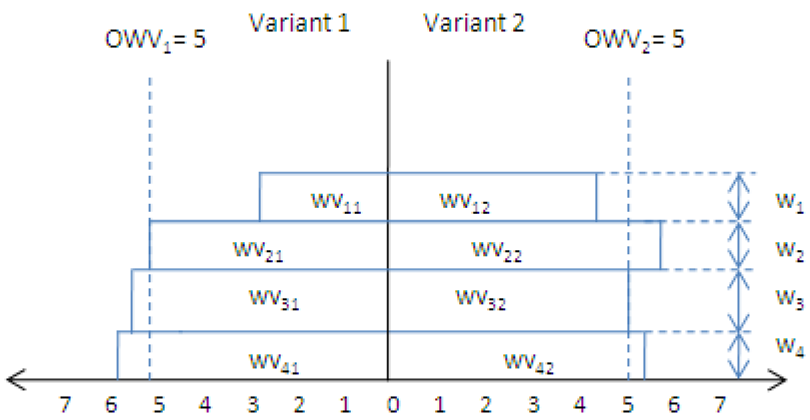


Figure 2.12. Value profile for the comparison of two variants ($\sum W_i=1$).

In figure 2.12, the lengths of the bars correspond to the weighted values and the thicknesses to the weighting factors. As can be seen in figure 2.12, both variants have equal weighted overall value. However, the variant 1 has a serious weak point (''wv_{11}'' is very low). Therefore the variant 2 should be optimum solution for this example. If needed, this profile will be used in later sections.

2.6. Flexible Manufacturing System and FMS Modeling Techniques

It is necessary for a designer who looks for flexibility to know the FMS system features very well and to be able to apply system modeling techniques successfully. Now, system modeling techniques and main FMS features will be explained in more detail.

2.6.1. FMS Features

According to Paul G. Ranky, the FMS system utilize highly automated and reprogrammable cells capable of ‘’taking care of themselves’’ (i.e. incorporating powerful controllers and self diagnostic systems), capable of changing their tools and parts, preferably unmanned, and keeping in touch with a computer or with a node controller from where the production plan, the part programs and further necessary data arrive and are fed back. It links these cells into a system by providing preferably direct access, or random material handling systems (e.g. Automated Guided Vehicle), rather than serial access (e.g. conveyor lines).

Addition to these above, it creates a part tool and pallet (modular, flexible fixture and clamping device) storage facility (i.e. warehouse, part tool station). It provides high level computer control ‘’inside’’ and ‘’outside’’ the system based on distributed processing subsystems and local area networks. Finally, the FMS system ensures that if any cells break down the production planning and control system can dynamically reroute and reschedule production. In other words, design in the system not only programmable (i.e. flexible) production facilities, but also ensure that the routing of parts can be dynamically altered.

To be able to supply the above features the FMS system should generally consist of the following building blocks:

- The robot arm (or arms), with its controller.
- The necessary grippers and/or tools (preferably in a tool magazine enabling automated robot hand changing).

- Part feeding mechanisms (with the necessary sensors that are capable of reporting status information of various kinds t the cell controller).
- Palletized part docking (if required), providing a standard part locating device (Note that it is assumed that parts are delivered to each cell known orientation and location).
- Other electronic and sensory-based devices (e.g. vision, force, torque sensing, position calibration, etc.) which are interfaced with the cell and wich are used for guidance safety or generating feedback data in real time.
- Modular fixturing techniques.

From a control of view, the FMS cell controller should be able to handle and support followings:

- Multi-axis control, motion control, acceleration control, etc. (i.e. robot control).
- Digital and analogue interfaces.
- Standard communication interfaces to remote controllers and to LANs (Local Area Networks).
- Standard peripherals, such as a teach pendant, disk, display, keyboard, operator's panel. (They are important devices if the cell is a stand-alone device, programmed and operated as a single and separate unit. In most cases when more cells are linked together, peripherals such as the keyboard or the display are used only in ''panic'' situations, as well as during debugging and maintenance.)
- Tool changing devices and tool magazine data management, enabling the cell to store several tool (i.e. robot hands).
- Part docking and part identification tasks (for parts typically arriving on standard size pallets, (i.e. standard size within a particular system in a known orientation and location), preferably using a direct access material handling system (e.g. AGV), and wireless coded pallets which are capable of storing data in an on-board microchip.

- Safety devices and diagnostic software, including interlocks, built-in error detection sensors, power interruption control, extra power sources for sensors, or tools requiring a separate power supply, etc., and preferably cell diagnostic expert system.

A fully automated flexible rework system must have all building blocks of the FMS system above. Therefore, during design process these building blocks will be introduced into the rework system to achieve a fully automated flexible rework system.

2.6.2. System Modeling Techniques

System modeling techniques have evolved because of the need to represent the operations and activities that occur within the growing number of increasingly complex manufacturing and other types of systems that are being designed. This is primarily in order to facilitate the study of existing systems and to aid the design of new complex systems. In this context a system is defined as a set of interacting components with relationships between them (Paul G. Ranky, 1990).

Modeling techniques are considered generally under two main headings: these are static models and dynamic models. Static models are used for system definition. Some static models that are currently used in worldwide are the dataflow diagramming (DFD) and SADT (Structured Analysis and Design Technique or IDEF). Dynamic models are built around the static models and are used to simulate the system's operational performance. Some dynamic models that are currently used in worldwide are discrete event modeling, solid modeling and simulation, and petri-net modeling.

Static models DFD and SADT (IDEF) will be explained in more detail. Since one of them will be used during design phase in order to describe the system.

Data Flow Diagrams (DFDs): DFDs show the transformations that occur within systems without making assumptions about how they occur. They identify the functional elements of a system and the information flow between the elements.

DFDs use different symbols for describing systems. Processes are typically represented by ellipses, data sources/sinks by boxes, and data stores/files by two parallel lines. A DFD for an automated drilling operation is shown in figure 2.13.

When designing and drawing such diagrams, designer should start with the identification of the major processes, then continue with the data sources and sinks, and conclude with the data flow and finally data stores (Paul G. Ranky, 1990).

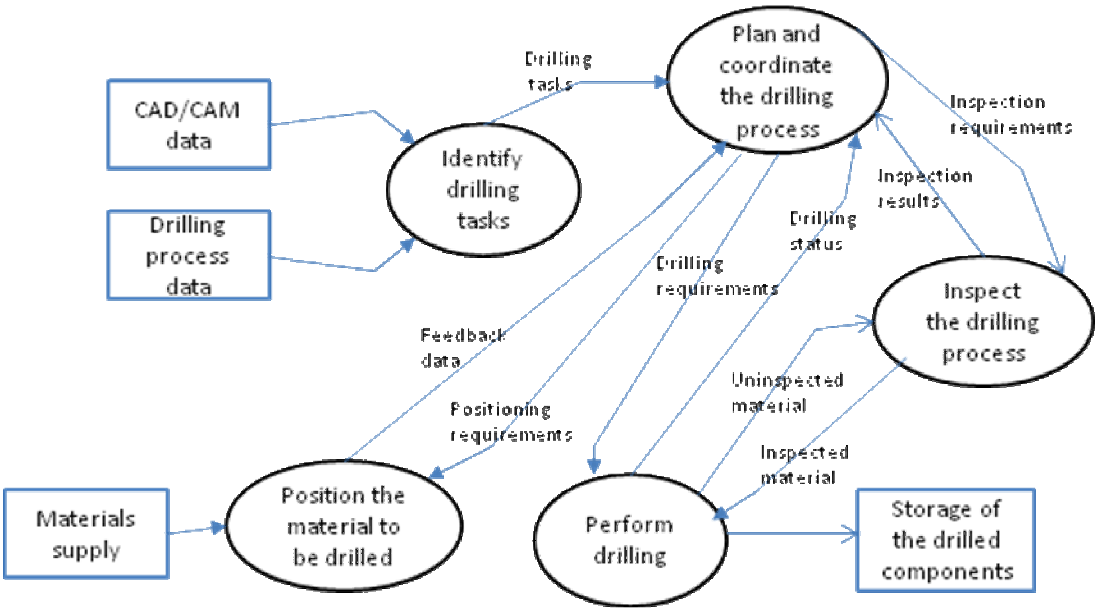


Figure 2.13. The DFD for an automated drilling operation.

The DFD is very useful and simple to be constructed in order to describe a FMS system. Therefore this diagram will be used in later section at the end of the design process to describe the system.

IDEF (Integrated Computer-Aided Manufacturing Definition Methodology or SADT: The IDEF modeling technique is useful as both a descriptive and as an analytical tool. As a descriptive tool it is used to identify the components of a system which cause change over a period of time. As an analytical tool it can be used as a basis for simulation to test the performance of an FMS design.

IDEF is a hierarchical tree of parent and child diagrams. As can be seen in figure 2.14, at the top of tree there is a very high-level description of the entire system (parent diagram). In figure 2.14, inputs are transformed into outputs, controls constrain or dictate under what conditions transformations occur, and mechanisms describe how the function is accomplished. The arrows represent ‘’things’’, where things can be plans, data machines, information, etc. All the inputs on the left side of the activity box are converted, under the influence of the mechanism and control, into the output on the right.

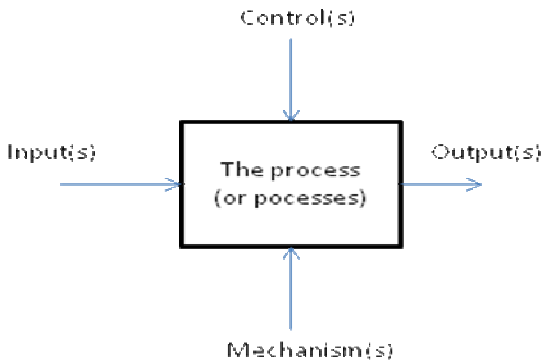


Figure 2.14. High-level description of the entire system.

Then the parent diagram is decomposed into child diagrams, as in figure 2.15. The child diagrams can detail the information in the parent diagram by identifying the major activities involved in manufacturing the particular component, i.e., studying the engineering drawing, determining the manufacturing process(es) required and manufacturing the component (Paul G. Ranky, 1990).

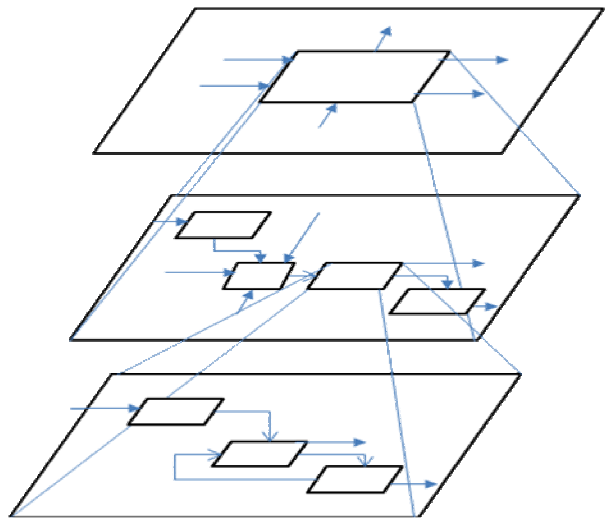


Figure 2.15. General structure of IDEF.

When necessary, this method will be used during design process in order to describe the fully automated PCBA rework system in following chapter.

3. MATERIAL AND METHOD

This study aims to propose a flexible fully automated PCBA rework system for advanced SMCs by the help of systematic design techniques and FMS modeling techniques that have been explained in detail in chapter 2. This system will be based on the data that has been provided by Çakırca (2004) in chapter 2.

For this purpose a design methodology for a flexible fully automated PCBA rework system is prepared as in figure 3.1. As a result of this methodology, design and development of the hardware for a fully automated flexible PCBA rework system is going to be eased and better systemized. This design methodology will be followed step by step in chapter 4. Now, the design methodology steps will be explained in preceding sections:

3.1. Specifying the Need (1)

In this step, need is specified by either directly the customer or a market survey by the use of some methods such as quality function deployment (QFD), etc. In this study the need is directly specified by the customer and is clarified by the designer in next step.

3.2. Preparation of a Requirements List (2)

After specifying the need, a requirements list should be prepared in order to clarify the task (or the need). All requirements (design criteria) and constraints for reworking a PCBA having advanced SMCs should be gathered within this list. The requirements and constraints are directly extracted from existing rework systems such as manual, semi-automated or fully automated rework systems. The requirements and constraints in the requirements list should be classified as either wish or demand. The requirements and constraints that are classified as a wish should be accomplished by the rework system. The requirements or constraints that are classified as a demand must be certainly accomplished by the rework system. The other steps in the design methodology are mostly based on this document.

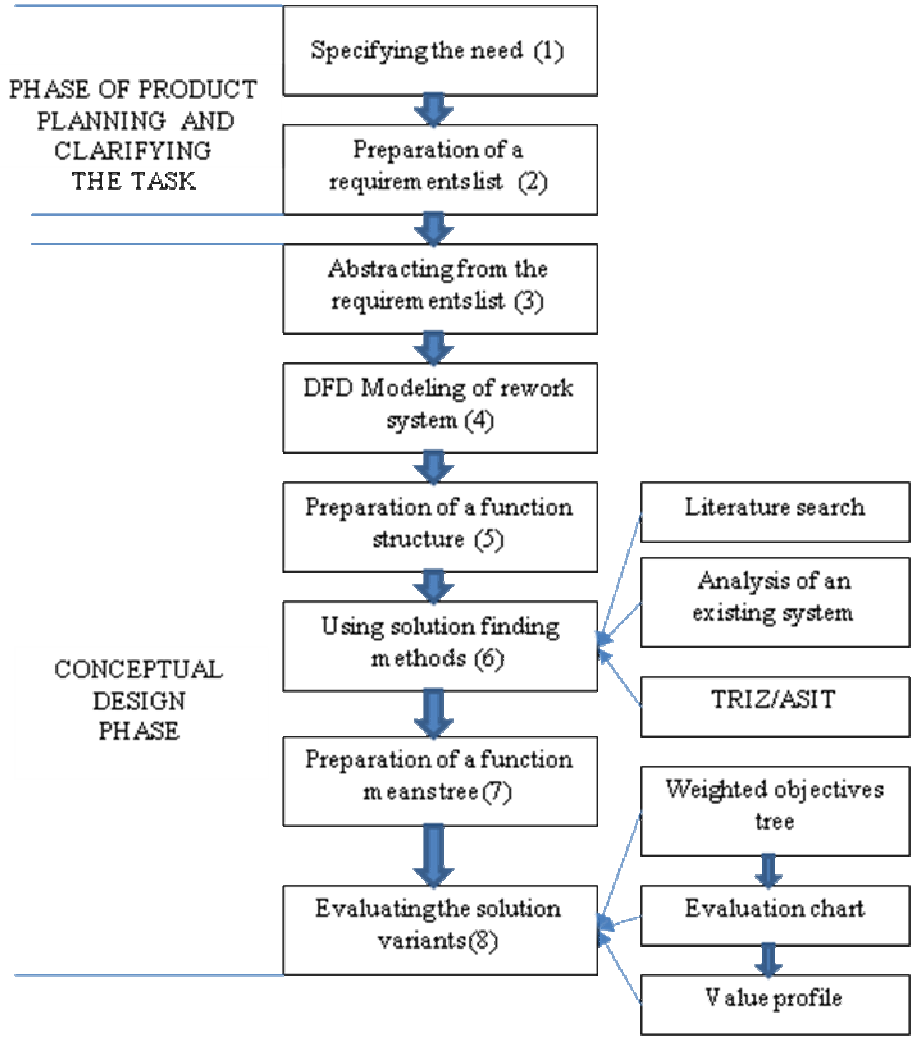


Figure 3.1. Developed design methodology for a hardware of manufacturing cells.

3.3. Abstracting from the Requirements List (3)

With this step, the task clarified in the requirements list is defined in general terms. Abstraction leads us to directly the crux of the task. It will be used in preparation of a function structure.

3.4. DFD Modeling OF FMS (4)

With this step, a flexible rework system is modeled by the help of FMS modeling techniques. So that FMS system building blocks, which in turn will increase the flexibility of the rework system, around rework steps given in figure 2.2 will be determined. Then, this model will be used in preparation of a function structure in later step.

3.5. Preparation of a Function Structure (5)

The requirements in the requirements list determine the function. Therefore, a function structure based on the requirements list is prepared in order to demonstrate the task or subtasks that the system must fulfill and relationship between inputs and outputs of the rework system.

As explained in chapter 2, a function structure basically consists of overall function, sub-functions, inputs and outputs. Overall function will be formulated by the use of the abstraction. Inputs and outputs will be added to the overall function. Then, overall function with inputs and outputs will be broken down into sub-functions which will be determined from the requirements in the requirements list. Finally, by introducing the FMS building blocks in FMS model into this structure, a function structure will be prepared. Every function in the function structure must be fulfilled by the rework system.

3.6. Using Solution Finding Methods (6)

Now, one solution or solutions for every function in the function structure should be found using solution finding methods such as TRIZ, ASIT, design catalogues, classification scheme, etc. These solutions must fulfill the functions in the function structure completely. This step is the vital part of the design methodology (figure 3.1).

