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Invited Review

# A survey of surface mount device placement machine optimisation: Machine classification

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**Abstract**

The optimisation of a printed circuit board assembly line is mainly influenced by the constraints of the surface mount device (SMD) placement machine and the characteristics of the production environment. This paper surveys the characteristics of the various machine technologies and classifies them into five categories (dual-delivery, multi-station, turret-type, multi-head and sequential pick-and-place), based on their specifications and operational methods. Using this classification, we associate the machine technologies with heuristic methods and discuss the scheduling issues of each category of machine. We see the main contribution of this work as providing a classification for SMD placement machines and to survey the heuristics that have been used on different machines. We hope that this will guide other researchers so that they can subsequently use the classification or heuristics, or even design new heuristics that are more appropriate to the machine under consideration.


*Keywords:* Scheduling; Printed circuit board assembly; Component placement sequencing; Feeder setup; Heuristic

## 1. Introduction

SMT (surface mount technology) assembly lines usually involve solder paste, component placement and solder reflow operations (a soldering process to adhere components to the printed circuit board (PCB)) (Tirpak, 2000). An SMD (surface mount device) placement machine is very expensive (US$300,000 to US$1,000,000) and yet SMT lines are typically designed such that the SMD placement machine is the limiting resource or "bottleneck" which is the key issue for assembly line optimisation (Csaszar et al., 2000a; Moyer and Gupta, 1997; Tirpak et al., 2000).

Typically, the placement operation begins by loading the PCB into the SMD placement machine (e.g. via a conveyer system). Next, a "fiducial marks" operation is performed to identify the exact position and orientation of the PCB inside the

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SMD placement machine. The "fiducial marks" are special points (typically 2–4 points) that are usually located at the corners of the board (Magyar et al., 1999). Then, the components are assembled onto the PCBs guided by the optimisation software that has been installed in the SMD placement machine. Finally, once completed (or partially completed, e.g. due to component runs out or job completion), the PCB is transferred out of the SMD placement machine. Before undergoing a solder reflow operation, the components are secured onto the PCB by using adhesive or solder paste (Leu et al., 1993).

Owing to the lack of standardisation among SMD placement machines, the optimisation of the pick-and-place operations in a PCBA (printed circuit board assembly) line is mainly influenced by the constraints of the SMD placement machine and the characteristics of the production environment (Duman and Or, 2004; Leipälä and Nevalainen, 1989; Shih et al., 1996). Crama et al. (2002), Jeevan et al. (2002) and Sun et al. (2005) also agree that the technological characteristics of the placement machine influences the nature of some of the planning problems to be solved and the formulation of the associated models. As a result, little consensus exists as to what a suitable model should be for the characteristics of a given machine, and the formulations proposed by different authors tend to be difficult to compare.

Electronic components (possibly hundreds or thousands) are assembled onto a PCB using an SMD placement machine. Optimisation of the feeder setup and component pick-and-place sequence, are important factors, which influence the efficiency of SMD placement machines. Faced with mounting hundreds of electronic components, of different shapes and sizes, finding an optimal travelling route for the robot arm of the SMD placement machine is a challenging optimisation problem (Su and Fu, 1998). In general, the component pick-and-place sequencing problem is modelled as a travelling salesman problem (TSP), which is a strongly NP-hard (Garey and Johnson, 1979; Truss, 1999) problem. Hence, this problem is also a strongly NP-Hard optimisation problem and most practical instances are difficult to solve to optimality in a reasonable time (Ellis et al., 2001; De Souza and Lijun, 1995). Indeed, the general PCB assembly problem is at least as complex as the TSP, which is known to be NP-complete (Nelson and Wille, 1995).

The complexity of concurrent machine operations also causes difficulties in formulating a realistic mathematical programming model (De Souza and Lijun, 1995). Many technical constraints also have to be considered (De Souza and Lijun, 1995). These include:

(a) The head(s), feeder carrier(s) and PCB table(s) usually move independently and at different speeds. Indeed, the speed changes when different sized components have to be placed.
(b) Smaller size components are usually placed before larger sized components since the larger components that have already been placed may be displaced when the placement heads and the PCB table increase their speed in order to place smaller components.
(c) Since the head(s), feeder carrier(s) and PCB table(s) move concurrently, the movement should be considered simultaneously in order to improve the throughput of the machine.