3.7. Preparation of a Function Means Tree (7)

After finding solution or solutions for the related functions by the use of solution finding methods, solution/solutions together with related functions should be demonstrated in a function means tree. Then, during evaluation the solutions found by the use of solution findings method for the related functions, the function means tree can be referred, when it is necessary.

3.8. Preparation of Weighted Objectives Tree (8)

After preparation of the function means tree, the evaluation procedure begins. The evaluation procedure should be applied for every function which has more than one solution in the function means tree. So that the optimum solution for the related function that has more than one solution can be determined by the use of evaluation procedure.

As explained in chapter 2, the evaluation procedure that consists of four tools should be followed. One of these tools is weighted objectives tree. An objectives tree for a function in the function means tree should be prepared by the help of the requirements (design criteria) in the requirements list and specific properties of the tools that have been found earlier for this function. Then, every objective in the objectives tree assigns a value which demonstrates relative importance of the design criteria (or requirement) by designer. Assigning the value for every objectives results in the weighted objectives tree for this function. The weighted objectives tree will be prepared in chapter 4, when it is needed.

3.9. Preparation of Evaluation Chart (9)

Evaluation chart is one of the tools that build the evaluation procedure. After preparation of the weighted objectives tree for a function in the function means tree, the objectives, weighting values for these objectives and solution variants that are found using solution finding methods are entered into an evaluation chart. By the use of use value analysis, the objectives in the weighted objectives tree are given another number that describes how successfully the solution variant accomplishes the related objective. This numbers are also entered into the chart. Multiplication of the weighting value and this number for every objective and then summation of the results gives the designer the overall weighted value. The solution variant which has bigger overall weighted value is the optimum solution for the designer. If they have equal overall weighted value, then next step will follow this step.

3.10. Preparation of Value-Profile (10)

If the solution variants have equal overall weighted values, a value profile should be prepared in order to determine the optimum solution for the related function. By the use of value profile, the designer can detect weak points of the solution variant. So that this solution variant will be eliminated and the other solution will be optimum solution.

Now, it is time to apply this design methodology in order to design a flexible fully automated PCBA rework system.

4. RESULTS AND DISCUSSIONS

This study intends to develop a systematic design technique for a design of a flexible PCBA rework cell that is able to rework PCBAs of various sizes and PCB densities. In order to get highly flexible rework system main components of the flexible system must be highly flexible. Since the flexibility increases through a computer control, selected techniques or components must have computer control feature. Technique selection which leads to determination of components takes place during design process. The systematic design technique, developed in this study, will be a tool for the design of flexible PCBA rework cell, and it, also, will be quite for similar FMS designs such as flexible material handling, part tool storage, etc.

As explained earlier, the design process is broken down into four phases that are product planning and clarifying the task, conceptual design, embodiment design and detail design. In this section the methods and tools used in product planning and clarifying the task, and conceptual design phases will be used to propose a flexible PCBA rework system by following the design methodology in figure 3.1:

4.1. Specifying the Need

The design methodology begins with ‘’specifying the need’’. Therefore, the need should be specified firstly as followings:

The PCBA with defective component or components are not scrapped off easily because of the fact that PCBs include heavy metals which are hazardous waste for environment and especially they are of high value and have a complex structure. When the PCBA populated with small miniaturized components the requirement further increases. Hence, there is an essential requirement of PCBAs which are populated with new generation electronic components.

4.2. Preparation of a Requirements List

After specifying the need, a requirements list should be prepared in order to clarify the task based on the need, as in table 4.1.

Table 4.1. The requirements list for an electronic flexible manufacturing and rework system

User		Requirements list for an electronic flexible manufacturing and rework system	
Changes	D W	Requirements	
		• Circuit Boards (PCBs)	
		Geometry	
	D	Various sizes and dimensions	
		Material	
	D	Epoxy-glass sheet	
	D	PCBs glass transition temperature range: 125 ^{0}C – 180 ^{0}C	
		• Solder Alloy	
		Material	
	D	Solder alloys: Sn/Pb solder alloy, Sn/Ag/Cu solder alloy and Sn/Ag solder alloy	
	D	Thermal profile of Sn/Pb solder alloy: Melting temperature: 183 ^{0}C	
	D	Preheating stage:	
	D	Preheat temperature range for all solder types and PCBAs: 100 ^{0}C – 150 ^{0}C	
Date of change	D	Heat application during preheating: 75% of total heat from bottom side of PCBA and 25% of total heat from top side of PCBA Soaking stage:	
	D	Ramp rate range at the soaking stage: 0.3-0.8 ^{0}C/s for 40-100 s	
	D	Maximum temperature at the soaking stage: 180 ^{0}C Reflow stage:	
	D	Reflow atmosphere: nitrogen	
	D	Reflow peak temperature: 220 ^{0}C	
	D	Required dwell time range for Sn/Pb solder alloy at liquidus during reflowing and after SMC placement: = 40-60 seconds Cooling stage:	
	D	Cooling rate of Sn/Pb solder joint after reflow: < 6 ^{0}C/s Thermal Profiles of Sn/Ag/Cu and Sn/Ag solder alloys:	
	D	Melting temperature: 217 ^{0}C Preheating stage: same as Sn/Pb solder alloy (see Sn/Pb solder alloy)	
	D	Soaking stage: Ramp rate range at the soaking stage: 1-2 ^{0}C/s	
	D	Maximum temperature at the soaking stage: 215 ^{0}C Reflow stage:	
	D	Reflow atmosphere: nitrogen	
	D	Reflow peak temperature range: 235 ^{0}C- 250 ^{0}C	
	D	Required dwell time range for Sn/Ag/Cu and Sn/Ag solder alloys at liquidus during reflowing after SMC placement: = 60-90 seconds Cooling stage:	
	D	Cooling rate range of Sn/Ag/Cu and Sn/Ag solder joints after reflow: 2 - 4 ^{0}C/s	

		• Surface Mount Components (SMCs)	
		Geometry	
		Ball grid arrays (BGAs):	
	D	Body size: 7*7 to 50*50 mm	
	D	Pitch size: 0.5 - 1.5 mm	
	D	Solder ball diameter: 0.30 – 0.75 mm	
	D	Pad diameter: 0.25 - 0.55	
		Chip scale packages (CSPs):	
	D	Body size: 4*4 to 22*22 mm	
	D	Pitch size: 0.4 to 1.0 mm	
	D	Solder ball diameter: 0.25 – 0.50 mm	
	D	Pad diameter: 0.2 - 0.4	
		Flip chips (FCs):	
	D	Body size: 3.81*3.81 to 12.7*12.7 mm	
	D	Pitch size: 0.1 – 0.75 mm	
	D	Solder ball diameter: 0.08 – 0.2 mm	
	D	Pad diameter: 0.06 – 0.15	
		Material	
	D	SMCs: BGAs, CSPs and FCs	
	D	Maximum allowable temperatures range for SMCs: 240 ^{0}C - 260 ^{0}C	
	D	The preheat ramp rate: 2 ^{0}C/s for plastic SMCs and 1 ^{0}C/s for ceramic SMCs	
	D	Maksimum rise of the temperature of SMC body and interconnects during reflow: < 3 ^{0}C/s for Sn/Pb solder alloy and =< 3.5 ^{0}C/s for Sn/Ag/Cu and Sn/Ag solder alloys	
		• Underfiller	
		Material	
	W	Reworkable types	
	D	Board temperature range for cleaning off the underfiller during site scavenging: 120 ^{0}C – 150 ^{0}C	
	D	Bottom side heating range of PCB for cleaning off the underfiller during site scavenging: 85 ^{0}C - 100 ^{0}C	
	D	Temperature of PCBA during dispensing underfiller: 90 ^{0}C	
	D	Board temperature range and dwell time range at this temperature to easily remove underfilled SMCs: 210 ^{0}C – 220 ^{0}C, and 30-90 seconds for FCs and 60-90 seconds for CSPs/BGAs	
	D	Underfiller curing temperature range after component placement: 150 ^{0}C – 160 ^{0}C	
		System to Be Developed	
		Geometry	
	W	Minimum space requirement	
	D	Consider connection constraints to the system	
		Kinematics	
	D	Precise positioning of printed circuit board assemblies (PCBAs) with the	

		help of improved direct inspection techniques	
	D	Linear offset for BGAs: =< 0.0167 mm	
	D	Linear offset for CSPs: =< 0.013 mm	
	D	Linear offset for FCs: =< 0.004 mm	
	D	Rotational offset for BGAs: 0.0138^{0}	
	D	Rotational offset for CSPs: 0.0255^{0}	
	D	Rotational offset for FCs: 0.0130^{0}	
	D	SMC holding tool which is capable of twisting SMC to remove underfilled SMCs during component removal	
	W	Minimum handling time	
		<u>Force</u>	
	D	Minimum holding force for component removal	
	D	SMC placement force range and minimum required dwell time to place the component on the underfiller at no flow underfilling technique : 150-350 grams for 0.02 seconds	
	D	Weight of PCBA: =< 2.5 kg	
		<u>Energy</u>	
	D	Electrical and/or pneumatic (6-8 bar)	
		<u>Material</u>	
	D	Free from dust	
	D	Moisture free PCBAs	
	D	Prebaking temperature to achieve moisture free PCBAs: 125 ^{0}C for at least 12 hours	
	D	Consideration of thermal specifications of solder, underfiller, PCBs and SMCs during preheat, soak, reflow and cool down stages (see PCBs, SMCs, solder alloys and underfiller)	
	D	Solvent after scavenging and brushing to clean site: isopropyl alcohol	
		<u>Rework Steps</u>	
		Reflow:	
	D	Consideration of thermal properties of solder alloys during reflow (see solder alloys)	
	D	Thermal energy during reflow heating: directed through the component body to the solder joints without heating adjacent components	
	D	Adjacent component temperature during reflow: < 150 ^{0}C	
	D	Thermal gradient across PCBA during reflow < 25 ^{0}C	
	D	Thermal gradient between solder balls during reflow: < 5 ^{0}C	
		Site scavenging:	
	D	Appropriate flux application prior to site cleaning	
	D	Consideration of thermal properties of underfiller during site scavenging (see underfiller)	
	D	Mechanical brushing application to remove the remaining underfill after site scavenging	
	D	Rotary tool speed during mechanical brushing application: 30000 rpm	
	D	Mechanical brushing application temperature: room temperature	
	D	Uniform and non-damaged reworked sites after site cleaning	
		Solder/flux and underfiller dispensing:	
	D	Consideration of thermal properties of underfiller during dispensing (see underfiller)	
	D	Suitable solder/flux and underfiller application technique which is applicable to fine pitch components and high value PCBAs with high level of reliability	

	D	Less prone to separation and plugging during solder and underfill dispensing	
	D	Highly repeatable solder and underfill dispensing	
	D	Low dispense cycle time	
	D	Void free underfilling application	
		Safety:	
	D	Operational safety	
		Operation:	
	D	Destination: rework line	
		High level of flexibility:	
	D	Capable of rework of underfilled or non-underfilled SMCs	
	D	Ability to rework all SMCs and PCBAs of different properties and sizes	
	D	Consideration of FMS features such as AGV, tool parking, etc	
		Maintenance:	
	W	Maintenance interval > 10^4 reworks of PCBs	

Literature survey for manual, semi-automated and fully automated PCBA rework processes has indicated that the rework process basically consists of the steps shown in fig 2.2 in chapter 2. All necessary data about these rework steps and specifications of the materials that form the PCBA was also given in chapter 2. Demands and wishes in the requirements list have been specified by the help of this available data. Every demand or wish is a design specification and should/must be fulfilled in later steps.

With preparation of the requirements list the task which must be accomplished is clarified in more detail. Now, we can go on as followings.

4.3. Abstracting from the Requirements List

By the way of abstraction, the task is defined in more general terms as followings:

Rework PCBAs with advanced type SMCs, which have different board sizes and wiring densities, using different types of solder alloy and different SMC placement method.

The abstraction above is completely based on the requirements list and it will be used in later steps.

4.4. DFD Modeling of the FMS System

One of the design criteria in the requirements list is that system must be highly flexible. In chapter 2, it was explained that which building blocks or features a FMS system should have been. It can be very useful to prepare a data flow diagram (as in figure 4.1 and 4.2) based on these building blocks or features in order to model the system, before considering later steps. Then, a function structure based on this diagram and the rework steps in figure 2.2 can be prepared in following step.

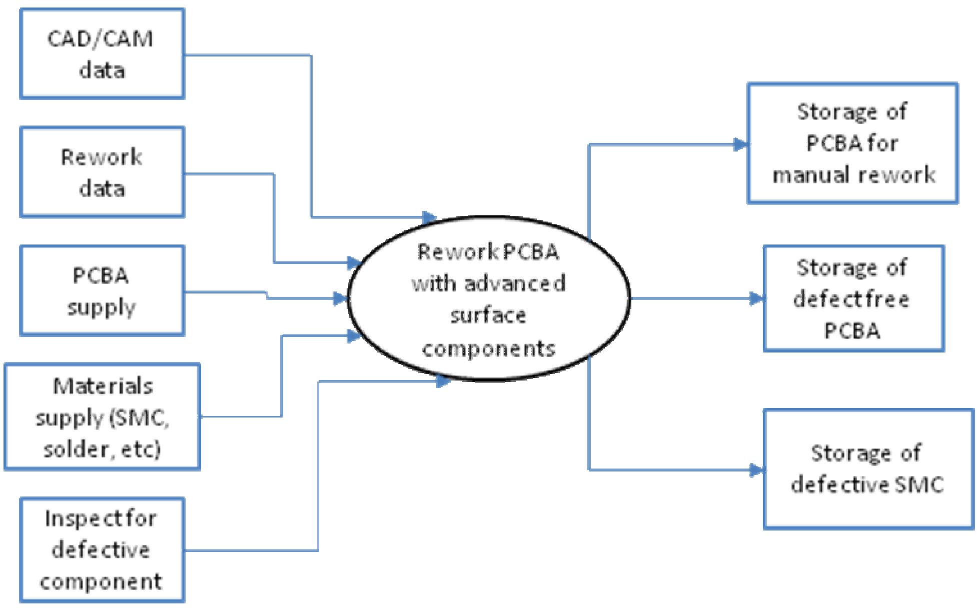


Figure 4.1. Top level data flow diagram (DFD)

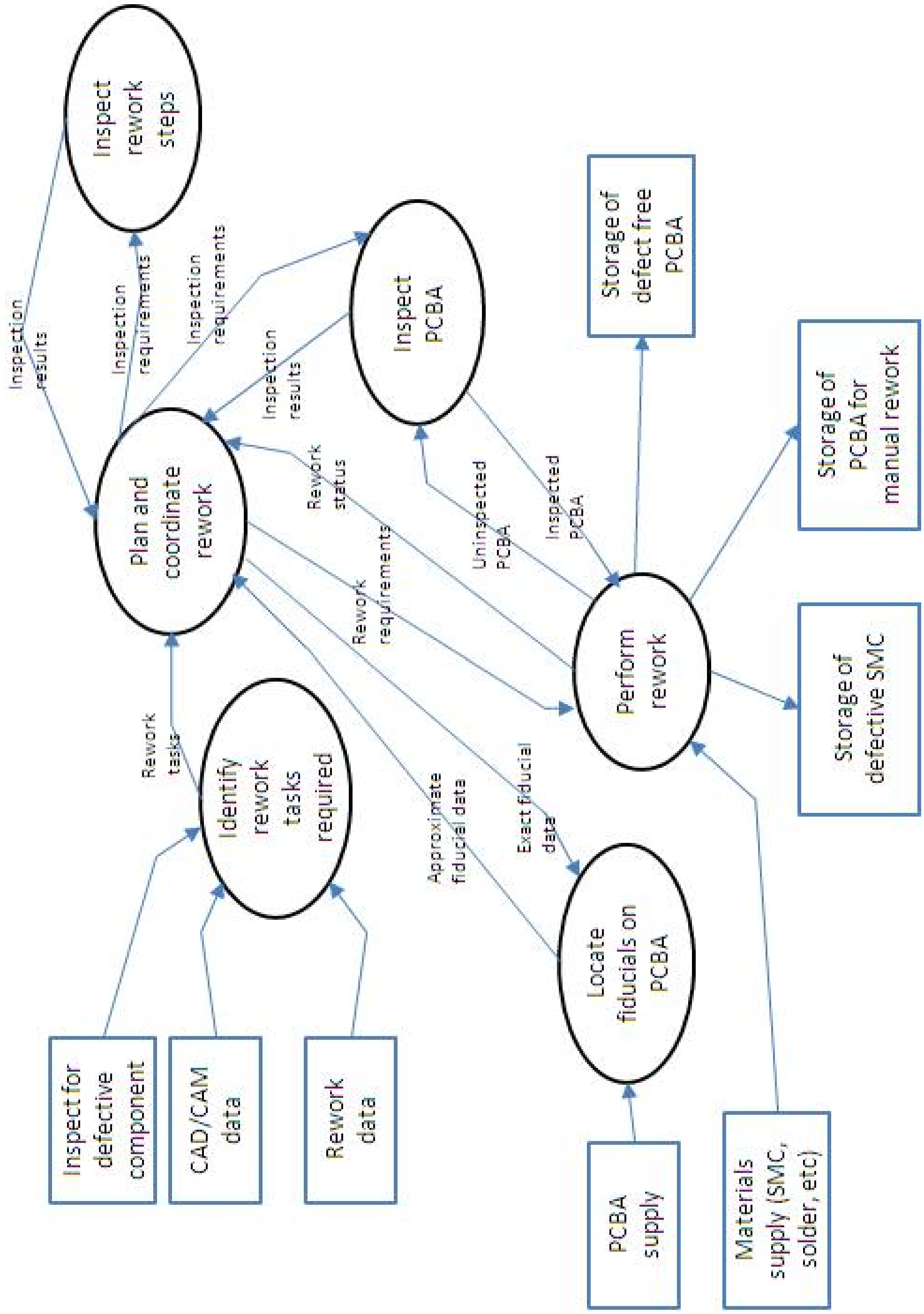


Figure 4.2. First level data flow diagram for a fully automated PCBA reflow system.