Due to the problem size, it is not realistic to use mathematical programming approaches. Alternatively, the problem has to be generalised or simplified (Moyer and Gupta, 1996a). For example, Ahmadi (1993), Ball and Magazine (1988), Bard et al. (1994), Chiu et al. (1991), Crama et al. (1996, 1997), Gavish and Seidmann (1988), Leipälä and Nevalainen (1989) and Van Laarhoven and Zijm (1993) have abstracted the problem by isolating it into subproblems. A heuristic approach which finds a near-optimal solution in an acceptable time is, therefore, more appropriate in solving the problem (De Souza and Lijun, 1995).

The structure of this paper is as follows. In the next section we describe the characteristics of various SMD placement machines and their operational methods, and also discuss some of the optimisation issues that arise. In Section 3, we classify the SMD placement machines into five categories, based on their specifications and operational methods. In Section 4, we survey each of the machine classifications described in Section 3, with respect to the heuristic methods that have been used on these machines. Section 5 concludes the paper.

This work represents a significant extension to our previous survey (Ayob et al., 2002). We hope that researchers find it a useful resource in being able to classify various SMD machines and also provide access to the literature as to the heuristics that are available.

## 2. Surface mount device placement machines

In the early 1980s, the first pick-and-place SMD placement machine, with only one placement head, was introduced (Bentzen, 2000). Nowadays, there are many types of SMD placement machines available, such as sequential pick-and-place, rotary disk turret, concurrent pick-and-place, etc. (Grotzinger, 1992; Gastel, 2002; Khoo and Loh, 2000). As different SMD Placement machines have different characteristics and constraints this, inevitably, influences the production process (Burke et al., 2001; Wang et al., 1999).

To date, SMD placement machines have been classified into a few categories. For example, Moyer and Gupta (1996a,b, 1997) defined three types of typical SMD placement machines, these being single compliance robot for assembly (SCARA), cartesian/gantry and high speed chip shooter. SCARA machines are usually pick-and-place machines, which have three joints that permit greater flexibility within the work area. Generally, SCARA machines are recommended for high mix, low volume assemblies as well as for odd shape components (Moyer and Gupta, 1998). The cartesian/gantry SMD placement machine has better throughput compared to SCARA. However, Moyer and Gupta (1996a,b, 1997) do not discuss the machine specification and operation. The high speed chip shooter SMD placement machine has a turret head that rotates between fixed pickup and fixed placement locations. However, these mechanical attributes do not generally affect the optimisation problems that have to be addressed.

There was also an attempt to classify the placement machines based on basic operational methods, these being concurrent and sequential, by McGinnis et al. (1992), or fixed pick-and-place point (FPP) and dynamic pick-and-place point (DPP) by Wang et al. (1998). Just having two categories, however, is not broad enough to allow the formulation of optimisation problems, which can be applied to many different machine types. Recently, Magyar et al. (1999) classified the placement machines into three categories, these being insertion, pick-and-place and rotary turret machines; whereas Bentzen (2000) classifications were turret head, pick-and-place and pick-and-place with rotary head; and Jeevan et al. (2002) classified them as multi-head, high speed chip shooter machine and robotic arm placement machine. However, they do not explicitly discuss the machine characteristics and the operational methods. Again, these three categories are too broad. Therefore, this work proposes five categories of machines based on their specifications and operational methods; these being dual-delivery, multi-station, turret-type, multi-head and sequential pick-and-place SMD placement machines. This grouping aims to guide future researchers in this field to have a better understanding of the various SMD placement machine specifications and operational methods, and subsequently use them to apply, or even design, heuristics which are more appropriate to the machine characteristics and the operational methods.