In figure 4.1 and 4.2 rework processes such as inspection, rework, etc were represented by ellipses, data sources/sinks such as rework data, PCBA supply, etc. by boxes, and data flow by two parallel lines.

4.5. Preparation of a Function Structure

Function structure is prepared by the use of the abstraction, the rework steps in figure 2.2 and DFD in figure 4.2. Overall function, figure 4.3., is generated simply by taking the term ‘‘*rework PCBA*’’ from the abstraction and introducing into it inputs and outputs such as energy, defective PCBA, etc. As can be seen in figure 4.3, defective PCBA and new SMCs as inputs were considered as material flow and so they were indicated by thick arrows. Also, CAD/CAM data and data concerning the rework steps as inputs were shown by intermittent lines. Outputs such as defective SMCs, repaired PCBA and manual rework were shown by thick arrows in order for indicating material flow. Again, energy flow as an input was shown by a line which is neither thick nor intermittent.

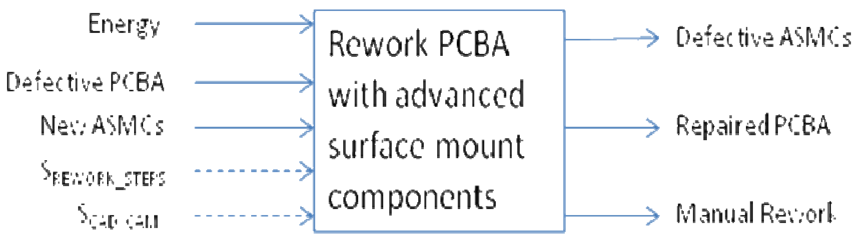


Figure 4.3. Overall function

Now, the overall function can be broken down into sub-functions of lower complexity. These sub-functions together with the inputs and the outputs then constitute function structure as in figure 4.4. In figure 4.4., the rectangles which are constructed from continuous lines demonstrate main sub-functions and the rectangles which are constructed from intermittent lines demonstrate auxiliary sub-functions.

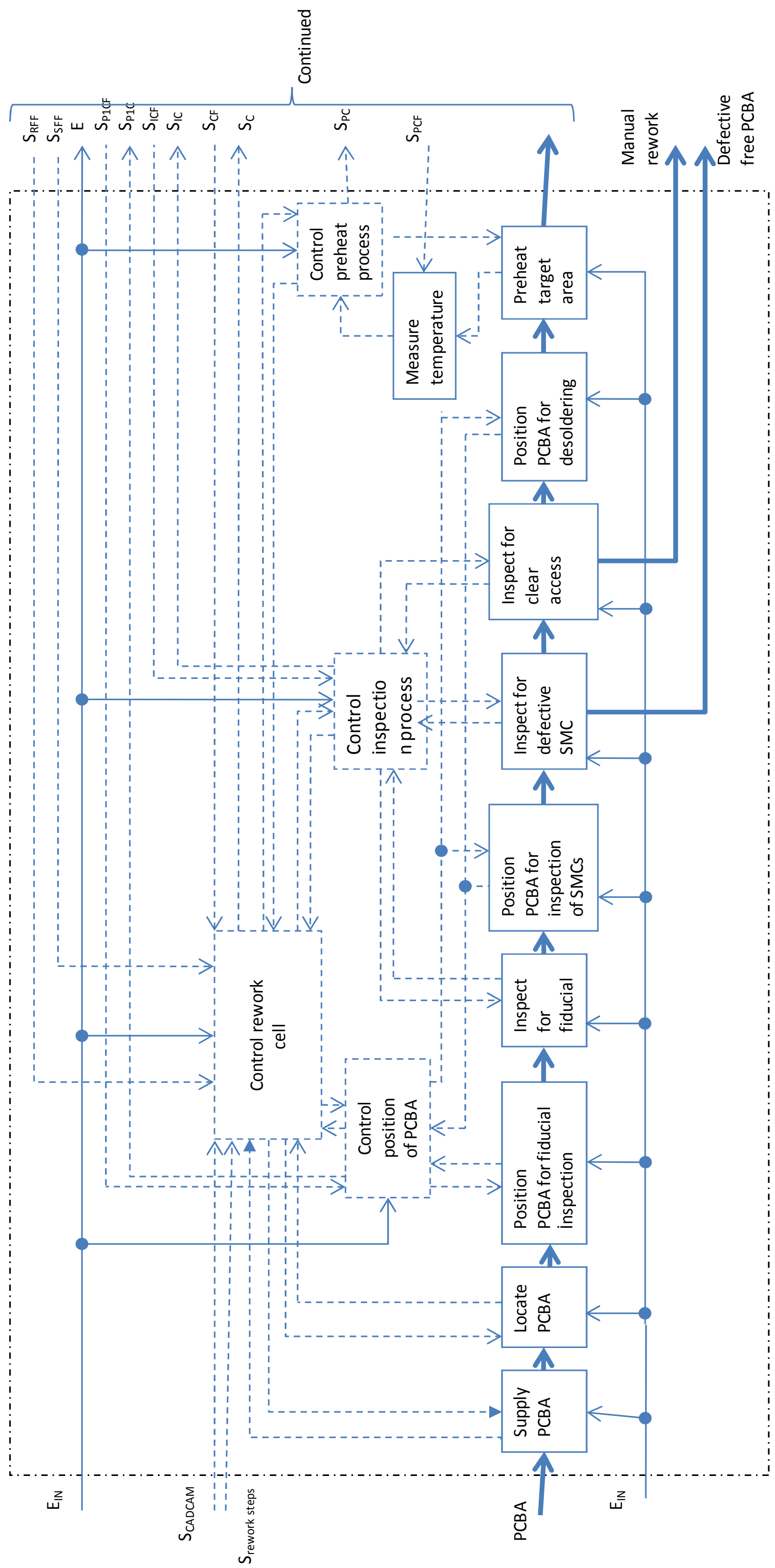


Figure 4.4.a. Completed function structure for a rework

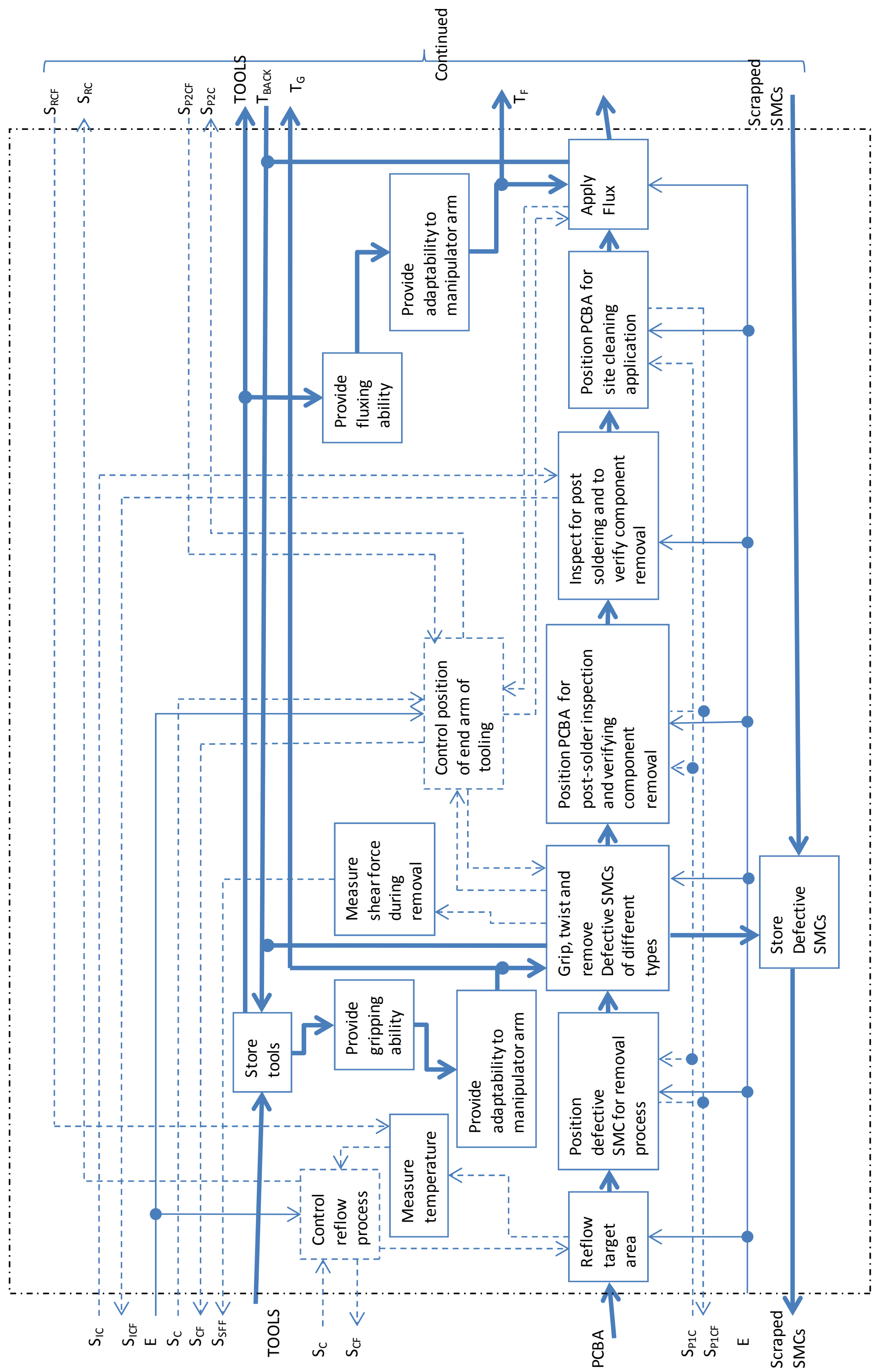


Figure 4.4.b. Continued

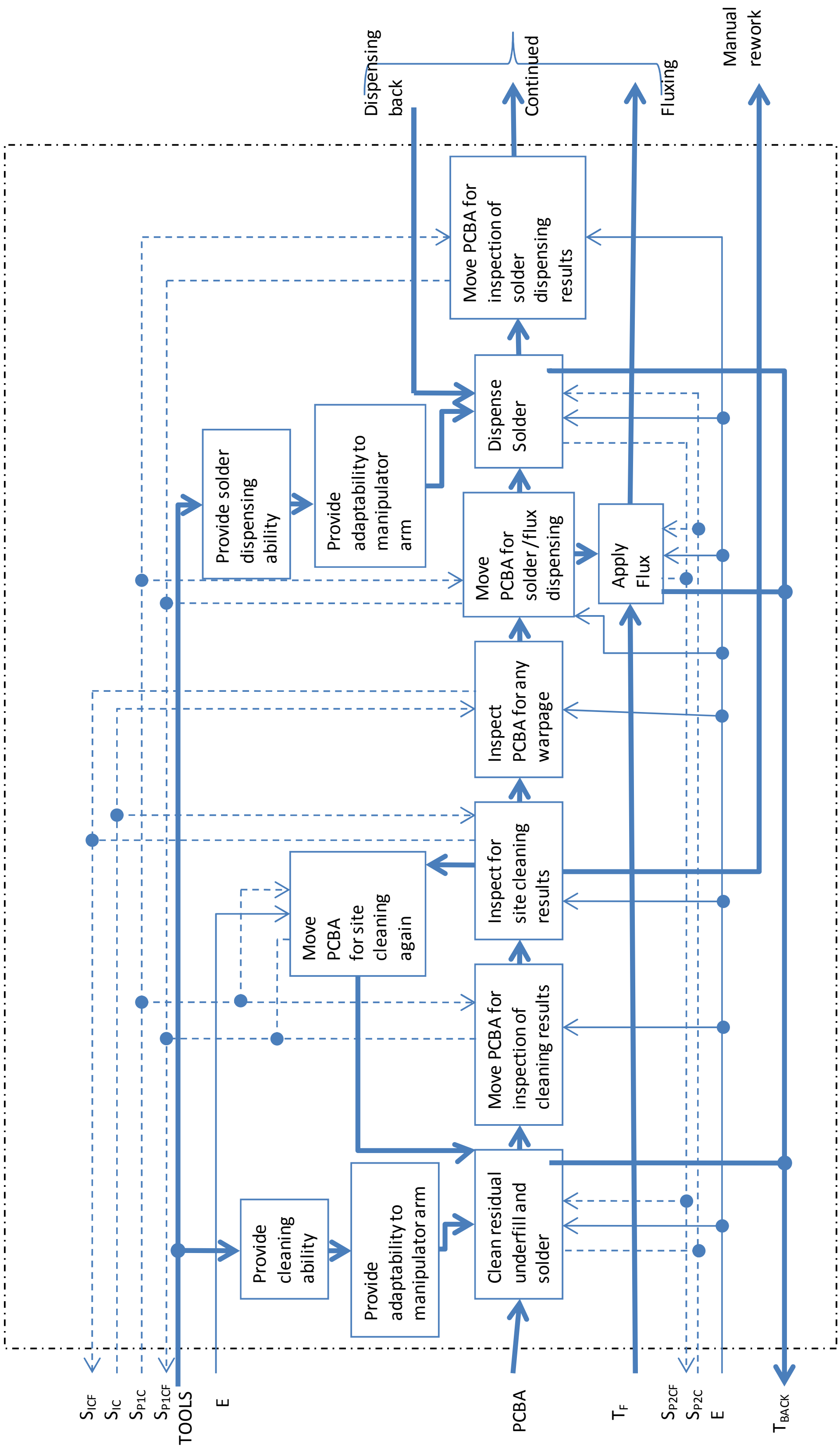


Figure 4.4.c. Continued

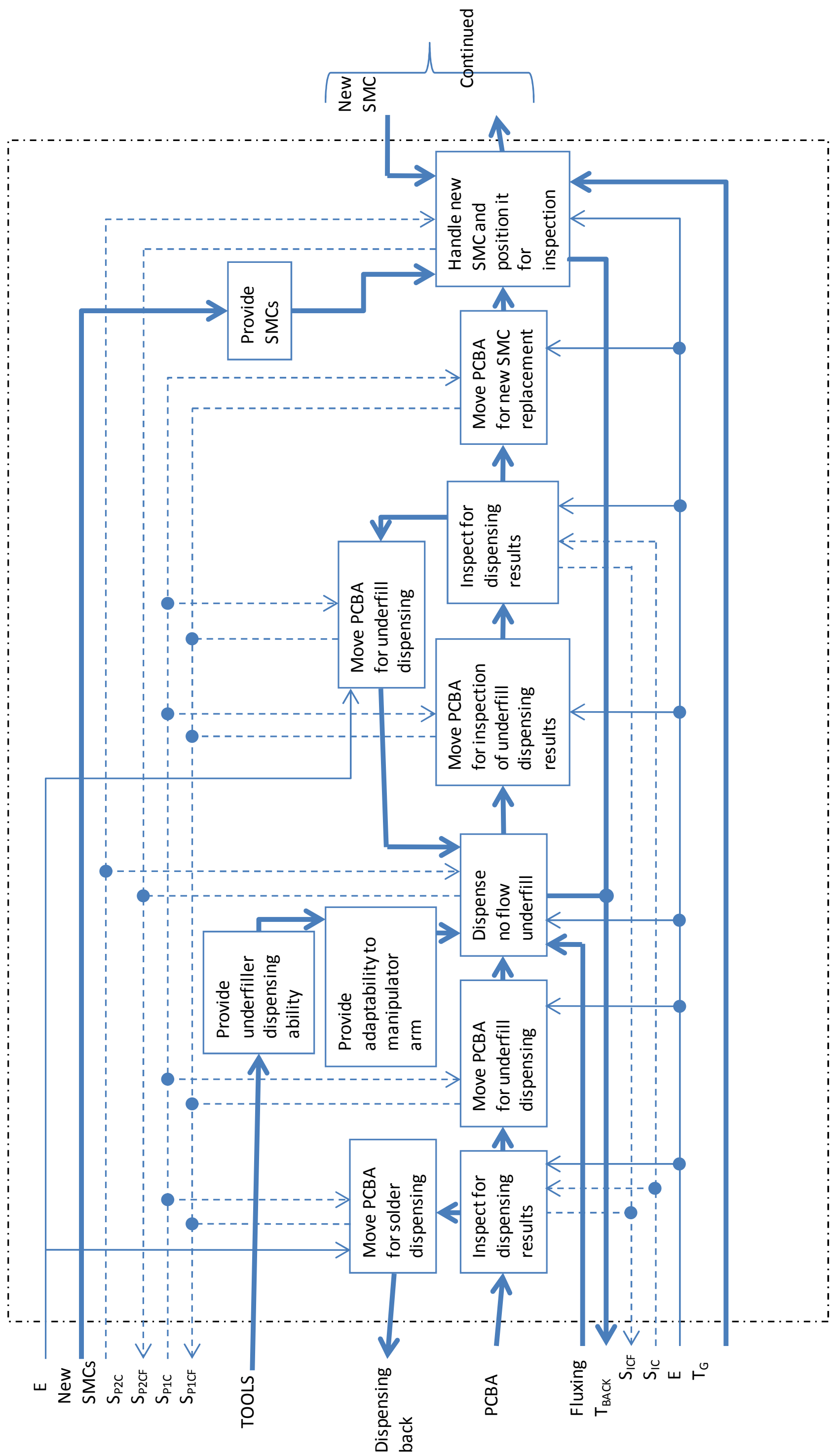


Figure 4.4.d. Continued

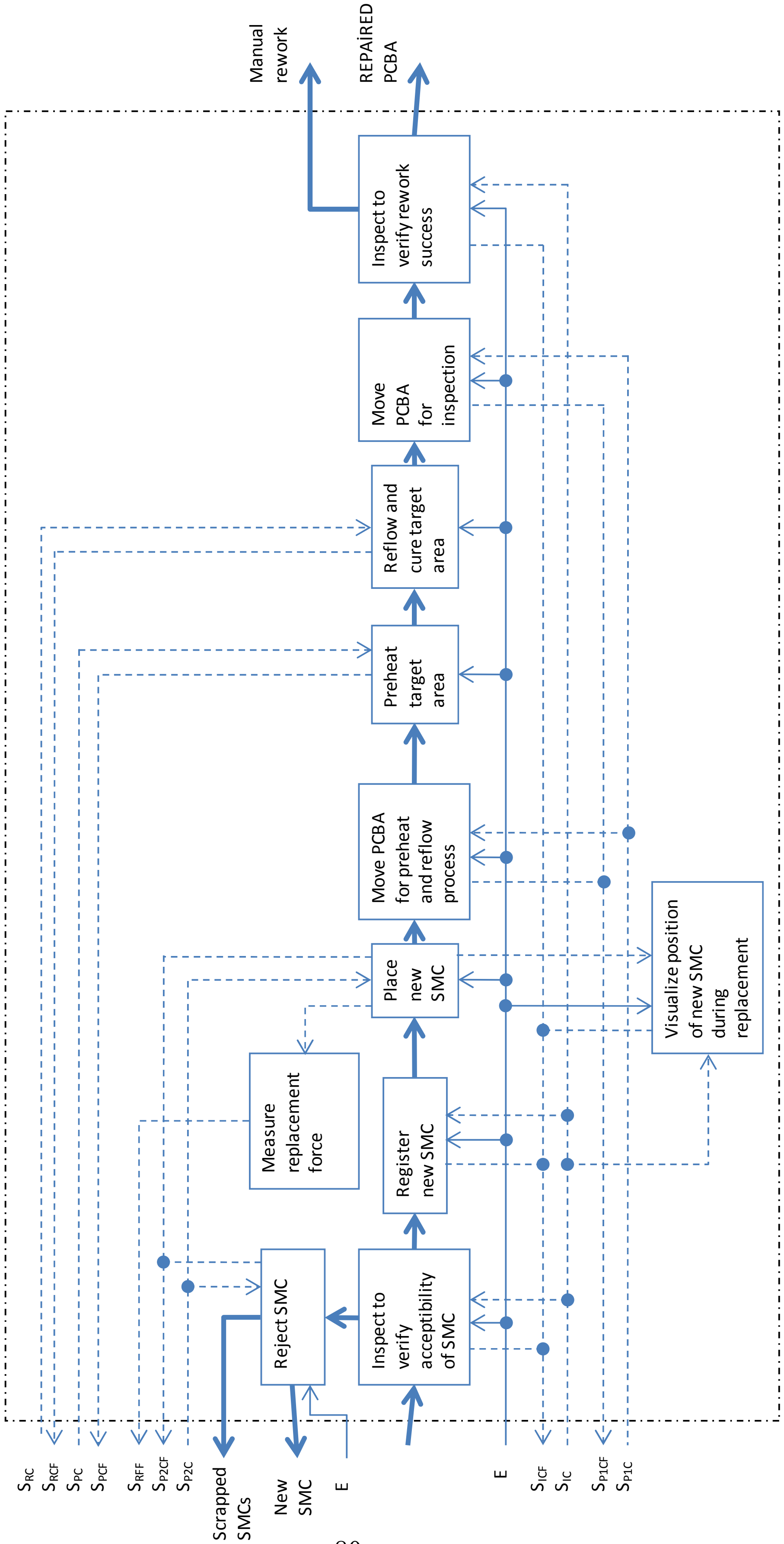


Figure 4.4.e. Continued

As can be seen in the function structure in figure 4.4, the function structure involves not only main rework functions that must be overcome, but also the functions such as “Control rework cell”, “Supply PCBA”, etc. by fulfillment of which results in FMS system that was explained in detail in chapter 3. Therefore, the function tree in figure 4.4 gives the designer possibility to analyze and determine the behavior of the system at early stage.

The sub-functions in figure 4.4 were determined by the help of the requirements list and the rework steps in figure 2.2. Inputs and outputs in the function structure and their meanings are explained in table 4.2.

Now, it is beneficial to explain behavior of the system in the figure 4.4.a. Rework process begins with the function “Supply PCBA’’. This function is controlled by the auxiliary function ‘’ Control Rework Cell’’. The auxiliary function ‘’ Control Rework Cell’’ controls all steps of PCBA rework cell. It sends control signals to the functions to control them and takes feedback signals from them to be able to follow the functions which are carried out. In addition to control and feedback signals, energy is supplied to the functions where it is needed. The rework process goes on with the function ‘’Position PCBA for Fiducial Inspection’’. Position of PCBA is controlled by the auxiliary function ‘’Control Position of PCBA’’. The function ‘’Control Rework Cell’’ controls positioning process via this function. Then the function ‘’Inspect for Fiducials’’ comes. This function is controlled by the auxiliary function ‘’Control Inspection Process’’. The function ‘’Control Rework Cell’’ controls inspection process via this function. After the function ‘’Position PCBA for Inspection of SMC’’ in figure 4.4.a., the functions ‘’Inspect for Defective SMC’’ and ‘’Inspect for Clear Access’’ comes. As a results of the function ‘’Inspect for Defective SMC’’, either the rework process continues or the PCBA is rejected from the system as defect free PCBA. Again as a result of the function ‘’Inspect for Clear Access’’, either the rework process continues or the PCBA is rejected for manual rework. After the function ‘’Position PCBA for Desoldering’’ in figure 4.4.b., the function ‘’Preheat Target Area’, which is the last function in figure 4.4.b., comes. The auxiliary function ‘’Control Preheat Process’’ controls this function. It sends control signal and takes a feedback signal from this function via a function

''Measure Temperature''. Again, the function ''Control Rework Cell'' controls preheating process via the function ''Control Preheat Process''. Some functions such as ''Control Rework Cell'' are needed in the continuation of the function structure. Therefore control signals from these functions are sent to the related functions within the function structure in order to be used and feedback signals are fed back to these functions.

Table 4.2. Symbols in the function structure and their meaning.

E_{IN}	Energy flow
PCBA	Material (defective PCBA) flow
$S_{rework\ steps}$	Data flow concerning with rework steps
S_{CADCAM}	Data flow concerning with CAD/CAM data
S_{P1C}	PCBA positioning control signal
S_{P1CF}	PCBA positioning feedback signal
S_C	Cell control signal
S_{CF}	Cell feedback signal
S_{IC}	Inspection system control signal
S_{ICF}	Inspection system feedback signal
S_{PC}	Preheating system control signal
S_{PCF}	Preheating system feedback signal
S_{RFF}	Replacement force feedback signal
S_{SFF}	Shear force feedback signal
S_{P2C}	Positioning SMCs and toolings control signal
S_{P2CF}	Positioning SMCs and toolings feedback signal
TOOLs	Necessary toolings for rework
T_{BACK}	Tool that returns back after carrying out the task
T_G	SMC handling tool
T_F	Fluxing tool
Scraped SMCs	Defective SMCs
S_{RC}	Reflow system control signal
S_{RCF}	Reflow system feedback signal
New SMCs	Defective free SMC

As a consequence, the function structure established above fully proves extremely useful in determining the behavior of the system at a very early stage of its development. Then we go on with finding possible solutions for the functions in the function structure as below.

4.6. Using Solution Finding Methods

Now, possible solutions for every function can be found by the help of solution finding methods. As outlined in chapter 2, there are many solution finding methods. "Literature search" and "analysis of existing technical systems" from these methods can reveal some solutions or solution for every function. There are three fully automated rework systems developed to analyze. These systems are explained in detail in chapter 2. Analysis of these existing rework systems and literature search lead us solutions or solution for the functions in the function structure but one function. This function is ''Grip, twist and remove defective SMCs of different types''. Currently used methods in electronic industry are vacuum suction tool and gripper. However these methods don't fulfill the function completely. Of these, vacuum suction tool does not have ability to form twisting force which is necessary to remove underfilled SMCs. And the gripper is not so flexible to handle all SMCs of different types. Therefore any one of these drawbacks must be overcome by the use of solution finding methods, if possible. TRIZ and ASIT methods can be very useful to solve this problem.

In ASIT method, as outlined in chapter 2, there are five idea-provoking tools. These are unification, multiplication, division, breaking symmetry and object removal. Of these, multiplication which is ''Solve a problem by introducing a slightly modified copy of an existing object into the current system'' exactly leads us to a solution. As a result, in addition to the gripper (existing object), introducing a new gripper with different tip widths (slightly modified copy) into the system will fulfill the function completely.

We can also use TRIZ method to find solution for this function. As outlined in chapter 2, there are 40 principles in TRIZ to lead designer for creative thinking. Of these, partial or excessive actions (principle 16) which is '' If 100 percent of an object is hard to achieve using a given solution method then, by using 'slightly less' or 'slightly more' of the same method, the problem may be considerably easier to solve'' leads us to same solution above.

Specifications of the solutions that have been found by the use of solution findings methods were explained in detail in chapter 2. These solutions will be used in later steps to evaluate the optimum solution.

4.7. Preparation of Function/Means Tree

After finding the solutions for the functions by the use of TRIZ/ASIT, literature search and analysis of existing rework systems, now we can make use of the function/means tree to demonstrate these possible solutions for the related functions, as in figure 4.5. As can be seen on the figure 4.5, the circles demonstrate the functions which must be fulfilled by solutions and rectangles demonstrate the means which may possibly fulfill the related functions.

The function/means tree provides facility for the designer to see all possible solutions for related functions at a glance. Therefore the function/means tree including all possible solutions will be referred in evaluating optimum solutions for related functions in the following steps.

The function means tree in figure 4.5 will be used during evaluation process to glance at possible solutions for the related function. These possible solutions, then, will be evaluated to select he optimum solution in later section.

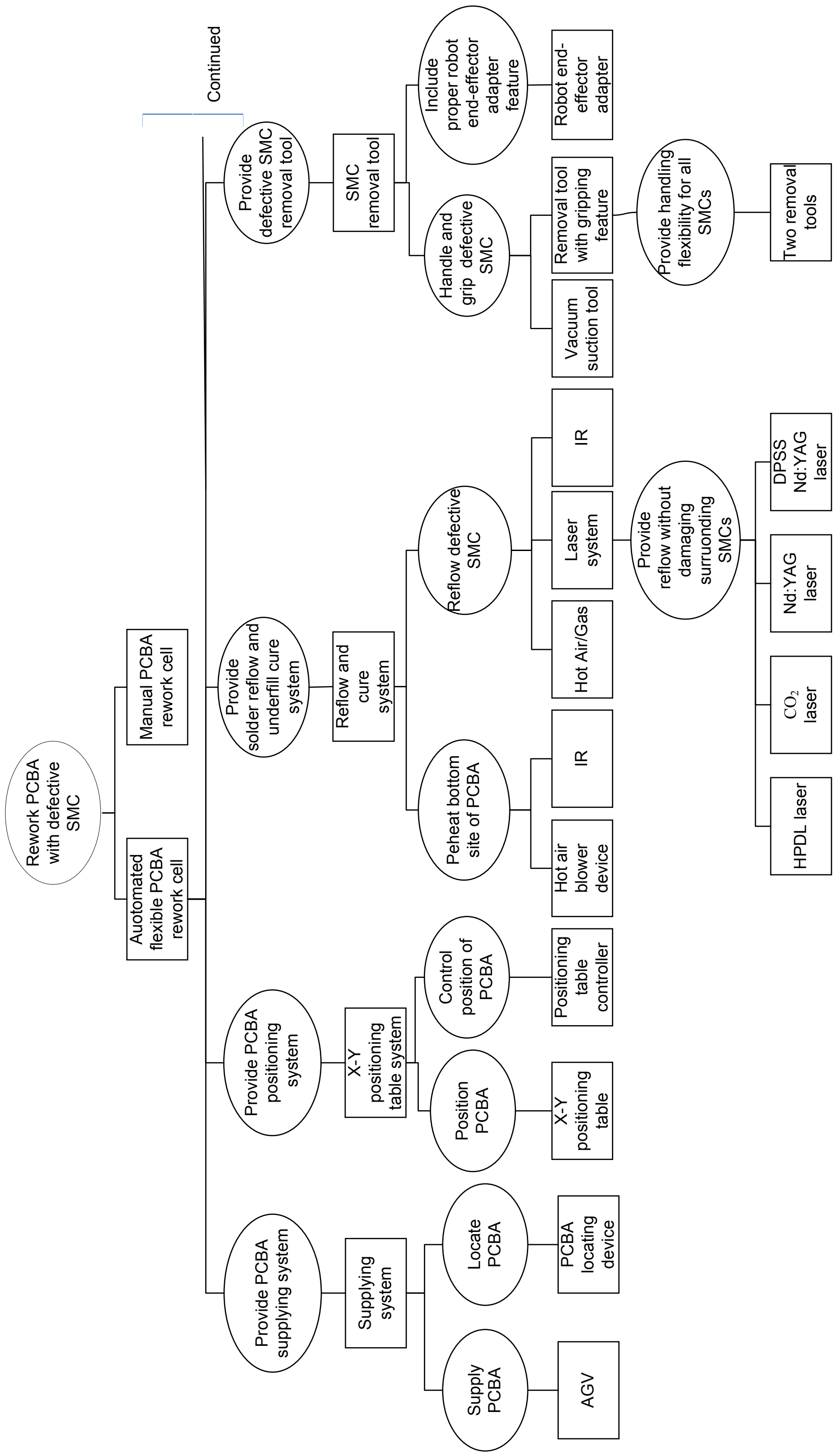


Figure 4.5. The function means tree for a flexible and fully automated PCBA rework system

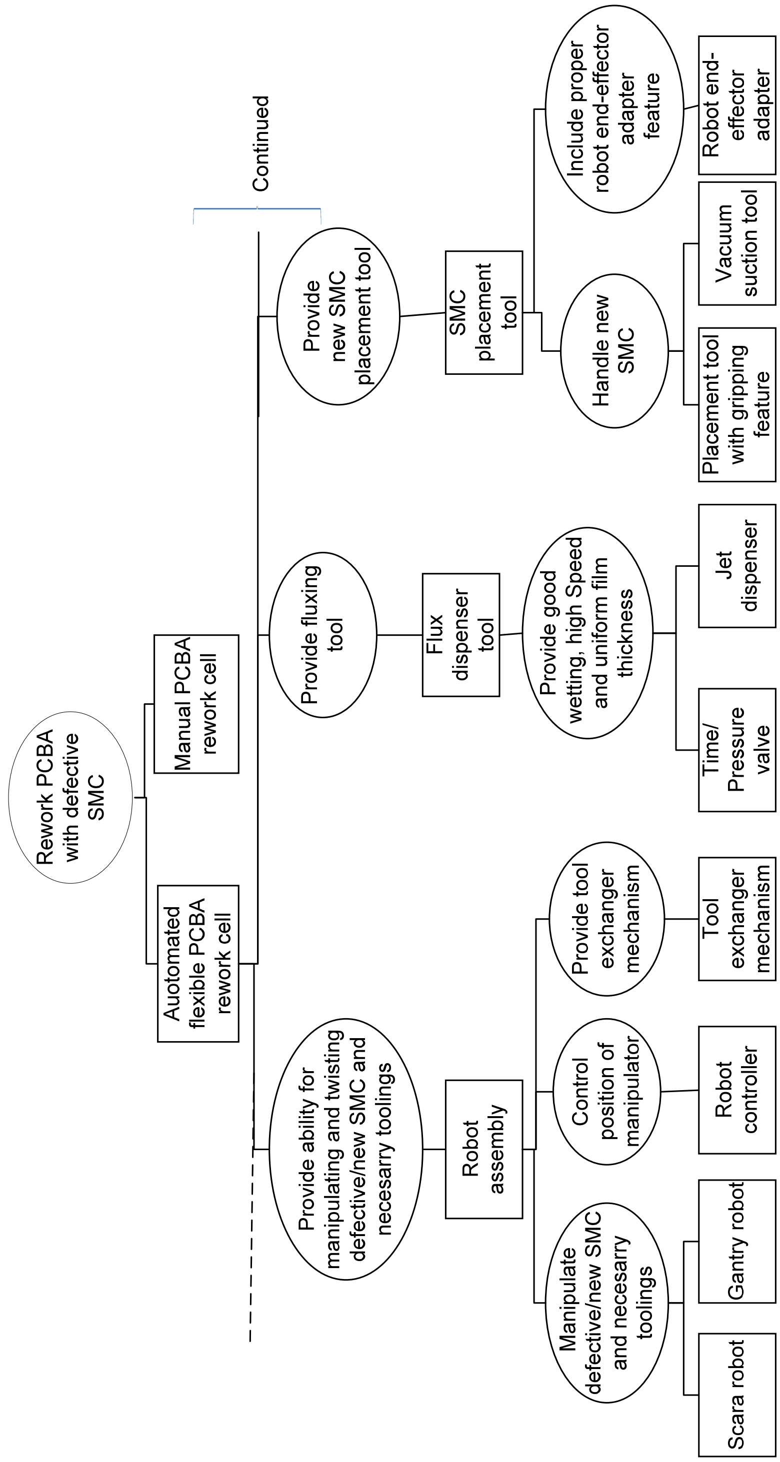


Figure 4.5. Continued.