A typical SMD placement machine usually has a feeder carrier (or feeder magazine), PCB table, head, pipette (or spindles) and a tool magazine (tool bank). The feeder carrier, PCB table and head can either be stationary or moveable, depending on the specification of the machine. The feeder carrier is mounted on one, two, three, or four sides of the machine and holds several feeder banks. The feeder bank consists of several feeder slots where the component feeders are located. The component feeders are used to provide the machine with a continuous supply of components. Several kinds of component feeders are available to handle the various types of component packaging; tape, sticks and trays (or waffle). Fig. 1 shows an example of an SMD placement machine (pictured at the Dima factory).

A typical component feeder consists of either tape reel feeders or vibratory ski slope feeders; or both (Ahmadi et al., 1988; Jeevan et al., 2002). The positioning of the feeder reels or vibratory ski slope feeders, in the feeder carrier, is an optimisation problem in itself. The component feeders might have different widths and several slots may

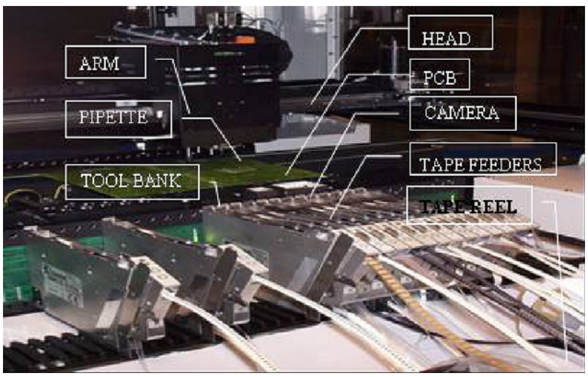


Fig. 1. An example of an SMD placement machine (Dima HP-10).

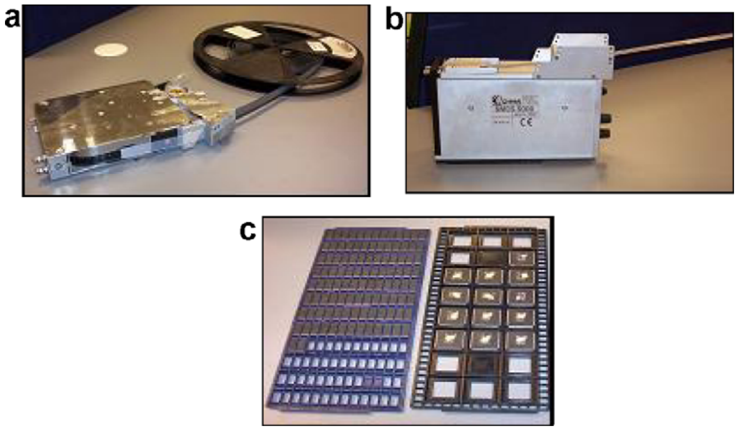


Fig. 2. Example of component feeders: (a) tape reel feeder; (b) stick feeder; (c) tray feeder.

be occupied by a component feeder (Sun et al., 2005). Fig. 2 shows a few types of component feeders (pictured at the Dima factory). These are tape reel, stick and tray feeders.

Tape reel feeders are used to feed components packed in embossed, paper or surf tape. Depending on the component size, the typical tape widths are 8 mm, 12 mm, 16 mm, 24 mm, 44 mm, 56 mm and 72 mm (Bentzen, 2000). If the components are supplied in sticks or tubes, then the stick feeders are used to feed the components. The two common mechanisms of feeding the stick feeders are vibrating and ski-slope. Due to a delicate handling of stick feeders, Bentzen (2000) recommended avoiding using components with stick feeders for mass production. Large sized components, supplied in trays, are fed using tray feeders. Some machines allow a single tray to be placed into the machine feeding area whilst others use an automatic tray-handling unit.

The robotic arm has a number of heads (possibly one) that are responsible for transporting components from the component feeder and placing them at the correct position on the PCB. Each head is equipped with a number of pipettes (possibly one), with each pipette being capable of holding a nozzle (tool or gripper). Placement heads come in different forms, such as a rotating turret head or a positioning arm head (Wang et al., 1999).