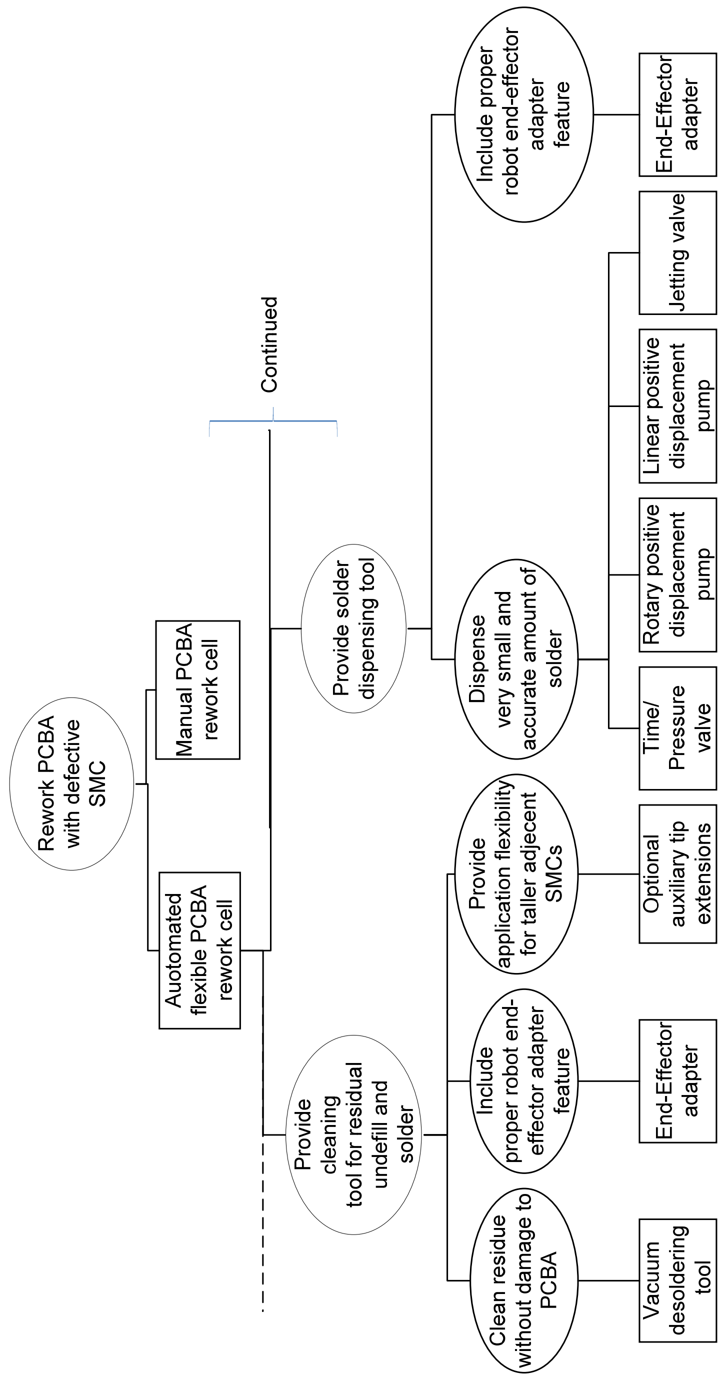


Figure 4.5. Continued.

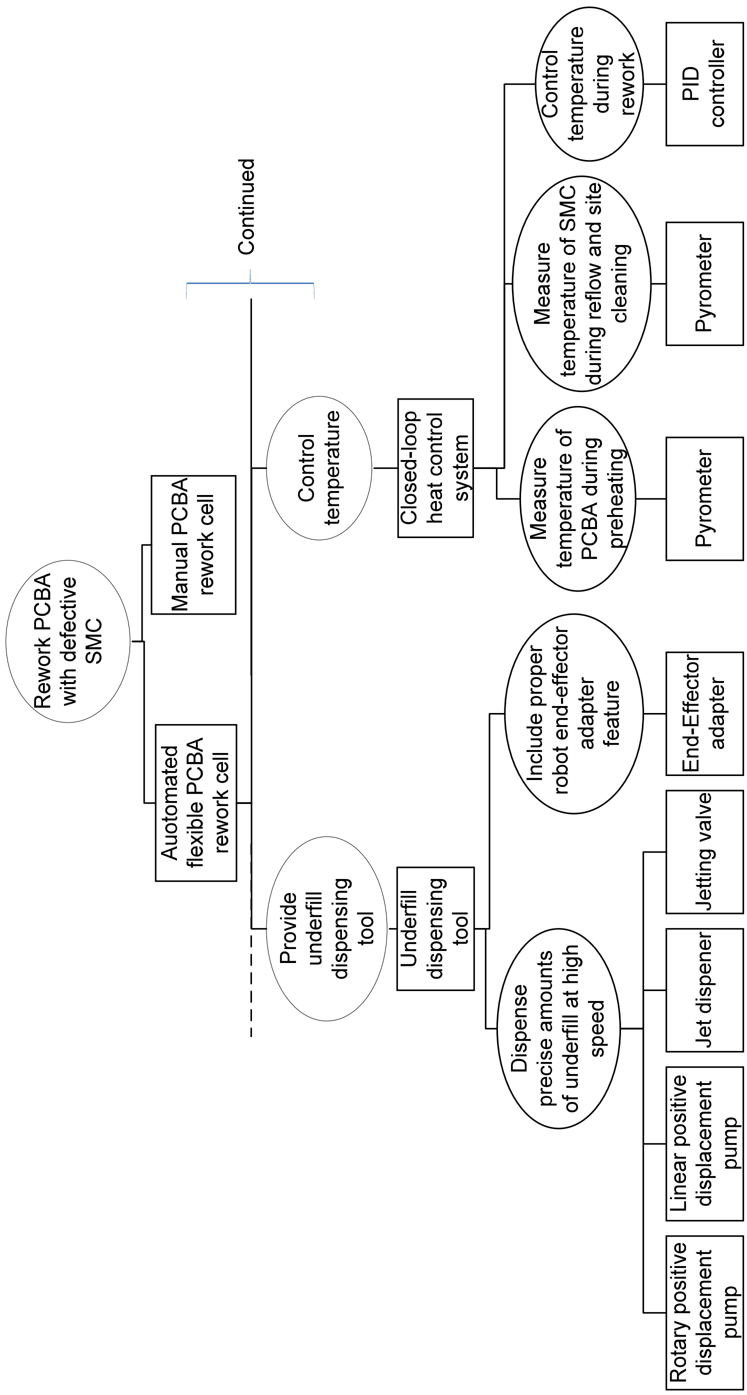


Figure 4.5. Continued.

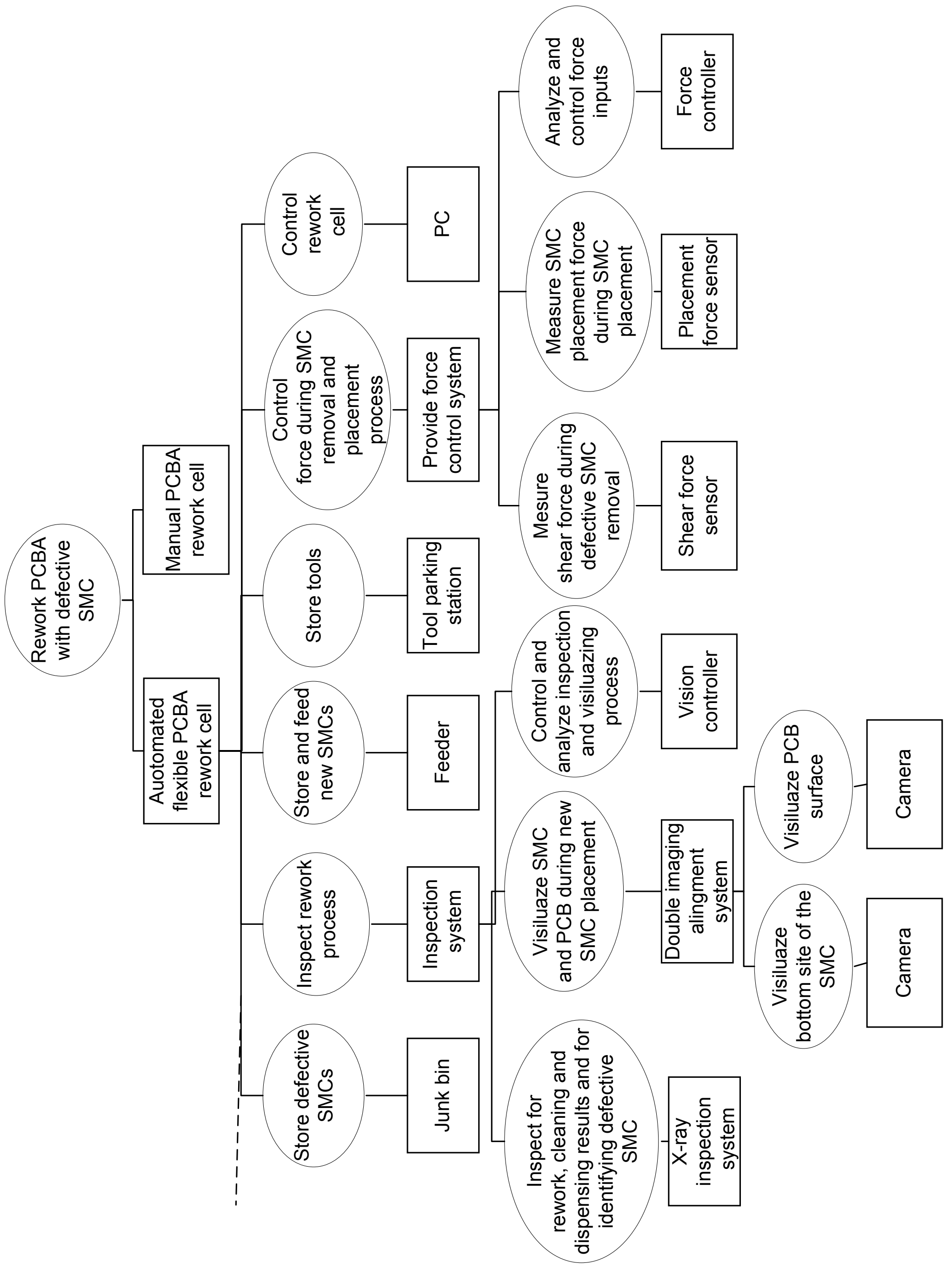


Figure 4.5. Continued.

4.8. Determining Optimum Solutions by the Use of the Evaluation Procedure

As can be seen in the function means tree, some functions have more than one solution. Therefore these solutions for related function must be evaluated in order to specify the optimum solution for this function. As explained in chapter 2, the use of weighted objectives tree, use-value analysis/guideline 2222, evaluation chart, and value profile respectively constitute an evaluation procedure. Following this procedure and using the function means tree, the optimum solutions for the related functions will be evaluated as below.

Determination of Reflow Method: Now, the function/means tree must be referred to see possible solutions for reflow process. Three candidates for reflow are available: hot air gas, non-focused IR and diode laser head source. As outlined in chapter 2, there are some evaluation methods available. Now, the evaluation procedure mentioned about above will be used to select reflow method. For this purpose a weighted objectives tree based on the requirements list must be structured as figure 4.6.

In the weighted objectives tree the individual objectives, which are determined from the requirements list, are arranged in hierarchical order. The sub-objectives are arranged vertically into level of decreasing complexity, and horizontally into objective areas such as technical, economic, etc. The values on the right hand side of every objective circle in the weighted objectives tree are given by designer according to the relative importance of the objectives. The weighting factors on the left hand side of every objective are determined by multiplication of the values on the left hand side of the objectives each other in hierarchical manner. For example the value 0.035 for the objective ''Good Temperature Ramp Rate Control'' was found by multiplication of 0.35, on the left side of the objective ''Good temperature ramp rate control'', 0.2, on the left side of the objective ''Good Temperature Control'', 0.5, on the left side of the objective ''Reliable and Flexible Reflow Operation'', and 1.0, on the left side of the objective ''Reliable and Flexible Reflow System''. The sum of these weighting factors must be 1.

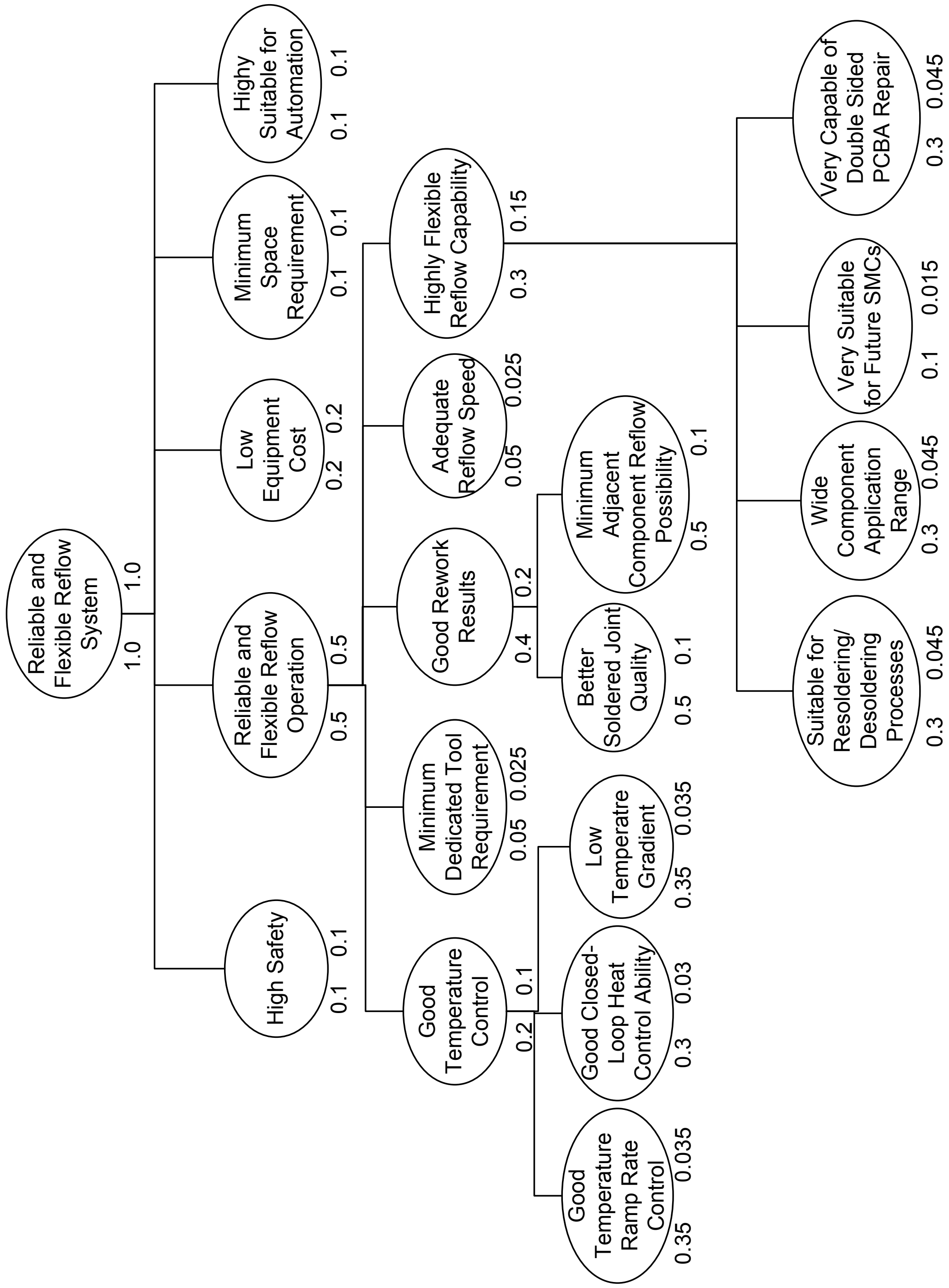


Figure 4.6. The weighted objectives tree for reflow

After establishing the weighted objectives tree as outlined above, evaluation chart can be prepared as in table 4.4. The objectives and weighting factors are entered into this chart. The objective parameters, which can be quantifiable or expressed by statements, are assigned to the objectives as in table 4.4. Then appropriate magnitudes for the objectives are entered into chart for every reflow method. These magnitudes are assigned a value taking into consideration the value scale in table 4.3.

The multiplication of the value assigned and the weighting factors results in weighted value for every objectives (evaluation criteria). The weighted values determined for every objective are entered into the evaluation chart for every reflow method. Finally, the overall weighted value for every variant is determined by summation of the weighted values.

Table 4.3. Points awarded in use-value analysis (Pahl and Beitz, 2005)

Value Scale	
Points	Meaning
0	absolutely useless solution
1	very inadequate solution
2	weak solution
3	tolerable solution
4	adequate solution
5	satisfactory solution
6	good solution with few drawbacks
7	good solution
8	very good solution
9	solution exceeding the requirement
10	ideal solution

Table 4.4. Evaluation chart for reflow tools.

Evaluation criteria			Parameters		Non-focused IR			Laser			Hot air gas		
No		Wt.		Unit	Magn.	V_{il}	W_{Vil}	Magn.	V_{il}	W_{Vil}	Magn.	V_{il}	W_{Vil}
1	High safety	0.1	Expected safety	-	average	4	0.4	average	4	0.4	average	4	0.4
2	Low equipment cost	0.2	Equipment cost	-	high	3	0.6	low	7	1.4	very high	3	0.6
3	Minimum dedicated tool	0.025	Dedicated tool	-	4	5	0.125	no	8	0.2	no	8	0.2
4	Adequate reflow speed	0.025	Reflow speed	-	fast	8	0.2	fast	8	0.2	fast	8	0.2
5	Good temperature ramp rate control	0.035	Temperature ramp rate control	-	Very good	8	0.28	Very good	8	0.28	good	7	0.245
6	High closed-loop heat control ability	0.03	Closed-loop controllability	-	possible	8	0.24	possible	8	0.24	weak	5	0.15
7	Low temperature gradient	0.035	Temperature gradient	^{0}C	±5 ^{0}C to±10 ^{0}C	5	0.175	±5 ^{0}C	5	0.175	±5 ^{0}C	5	0.175
8	Better soldered joint quality	0.1	Solder joint quality	-	good	7	0.7	Very good	8	0.8	average	5	0.5
9	Minimum adjacent component reflow possibility	0.1	Adjacent component refloww	-	possible	6	0.6	no	10	1	highly possible	4	0.4
10	Highly suitable for soldering/desoldering process	0.045	Soldering/ desoldering	-	capable	8	0.36	capable	8	0.36	capable	8	0.36
11	Wide component application range	0.045	Component application range	-	BGA, CSP, FC	8	0.36	BGA, CSP, FC	8	0.36	BGA, CSP,FC	4	0.18
12	Very suitable for future SMCs	0.015	Future SMCs	-	good	7	0.105	excellent	9	0.135	weak	2	0.03
13	Very capable of double sided PCBA repair	0.045	Double sided PCBA repair	-	capable	8	0.36	capable	8	0.36	capable	8	0.36
14	Minimum space requirement for tooling	0.1	Space requirement	-	low	8	0.8	Low	8	0.8	high	4	0.4
15	Highly suitable for automation	0.1	Suitability to automation	-	Very good	8	0.8	Very good	8	0.8	weak	2	0.2
		$\sum W_i$= 1				$\sum V_i$= 101	$\sum W_{Vi}$= 6.1		$\sum V_i$= 115	$\sum W_{Vi}$= 7.51		$\sum V_i$= 77	$\sum W_{Vi}$= 4.4

As can be seen in the evaluation chart, laser has 7.51 overall weighted value, IR has 6.1 overall weighted value and hot/air gas has 4.4 overall weighted value. Laser has higher overall weighted value than hot/air gas and IR. Therefore optimum solution for reflowing defective SMC is laser reflow. However there are also four laser reflow methods which are suitable for reflow, as can be seen in the function/means tree. These laser reflow methods which are CO_2, Nd:YAG, DPSS Nd:YAG and HPDL laser systems must be also evaluated to identify optimum laser reflow method. For this purpose, the same procedure same as above is followed. The weighted objectives tree and the evaluation chart for laser reflow systems are given in figure 4.7 and table 4.5.

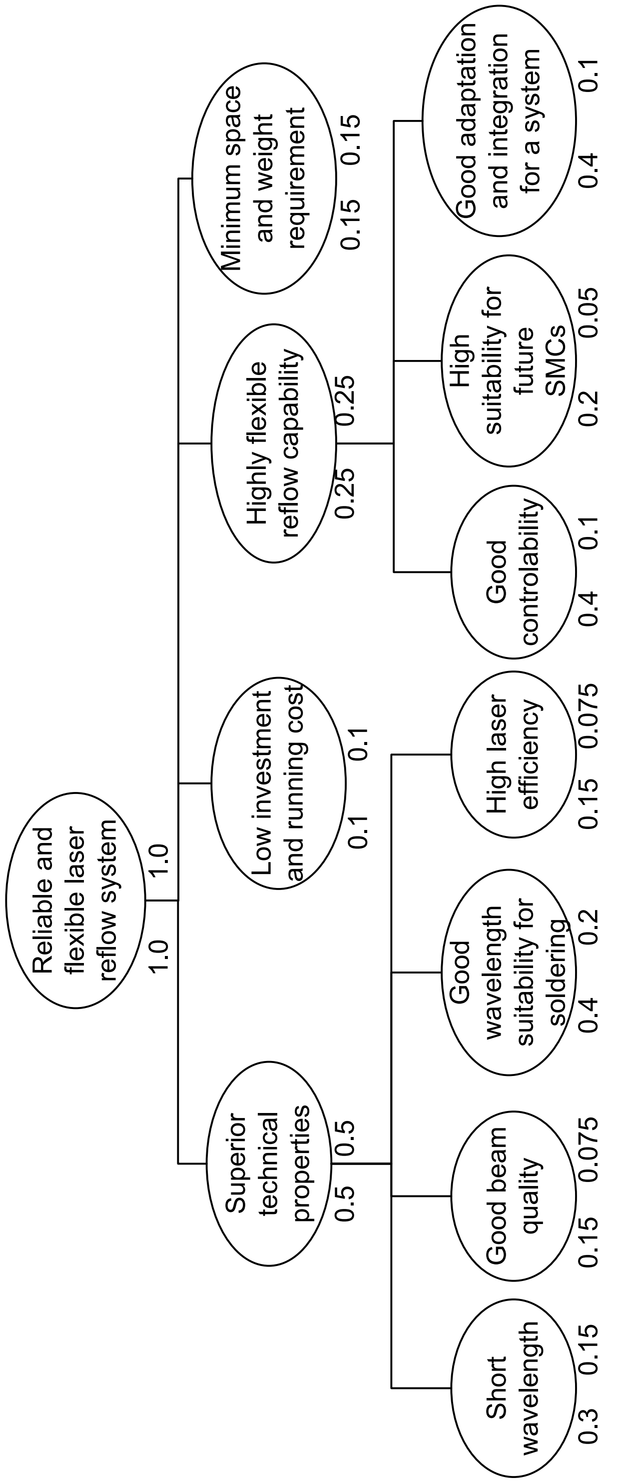


Figure 4.7. The weighted objective tree for laser reflow system.

Table 4.5. Evaluation chart for laser reflow tools.

Evaluation criteria			Parameters		CO_2 laser			Nd:YAG laser			DPSS Nd:YAG			HPDL		
No		Wt.		Unit	Magn.	V_{il}	W_{Vil}	Magn.	V_{il}	W_{Vil}	Magn.	V_{il}	W_{Vil}	Magn.	V_{il}	W_{Vil}
1	Short wave length	0.15	Wavelength	µm	10.6	3	0.45	1.06	8	1.2	0.8-1.06	9	1.35	0.8-0.98	9	1.35
2	Good beam quality	0.075	Bea m quality	-	Good	7	0.53	Good	7	0.53	Good	7	0.53	Average	4	0.3
3	Good wave length suitability for soldering	0.2	Wavelength suitability	-	Inferior	5	1	Good	7	1.4	Very good	8	1.6	Very good	8	1.6
4	High laser efficiency	0.075	Laser efficiency	%	10-15	4	0.3	1-5	2	0.15	25-30	5	0.375	>50	8	0.6
5	Low investment and running cost	0.1	Investment and running cost	-	High	2	02	Average	4	0.4	Average	4	0.4	Low	7	0.7
6	Good controllability	0.1	Controllability	-	Inferior	5	0.5	Good	7	0.7	Very good	8	0.8	Very good	8	0.8
7	High suitability for future SMCs	0.05	Suitability for future SMCs	-	Inferior	5	0.25	Inferior	5	0.25	good	7	0.35	Excellent	9	0.45
8	Good adaptation and integration for a system	0.1	Adaptability and integration	-	Average	6	0.6	Average	6	0.6	good	7	0.7	Excellent	9	0.9
9	Minimum weight and space requirement	0.15	Weight and space requirement	-	Inferior	5	0.75	Inferior	5	0.75	good	7	1.05	Excellent	9	1.35
		$\sum W_i = 1$				$\sum V_i = 42$	$\sum W_{Vi} = 4.58$		$\sum V_i = 51$	$\sum W_{Vi} = 5.98$		$\sum V_i = 61$	$\sum W_{Vi} = 7.16$		$\sum V_i = 71$	$\sum W_{Vi} = 8.05$

As can be seen in the evaluation chart above, CO_2 laser has a overall weighted value 4.575, Nd:YAG laser 5.975, DPSS Nd:YAG laser 7.15 and HPDL 8.05. HPDL has higher overall weighted value than the others. Therefore HPDL laser system is optimum solution for the laser reflow process. After selecting the reflow tool, we can evaluate and select other components and systems.

Determinatiom of Preheater: As can be seen in the function/means tree, there are two possible solutions for preheating. These are hot air and IR. The weighted objectives tree and evaluation chart for preheating process are provided in figure 4.8 and table 4.6.

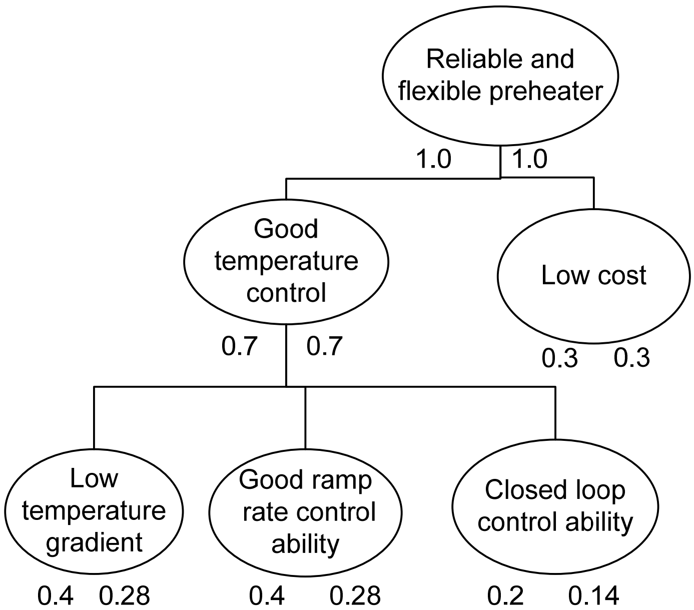


Figure 4.8. The weighted objective tree for preheating process

Table 4.6. Evaluation chart for preheating tools

Evaluation criteria			Parameters		Hot Air Gas			IR		
No		Wt.		Unit	Magn.	V_{il}	W_{Vil}	Magn.	V_{il}	W_{Vil}
1	Low cost	0.3	Equipment cost	-	Low	8	2.4	High	4	1.2
2	Low temperature gradient	0.28	Temperature gradient	^0C	±2 to ±5	7	1.96	±5 to ±10	4	1.12
3	Good ramp rate control ability	0.28	Ramp rate control	-	Low	4	1.12	Good	7	1.96
4	Closed loop control ability	0.14	Closed loop control	-	Possible	7	0.98	Possible	7	0.98
		$\sum W_i$= 1				$\sum V_i$= 26	$\sum W_{Vi}$= 6.46		$\sum V_i$= 22	$\sum W_{Vi}$= 5.26

As a result of evaluation process, hot air has the overall weighted value 6.46 and IR has overall weighted value 5.26. Hot air preheater has higher overall weighted value than IR. Therefore optimum solution for preheating process is the hot air preheater.

Determination of Robot Configuration for Positioning SMC: Two possible solutions are available for positioning PCBA, as can be seen in the function/means tree. Advantages and disadvantages of these solutions are in the previous sections. The same evaluation procedure can be applied to select optimum solution for the SMC positioning. The weighted objectives tree and evaluation chart for positioning SMC are provided in figure 4.9 and table 4.7.

As can be seen in the evaluation chart, gantry robot has the weighted value of 6.705 and SCARA robot has 5.83. Gantry robot has higher overall weighted value. Therefore optimum solution for positioning PCBA is gantry robot.

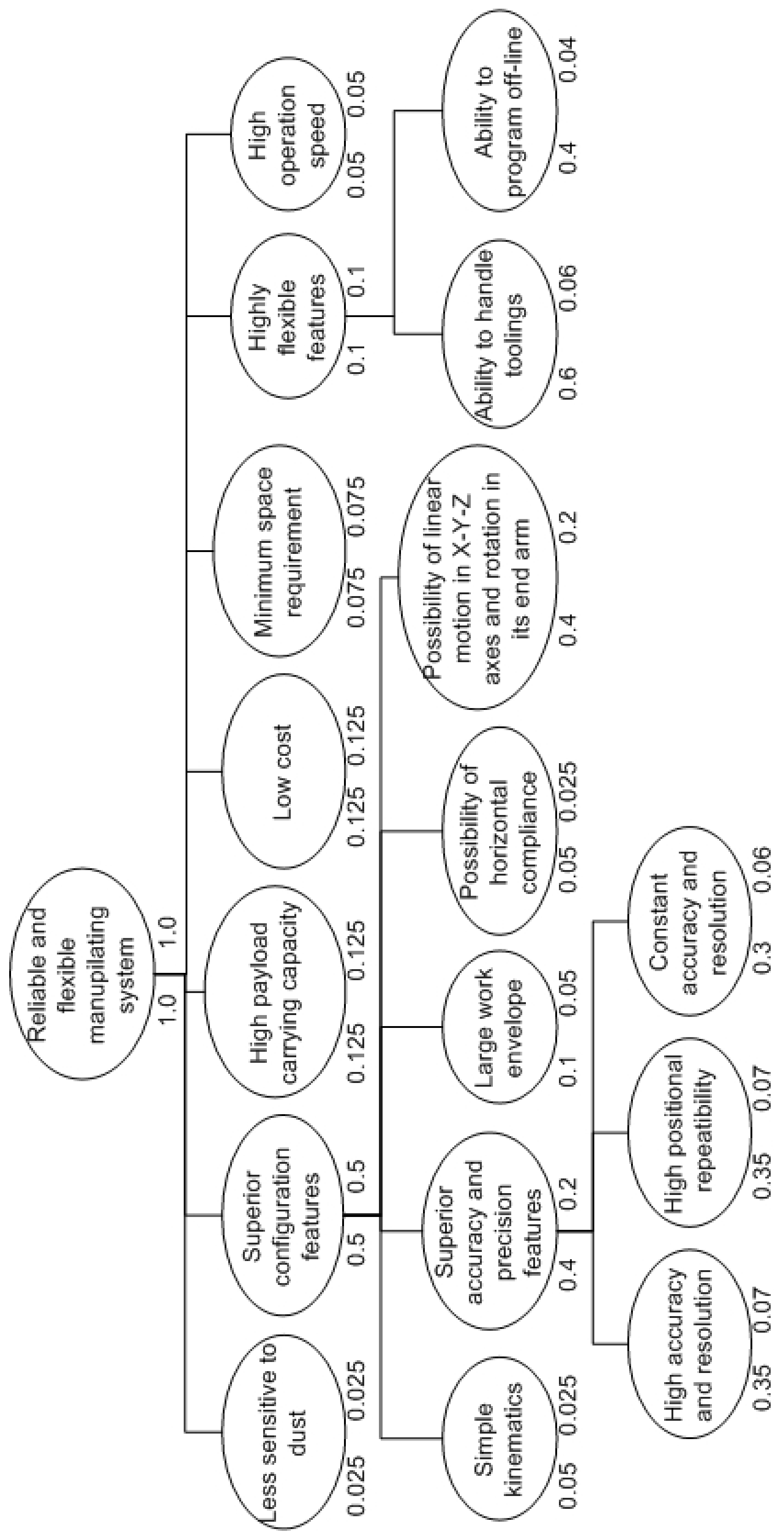


Figure 4.9. The weighted objective tree for positioning SMC.