Pipettes can move in the $Z$-direction (up–down) to perform pick-and-place operations. The nozzle is used to pick up the component from the feeder before mounting it on the PCB (Altinkemer et al., 2000). Due to the various types of component packaging, different nozzle sizes are required to handle them and an automatic nozzle change system is used to ensure the correct nozzle is used. A tool bank supplies nozzles of various sizes. Usually, vacuum nozzles are used to transport components from component feeders, whereas special nozzles with mechanical alignment are required for the handling of odd-shape components (Bentzen, 2000). Fig. 3 adopted from Bentzen (2000) shows different sizes of vacuum nozzles.

The PCB table (there is normally only one but there could be more) holds the PCB, so that the component is placed at the correct location on the board by the placement head. The table often moves (in either $X$–$Y$ direction or on a conveyor), in order to position the board under the head, but it can also be stationary.

In this paper, we use the term ‘subtour’ (we refer to a ‘subtour’ to differentiate from an overall tour, which is an operation to place all the required components onto a single board) to refer to an operation taken by the robot arm to pick up and place a number of components (depending on the number of pipettes per head) in a single trip.

Fig. 3. Example of vacuum nozzles.

## 3. Machine classifications

Based on the specification and operational methods, the SMD placement machines have been classified into five categories (Ayob et al., 2002). These being: dual-delivery, multi-station, turret-type, multi-head and sequential pick-and-place. In this paper, we further discuss the machine characteristics and optimisation issues of each machine category, which have not been addressed in our previous work (Ayob et al., 2002).

### *3.1. Dual-delivery placement machine*

The unique, and important, feature of this machine type is that each pick-and-place operation alternates between two sides, i.e. while one head is performing pick operations, the other head is placing components on the board (Ahmadi et al., 1995; Safai, 1996; Siemens, 2005). No movement of the PCB table and feeder carrier occurs during pick-and-place operations. Therefore, the cycle time is determined by the maximum time taken by the arm, PCB table and feeder carrier movements.

The machine used by Tirpak et al. (2000), a Fuji NP-132 (see Fig. 4), is a variant of a dual-delivery SMD placement machine. It has dual turret placement heads mounted on the two overhead servo-driven $X$–$Y$ gantries. Each head is equipped with an internal camera, for on-the-fly vision inspection and 16 nozzles. The pick-and-place operation can begin once the PCB has been loaded into one of the conveyers and the fiducial mark operations have been performed. First, the gantry moves to position the turret head for the first component pickup (assuming the head is equipped with the correct nozzles, otherwise nozzle changes are required). Next, the turret head rotates to locate the appropriate nozzle. Then the component is picked up from the feeder. This process is repeated until the turret head has rotated by 360° and all nozzles are holding components (or left empty due to incompatibility with the components etc.). Next, the gantry moves and locates the head to place the first component. Meanwhile the turret also rotates to position the appropriate component at the correct placement point. These steps are repeated for the next locations on the board that have to be placed on the same subtour. While the first head is placing components, the other can concurrently pick components. To avoid collision, only one head can perform placement operations at a time.

### *3.2. Multi-station placement machine*

In general, this type of machine has more than one placement module (or station), with each being mechanically identical and able to work concurrently. The PCB is fixed to the pallet and then transferred through the stations by a pallet circulating system ("conveyor") (Csaszar et al., 2000a). At each cycle (the interval between two conveyor steps), each station is supplied with all the pick-and-place coordinates needed for that cycle. Each station works autonomously. Once every station has completed its placement operations, the PCB's are moved and another cycle starts. Fig. 5 shows a sketch diagram of a multi-station SMD placement machine (adopted from Csaszar et al., 2000a,b).