Table 4.7. Evaluation chart for manipulating

Evaluation criteria			Parameters		SCARA robot			Gantry robot		
No		Wt.		Unit	Magn.	V_{il}	W_{Vil}	Magn.	V_{il}	W_{Vil}
1	Less sensitive to dust	0.025	Sensitivity to dust	-	Less possible	8	0.2	Possible	6	0.15
2	Simple kinematics	0.025	Kinematics	-	Complex	3	0.075	Simple	7	0.175
3	High accuracy and resolution	0.07	Accuracy and resolution	-	Good	5	0.35	Very good	8	0.56
4	High positional repeatability	0.07	Repeatability	-	High	5	0.35	Very high	7	0.49
5	Constant accuracy and resolution	0.06	Accuracy and resolution	-	Variable	3	0.18	Constant	8	0.48
6	Large work envelope	0.05	Work envelope	-	Larger	7	0.35	Smaller	3	0.15
7	Possibility of horizontal compliance	0.025	Horizontal compliance	-	Possible	8	0.2	Not possible	2	1.6
8	Possibility of linear motion in X-Y-Z axes and rotation in its end arm	0.2	X-Y-Z-θ motion	-	Possible	8	1.6	Possible	8	1
9	High payload carrying capacity	0.125	Payload carrying capacity	-	Medium payloads	4	0.5	High payloads	8	0.875
10	Low cost	0.125	Cost	-	Higher	4	0.5	Lower	7	0.225
11	Minimum space requirement	0.075	Space requirement	-	Smaller workspace	7	0.53	Larger workspace	3	0.48
12	Ability to handle toolings	0.06	Ability to handle toolings	-	Possible	8	0.48	Possible	8	0.32
13	Ability to program off-line	0.04	Ability to program off-line	-	Difficult	3	0.12	Simple	8	0.15
14	High operation speed	0.05	Operation speed	-	High	8	0.4	Low	3	0.15
		$\sum W_i$= 1				$\sum V_i$= 81	$\sum W_{Vi}$= 5.83		$\sum V_i$= 86	$\sum W_{Vi}$= 6.705

Determination of SMC Removal Tool: Two possible solutions are available for this purpose, as can be seen in the function/means tree. The same procedure above can be followed to select optimum solution. The weighted objectives tree and evaluation chart for removal process are in figure 4.10 and table 4.8.

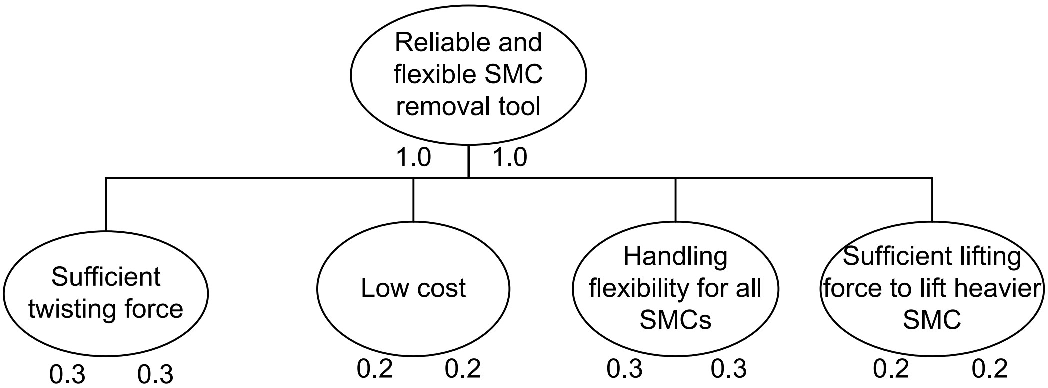


Figure 4.10. The weighted objectives tree for SMC removal process

As can be seen in the evaluation chart, the gripper has an overall weighted value 6.6 and the vacuum suction tool has an overall weighted value 5.6. The gripper has a higher value than the vacuum suction tool. Therefore the gripper is optimum solution for component removal.

Table 4.8. Evaluation chart for SMC removal tools

Evaluation criteria			Parameters		Gripper			Vacuum suction tool		
No		Wt.		Unit	Magn.	V_{il}	W_{Vil}	Magn.	V_{il}	W_{Vil}
1	Sufficient twisting force	0.3	Twisting force	-	Sufficient	8	2.4	Not sufficient	0	0
2	Low cost	0.2	Cost	-	High	4	0.8	Low	8	1.6
3	Handling flexibity for all SMCs	0.3	Handling flexibity	-	For all SMCs with optional tools	6	1.8	For all SMCs	8	2.4
4	Sufficient lifting force to lift heavier SMC	0.2	Lifting force	-	Sufficient	8	1.6	Sufficient	8	1.6
		$\sum W_i = 1$				$\sum V_i = 26$	$\sum W_{Vi} = 6.6$		$\sum V_i = 24$	$\sum W_{Vi} = 5.6$

Determination of SMC Placement Tool: There are two possible solutions for SMC placement process. These are vacuum suction tool and gripper. The same procedure above can be followed to select optimum solution. The weighted objectives tree and evaluation chart for placement process are determined and given in figure 4.11 and table 4.9.

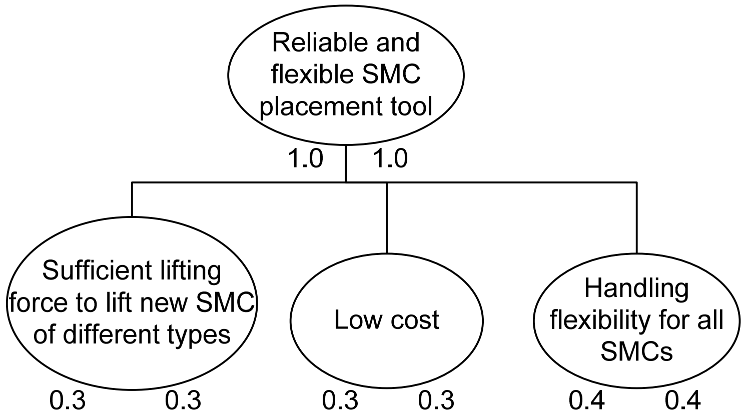


Figure 4.11. The weighted objectives tree for SMC placement

As can be seen in the evaluation chart, the gripper has an overall weighted value 5.7 and the vacuum suction tool has an overall weighted value 7.7. The vacuum suction tool has a higher value than the gripper. Therefore the vacuum suction tool is selected as an optimum solution for component placement.

Table 4.9. Evaluation chart for SMC placement tools

No	Evaluation criteria	Wt.	Parameters	Unit	Gripper Magn.	Gripper V_{il}	Gripper W_{Vil}	Vacuum suction tool Magn.	Vacuum suction tool V_{il}	Vacuum suction tool W_{Vil}
1	Sufficient lifting force to lift heavier SMC	0.3	Lifting force	-	Sufficient	7	2.1	Sufficient	7	2.1
2	Low cost	0.3	Cost	-	High	4	1.2	Low	8	2.4
3	Handling flexibity for all SMCs	0.4	Handling flexibity	-	For all SMCs with optional tools	6	2.4	For all SMCs	8	3.2
		$\Sigma W_i = 1$				$\Sigma V_i = 17$	$\Sigma W_{Vi} = 5.7$		$\Sigma V_i = 23$	$\Sigma W_{Vi} = 7.7$

Determination of Solder Dispenser: There are four possible solutions for this purpose, as can be seen in the function/means tree. These are time/pressure valve, rotary positive displacement valve, linear positive displacement pump and jetting valve. The same procedure above can be followed to select optimum solution. The weighted objectives tree and evaluation chart for solder dispensing tool are provided in figure 4.12 and table 4.10.

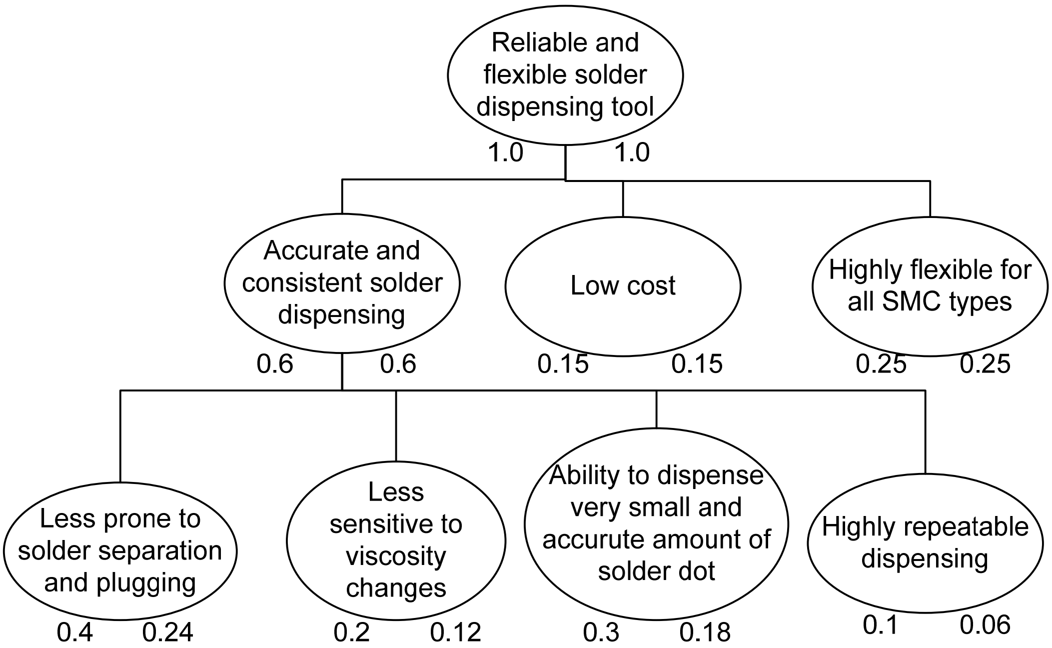


Figure 4.12. The weighted objectives tree for solder dispensing tool.

Table 4.10. Evaluation chart for solder dispensing

Evaluation criteria			Parameters		Time pressure valve			Rotary positive displacement pump			Linear positive displacement pump			Jetting valve		
No		Wt.		Unit	Magn.	V_{il}	W_{Vil}	Magn.	V_{i2}	W_{Vil}	Magn.	V_{i3}	W_{Vil}	Magn.	V_{i4}	W_{Vil}
1	Less prone to solder separation and plugging	0.24	Solder separation and plugging	-	Not possible	9	2.16	Not possible	9	2.16	Possible	2	0.48	Possible	2	0.48
2	Less sensitive to viscosity changes	0.12	Sensitivity to viscosity changes	-	High	2	0.24	Low	4	0.48	No	9	1.08	No	9	1.08
3	Ability to dispense very small and accurate amount of solder dot	0.18	Ability to dispense very small and accurate amount of solder dot	-	Inferior	6	1.08	Good	7	1.26	Excellent	9	1.62	Very good	8	1.44
4	Highly repeatable dispensing	0.06	Dispensing repeatability	-	Low	4	0.24	High	7	0.42	Very high	8	0.48	Very high	8	0.48
5	Low cost	0.15	Cost	-	Low	8	1.2	High	6	0.9	High	6	0.9	Very high	4	0.6
6	Highly flexibile for SMCs	0.25	Flexibility for all SMCs	-	Good	7	1.75	Very good	8	2	Very good	8	2	Very good	8	2
		$\sum W_i = 1$				$\sum V_i = 36$	$\sum W_{Vi} = 6.67$		$\sum V_i = 41$	$\sum W_{Vi} = 7.22$		$\sum V_i = 42$	$\sum W_{Vi} = 6.56$		$\sum V_i = 40$	$\sum W_{Vi} = 6.08$

As can be seen in the evaluation chart, the time/pressure valve has an overall weighted value of 6.67 and the rotary positive displacement pump has an overall weighted value of 7.22, linear positive displacement pump has an overall weighted value of 6.56 and jetting valve has an overall weighted value of 6.08. The rotary positive displacement pump has a higher value than the others. Therefore the rotary positive displacement pump is optimum solution for solder dispensing.

Determination of Flux Dispenser: There are two possible solutions for this purpose, as can be seen in the function/means tree. These are linear positive displacement pump and jetting valve. The same procedure above can be followed to select optimum solution. The weighted objectives tree and evaluation chart for flux dispensing process are given in figure 4.13 and table 4.11.

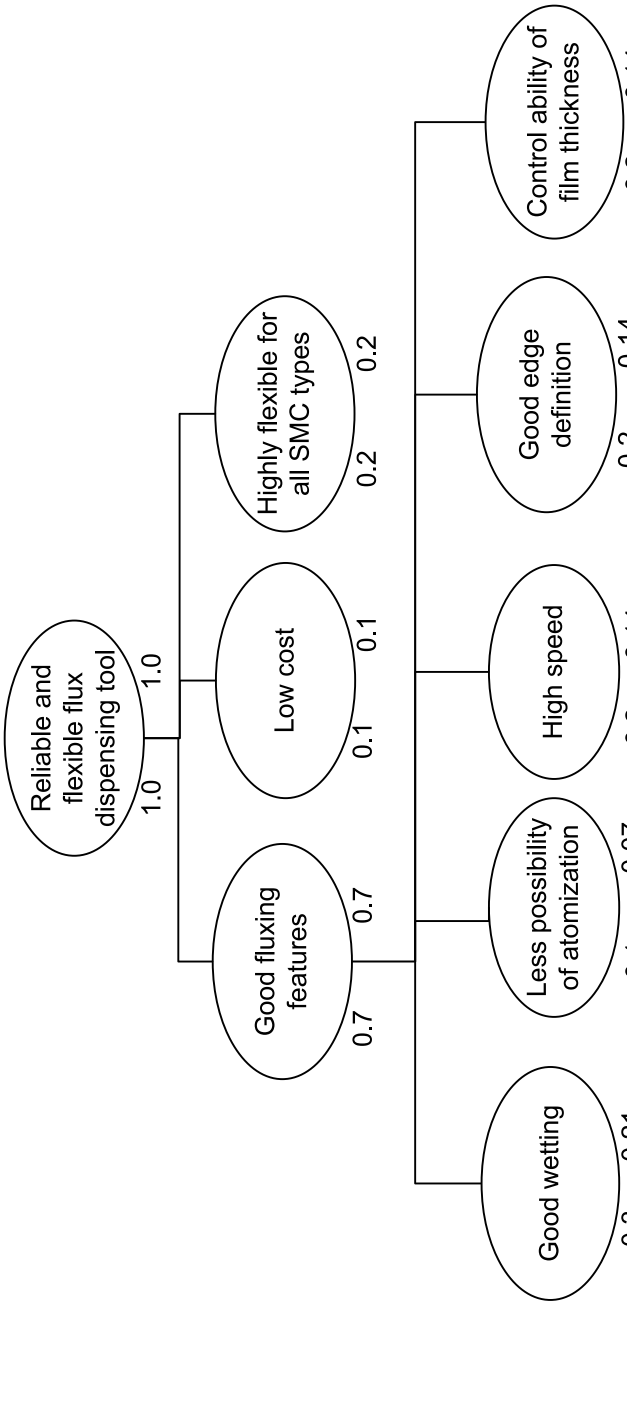


Figure 4.13. The weighted objective tree for flux dispensing tools.

Table 4.11. Evaluation chart for flux dispensers

No	Evaluation Criteria		Parameters		Spray valve			Jetting valve		
		Wt.		Unit	Magn.	V_{i1}	Wv_{i1}	Magn.	V_{i1}	Wv_{i1}
1	Good wetting	0.21	Wetting	-	Fair	6	1.26	Good	7	1.47
2	Less possibility of atomization	0.07	Atomization	-	Possible	4	0.28	No	8	0.56
3	High speed	0.14	Speed of fluxing	-	High	8	1.12	High	8	1.12
4	Good edge definition	0.14	Edge definition	-	Poor	4	0.56	Excellent	9	1.26
5	Low cost	0.1	Cost	-	Low	8	0.8	High	4	0.4
6	Control ability of film thickness	0.14	Control ability of film thickness	-	Good	7	0.98	Very good	8	1.12
7	Highly flexible for all SMC types	0.2	Flexibility for all SMC types	-	Good	7	1.4	Very good	8	1.6
		$\sum w_i=1$				$\sum v_i=44$	$\sum Wv_{i1}=6.4$		$\sum v_i=52$	$\sum Wv_{i1}=7.53$

As can be seen in the evaluation chart, the spray valve has an overall weighted value of 6.4 and the jetting valve has an overall weighted value of 7.53. The jetting valve has a higher value than the spray valve. Therefore the jetting valve is optimum solution for flux dispensing process.