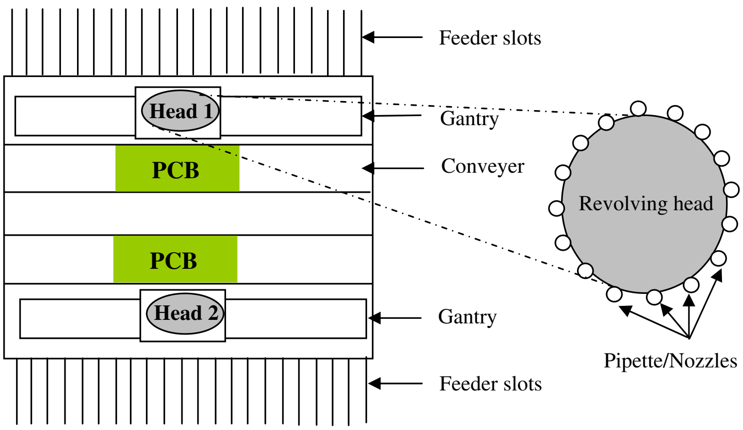


Fig. 4. A dual-delivery SMD placement machine (adopted from Tirpak et al., 2000).

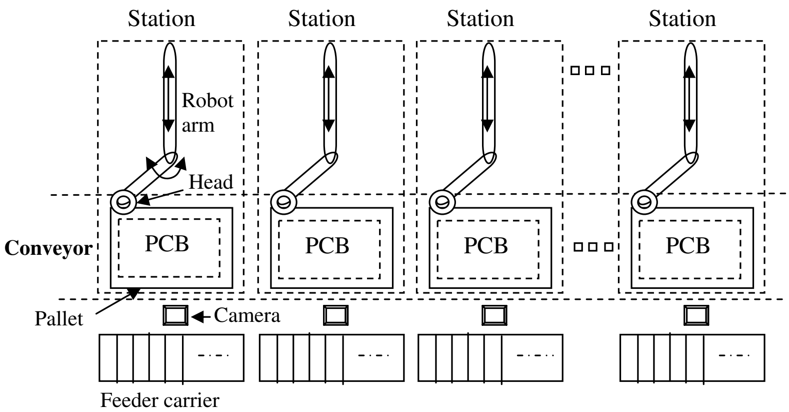


Fig. 5. A multi-station SMD placement machine (adopted from Csaszar et al., 2000a,b).

### 3.3. Turret-type placement machine

This machine type is usually called a chip shooter machine (Grunow et al., 2004; Ho and Ji, 2003; Moyer and Gupta, 1996a,b, 1997, 1998) or a concurrent chip placement machine (Yeo et al., 1996). Its placement mechanism is mounted on a rotating turret (drum or carousel) and has multiple placement heads. The heads rotate between fixed pickup and fixed placement points (Burke et al., 1999; Bentzen, 2000; Gastel, 2002).

While a pick operation is taking place, a placement operation can be performed at the same time (assuming there is component to be mounted) (Ellis et al., 2001; Klomp et al., 2000). Then, the feeder rack moves in order to position the next feeder in readiness for the next pickup operation. The PCB table simultaneously moves in order to position the next placement location after completion of the current placement operation. In fact, the movements of the PCB table, feeder carrier and turret may take place concurrently (Crama et al., 1996). Actually, the $i$th placement operation and the $(i+k)$th pickup operation (where $k$ is half of the sum of available heads) do not have to be performed concurrently, but are required to be done between the same two turret rotations (Crama et al., 1996). Typically, this machine has 12–24 placement heads, each equipped with three to six pipettes/nozzles which can be changed on-the-fly (Gastel, 2002). Due to the modus operandi of the machine, the rotating turret is only capable of simultaneously holding components up to half of the number of available heads.

While the turret rotates, several parallel operations are performed. Before arriving at the placement station, the picked component will undergo the following operations: a visual inspection of the component for orientation and diagnostics; a component ejection if the component is rejected, or otherwise the component is oriented for placement (Bard et al., 1994).

After passing the placement station, the nozzles are set up and reoriented for the next pickup operation. These are parallel operations that are dominated by the pickup and placement operations (Bard et al., 1994). In general, the PCB table can immediately move to position the next placement point at the placement station once the current placement operation has been completed. Similarly, the feeder rack can immediately move to position the next component at the pickup station after the completion of the current pickup operation. However, the turret rotation can only start after both the pickup and placement operations have been completed. Gastel (2002) argued that, in practice, the PCB table movement is the determining factor (in most cases) of the throughput rate of turret-type SMD placement machines compared to the turret rotation time.

Gastel (2002) has addressed some disadvantages of the turret-type placement machine:

(a) The movement of the PCB table is restricted by the acceleration forces on the pre-mounted components. If larger size components (referred to as slow components) have been placed onto the PCB, then movement of the PCB table will become slower.
(b) The accuracy of the machine is limited by the movement of the PCB table and the vibrations from the moving feeder carrier.
(c) Use of a tray feeder is not possible.

(d) An intelligent motorised feeder is required to perform pick corrections (to ensure an accurate pickup point) for small components.
(e) Due to the moving feeder carrier, a long footprint is required by the machine.

Due to a restriction of the mechanical structure of the turret head, the machine is not capable of performing a simultaneous pickup (concurrently pick many components) or simultaneous placement (concurrently place many components). However, due to many concurrency operations, this type of machine is still popular for high-volume production (Grunow et al., 2004).

Fig. 6 shows a sketch diagram of the Fuji CP IV/3, a turret-type SMD placement machine (adopted from Klomp et al., 2000).

### 3.4. Multi-head placement machine

Bentzen (2000) refers to the multi-head placement machine as a pick-and-place machine whilst Grunow et al. (2004) refer to it as a collect-and-place machine. The multi-head placement machine is the most flexible machine in that it can handle a wide range of component packages (Bentzen, 2000; Van Laarhoven and Zijm, 1993). The multi-head placement machine differs from the turret-type machines in the component transportation mechanism (Bentzen, 2000). It uses an $X$–$Y$ gantry head to transport components from component feeders and then place them onto the PCB, whereas the placement head of a turret-type machine is rotated to pick up the component at a fixed pickup location from a moveable feeder carrier and then places it at a fixed placement location of the moveable PCB table. Fig. 7 shows an example of a multi-head placement machine.

Jeevan et al. (2002) classified the multi-head placement machines into two types. The first type has a stationary PCB table and a feeder carrier with the arm and head being able to move concurrently in the $X$–$Y$ axis to perform the pick-and-place operations. Another type has an $X$–$Y$ motion table and a moveable feeder carrier with the arm and head travelling between the fixed pickup and placement locations (Jeevan et al., 2002).

We also classified a machine that has a turret (revolver) head located on top of the arm as the first type of multi-head machine (Ayob et al., 2002). An example of this machine type is a SIPLACE F (shown in Fig. 8) which has been used by Grunow et al. (2004). SIPLACE F has two stationary feeder carriers, one (or two) stationary PCB table(s), a single gantry revolving (turret) head equipped with six or twelve pipettes, a vision camera and a tool bank to permit automatic nozzle changes.

Typically, the tour of the heads begins by picking up a set of components from the feeders (assuming the heads are equipped with the correct nozzles, otherwise nozzle changes are required). This can be done simultaneously or sequentially (depending

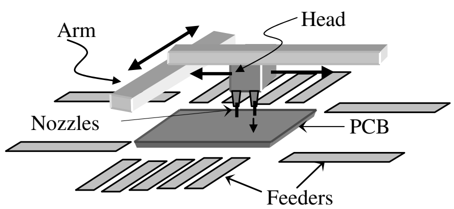


Fig. 7. A multi-head SMD placement machine.

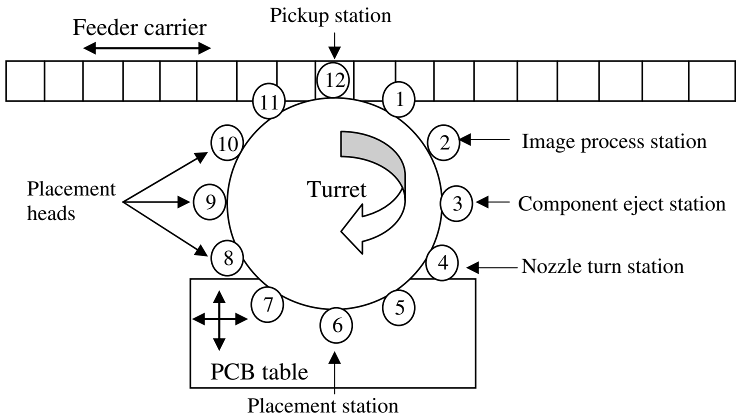


Fig. 6. The Fuji CP IV/3 (a turret-type SMD placement machine) (adopted from Klomp et al., 2000).