Determination of Underfill Dispenser*:* There are four possible solutions for this purpose, as can be seen in the function/means tree. These are time/pressure valve, rotary positive displacement valve, linear positive displacement pump and jetting valve. The same procedure above can be followed to select optimum solution. The weighted objectives tree and evaluation chart for underfill dispensing tool are given in figure 4.14 and table 4.12.

As can be seen in the evaluation chart, the time/pressure valve has an overall weighted value of 4.32 and the rotary positive displacement pump has an overall weighted value of 5.14, linear positive displacement pump has an overall weighted value of 8.82 and jetting valve has an overall weighted value of 8.26. The linear positive displacement pump has a higher value than the others. Therefore the linear positive displacement pump is optimum solution for solder dispensing.

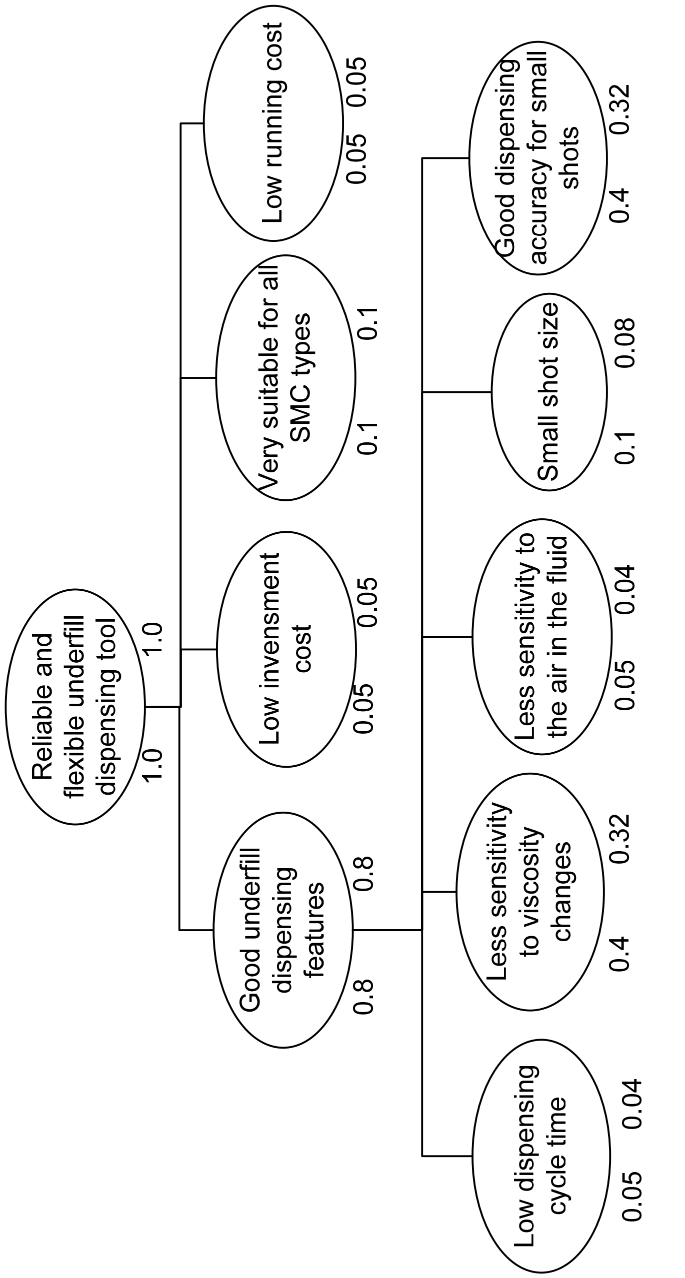


Figure 4.14. The weighted objective tree for underfill dispensing tools.

Table 4.12. Evaluation chart for underfill dispensing

Evaluation criteria			Parameters		Time pressure valve			Rotary positive displacement pump			Linear positive displacement pump			Jetting valve		
No		Wt.		Unit	Magn.	V_{il}	W_{Vil}	Magn.	V_{i2}	W_{Vil}	Magn.	V_{i3}	W_{Vil}	Magn.	V_{i4}	W_{Vil}
1	Low dispensing cycle time	0.04	Dispensing cycle time	-	High	4	0.16	Low	6	0.24	Low	6	0.24	Very low	8	0.32
2	Less sensitivity to viscosity changes	0.32	Sensitivity to viscosity changes	-	High	0	0	Low	2	0.64	No	10	3.2	No	10	3.2
3	Less sensitivity to the air in the fluid	0.04	Sensitivity to the air in the fluid	-	Possible	6	0.24	Possible	6	0.24	Possible	6	0.24	No	8	0.32
4	Small shot size	0.08	Shot size	-	Small	6	0.48	Small	6	0.48	Can be extremely small	8	0.64	Can be very small	7	0.56
5	Good dispensing accuracy for small shots	0.32	Dispensing accuracy for small shots	-	Good	7	2.24	Good	7	2.24	Excellent	10	3.2	Very good	8	2.56
6	Low investment cost	0.05	Investment cost	-	Low	8	0.4	High	6	0.3	High	6	0.3	Very high	4	0.2
7	Very suitable for all SMCs	0.1	Suitability for all SMCs	-	Moderate	4	0.4	Good	7	0.7	Very good	8	0.8	Very good	8	0.8
8	Low running cost	0.05	Running cost	-	Low	8	0.4	High	6	0.3	Very high	4	0.2	High	6	0.3
		$\sum W_i$= 1				$\sum V_i$ = 43	$\sum W_{Vi}$=4.3		$\sum V_i$= 46	$\sum W_{Vi}$= 5.14		$\sum V_i$ = 58	$\sum W_{Vi}$= 8.82		$\sum V_i$= 40	$\sum W_{Vi}$= 6.08

4.9. Total Robotic Rework Cell

By the use of systematic design techniques a flexible and fully automated PCBA rework system for advanced surface mount components (ASMCs) was proposed as given in figure 4.15.

As can be seen in this figure, firstly, necessary CAD/CAM data about PCBA that will be reworked and rework steps are entered into cell controller. Cell controller controls rework steps using these data via other controllers such as temperature controller, vision controller, etc.

A PCBA is supplied into the rework system by AGV and part locating device. Manipulating device (X-Y positioning table) positions the PCBA supplied by AGV and part locating device according to relating rework step. The PCBA positioned by manipulating device is firstly inspected by inspection system in order to define fiducial points and then location of defective component, respectively. In order to melt solder, the board is preheated by preheating system and then defective ASMC is reflowed by reflow system. The defective component is removed from the board by manipulating device (gantry robot) and ASMC removal tool. The removal tool is supplied by the gantry robot from a tool parking station that other tools are also parked. Gantry robot disposes the defective ASMC into a junk bin within the system. Solder and underfill residue is cleaned by site cleaning tool that is supplied and manipulated by gantry robot. Solder and then undefill is dispensed by solder dispensing tool, undefill dispensing tool that are supplied and manipulated by gantry robot. New ASMC is taken from an ASMC feeder and then placed on dispensed underfill by gantry robot that has in its end arm an ASMC placement tool. Finally, the PCB is preheated by preheating system and then new ASMC is reflowed by reflow system, respectively. This rework procedure results in a defective free PCBA.

As a result, this flexible rework system which includes the systems and tools in figure 4.15 is capable of reworking PCBAs with underfilled advanced surface mount components. This system also has flexibility to rework PCBAs that are assembled by the use of different solder alloys. With these subsystems, PCBA rework is carried out in fully automated manner without interfering human.

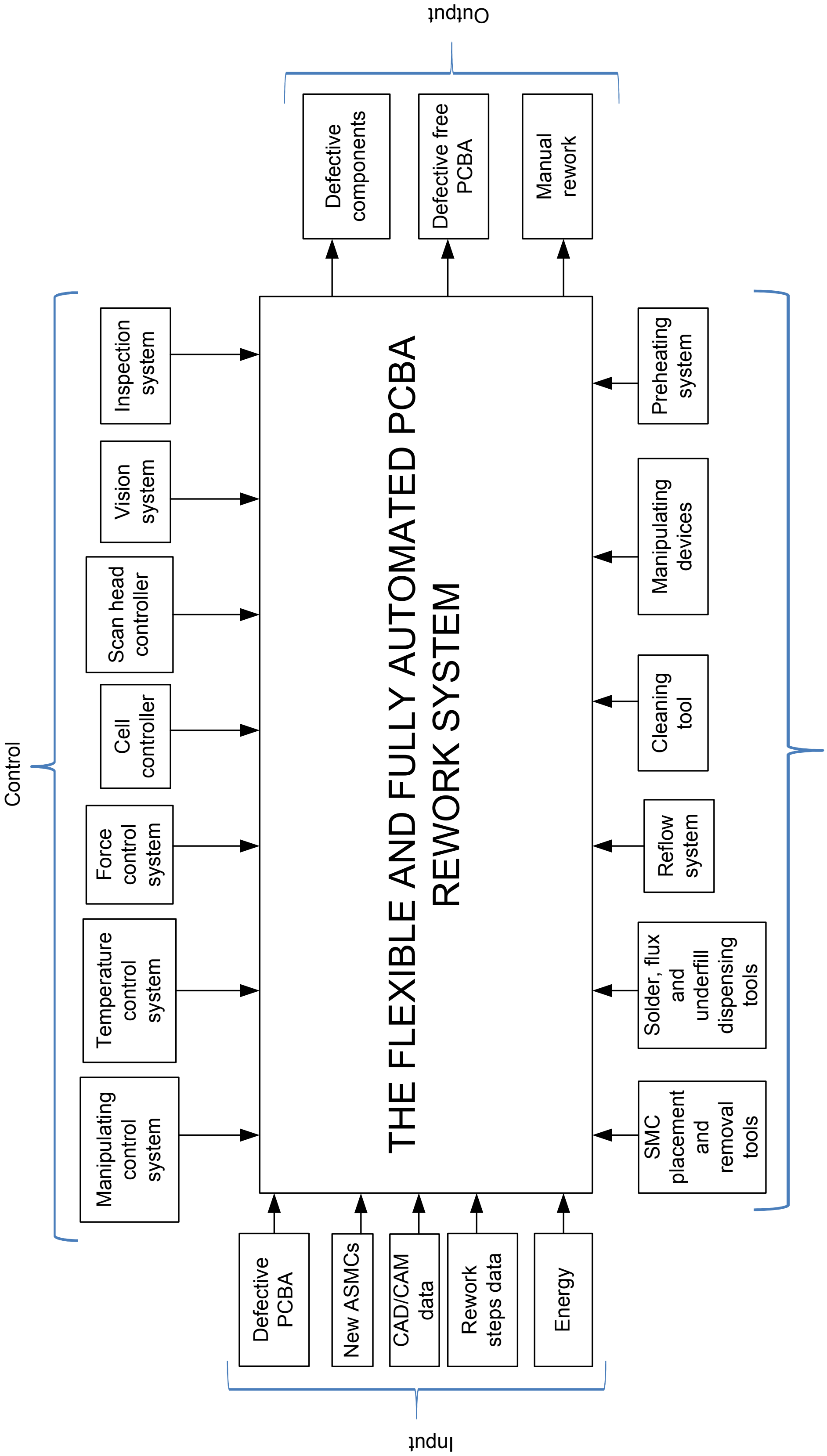


Figure 4.15. Subsystems of the PCBA rework system.

4.10. Justification of Developed Design Methodology

By the use of suggested systematic design techniques, firstly existing manual or semi-automated PCBA rework systems were scrutinized in order to gather data about the rework process that was carried out by these systems. These gathered data (requirements or constraints) up to the smallest detail were then entered to a requirements list (step 1 in the design methodology). The well prepared requirements list was very useful and indispensable for this study because of the fact that within it all necessary requirements and constraints relating to rework process could be given with the simplest expressions and then could be used during design process. It was continuously referred to the requirements list as a base document during design process.

Abstraction (step 2 in the design methodology) was used to define the problem or task in more general terms. Abstraction was very useful for the study especially to solve the problem of fixation and sticking with conventional ideas.

A data flow diagram (DFD) based on the abstraction was prepared (step 3 in the design methodology. DFD was very useful for the study to specify flexible manufacturing system features and data flow between them.

A function structure (including flexible manufacturing system features and data flow between them in DFD) based on the requirement list was prepared in order to specify functions that would carry out all requirements and constraints in the requirements list (step 4 in the design methodology). The function structure was necessary for the design process in order to analyze system' behavior in very early stage of the design process.

The most vital part of the design process was to find solution or solutions for the functions in the function structure (step 5 in the design methodology). For this purpose, four solution finding methods were used. These were literature search, analysis of an existing system, TRIZ and ASIT methods. Solution or solutions for every function in the function structure were easily found by the use of methods of literature search and analysis of existing system, but one function. A solution for this function was found by the use of TRIZ and ASIT methods. These methods proved to be extremely very useful to find solutions for the functions in the function structure during design process.

A function means tree was prepared by combining the functions in the function structure and solutions that were found by the use of solution finding methods (step 6 in the design methodology). It was very useful for the design process especially to demonstrate solutions and functions in one schema. The function means tree was then referred during evaluation process in order to look at functions that had more than one solution.

Finally, solutions for the related functions that had more than one solution in the function means tree were evaluated in order to determine optimum solutions following an evaluation procedure (step 7 in the design methodology). Methods that were used during the evaluation process were weighted objectives tree, evaluation chart and value profile. Firstly, weighted objectives trees for the solutions for the related function that had more than one solution in the function means tree were prepared. Weighted objectives trees prepared were completely based on the requirements list. Then evaluation charts for these solutions were prepared based on the weighted objectives trees. Value profile would be used, if it were needed after preparation of evaluation chart. This procedure also proved to be very useful to be able to determine optimum solutions for the related functions considering the smallest detail in the requirements list.

Using systematic design techniques, design process was carried out in a systematic way, as outlined above. So that:

- a very complex problem which was design a flexible and fully automated PCBA rework system was solved easily, whereas with conventional methods to solve this problem would be very difficult and time consuming.
- the risk to develop an unsuccessful PCBA rework system (with the conventional methods there was a risk to develop a PCBA rework system which might be unsuccessful in reworking PCBA) was diminished at a very big rate.

Due to two reasons above, systematic design techniques have been preferred to design a flexible and fully automated PCBA rework system for advanced surface components.

5. CONCLUSION

This study has been carried out as an extension of the Master thesis which has been carried out by Çakırca (2004). The results of Çakırca (2004) have been used as an input to this study. A fully automated flexible PCBA rework system has been proposed by the help of systematic design techniques and FMS modeling techniques using this input data.

In order to design such a system, a design methodology was followed as in figure 3.13. Firstly, the need based on customer or market research was specified. The need (or task) was clarified by the use of a requirements list. A general problem definition was made from the requirements list by the use of abstraction. A FMS system was modeled by the use data flow diagram (DFD) and then a function structure was prepared based on the DFD and rework steps which were defined by the use of the requirements list. Solution or solutions for every function in the function structure was/were found using different solution finding methods such as TRIZ, ASIT, analysis of an existing system and literature search, etc. The functions and solutions found were shown together in a schema called function means tree. To evaluate these solutions an evaluation procedure that included some methods such as weighting objectives tree, use value analysis and value profile, etc. was followed. Finally, by the use of this evaluation procedure and the function means tree, the optimum solutions for the related functions were determined.

With followed such a procedure above, it could be possible to overcome difficulties related to the complex nature of a fully automated rework system that harbored different scientific fields such as mechanics, electronic, etc., and have probability of success of new PCBA rework system increase. As evaluated the optimum solutions, in addition to technical properties of candidate solutions, design criteria such as cost, adaptability of the tool to a fully automated system, etc were also considered during the evaluation procedure. Therefore, the solution which is optimum is also optimum economic solution and then the system can be called as optimum economic PCBA rework system.

The rework system proposed as a result of applying the design methodology above is capable of reworking PCBAs which have different types of SMC such FC, BGA, CSP, etc. PCBA is supplied to the system by an automated guided vehicle, and oriented and located by a part docking device.

The rework process is planned and controlled by cell controller. All necessary data about the PCBA that will be reworked (CAD/CAM data) and rework steps must be supplied to the system by the operator. Cell controller controls all operations in the system via some tool controllers such as robot controller, vision controller, inspection controller, heat control unit, etc. It is also ability to study generic problems associated with the rework steps such as removal, placement, etc.

The tools that are controlled by cell controller via their controllers are gantry robot which manipulates necessary tooling and SMCs, X-Y positioning table which position the PCBA, diode laser heat source which reflows solder, hot air preheater which preheats PCBA, rotary positive displacement pump which dispense solder, linear positive displacement pump which dispense underfiller, jetting valve which dispense flux and vacuum desoldering tool which clean solder and underfill residual.

So that this system that includes these tools above carries out the rework of PCBAs that have different sizes, board properties and SMCs in fully automated manner.

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