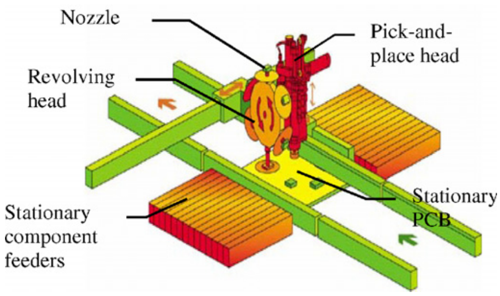


Fig. 8. A multi-head SMD placement machine with a revolver head (adopted from Siemens, 2005).

on the pickup positions). Due to the kinematical properties of the machine, a revolving multi-head machine is only capable of performing a sequential pickup where the revolving head is rotated to ensure the correct nozzle is used for each component pickup. In spite of this, it is still capable of picking up a set of components from the various component feeders in each subtour. Then, the head and the arm are positioned (moving in the *X*- and *Y*-direction simultaneously for the first type of multi-head machine) over the point where the component will be placed. Next, the pipette moves down (*Z*-direction) in order to place the component before returning to its original position. These steps are repeated for the remaining locations on the board that have to be placed in the same subtour. For a revolving multi-head machine, the head performs stepwise rotary movements (to position the correct component for the next placement) while the robot is travelling in *X*–*Y* direction to locate the head at the appropriate placement points. Therefore, the time required for placing (or picking) a component using a revolving multi-head machine is dictated by the maximum of the robot travelling time in the *X*- or *Y*-direction or a rotational cycle time of the revolving head (Grunow et al., 2004), plus the time for the pipette to move up/down for placing (or picking) a component, etc. Whereas, for the first type of multi-head placement machine, the time required for placing (or picking) a component is only dictated by the maximum of the robot travelling time in the *X*- or *Y*-directions (Ayob and Kendall, 2003a,b), plus the time for the pipette to move up/down for placing (or picking) a component, etc.

### *3.5. Sequential pick-and-place machine*

The operational method of this machine type is similar to the multi-head SMD placement machine, except that it can only pick-and-place one component in a subtour. Grunow et al. (2004), called this machine type a pick-and-place machine and described the machine characteristics as having a single moveable head (robot arm) with a stationary PCB table and feeder carrier. Fig. 9 shows a sketch of a sequential pick-and-place SMD placement machine. Previous works which focused on this machine type do not discuss the feeder carrier and PCB table movements. Therefore, we assume both of them can be stationary or movable. An example of the machine type is a Panaset RH (Leipälä and Nevalainen, 1989) that has an *X*–*Y* motion table and moveable feeder carrier with one head travelling between the fixed pickup and placement locations.

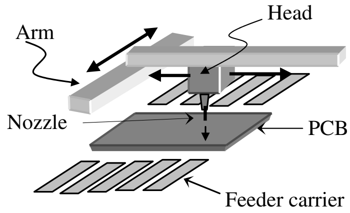


Fig. 9. A sequential pick-and-place SMD placement machine.

## 4. Models and heuristics

Since the optimisation of the SMD placement machine is a machine specific approach, this section surveys the relationships between machine technologies, models and heuristic methods and addresses some optimisation issues of the machine types.

### *4.1. Models and heuristics for dual-delivery surface mount device placement machine*

Since the two gantries cannot access the PCB simultaneously (as they could collide), their pick-and-place operations should be properly scheduled (Sun et al., 2005). To avoid collisions, a gantry that completes the pick operations should wait until the other gantry finishes its placement operations, and vice versa. Unlike the other types of SMD placement machine, the efficiency of dual-delivery SMD placement machines is largely determined by the gantry workload as well as the gantry scheduling (Sun et al., 2005). However, in the Motorola factory, the gantry workload was not necessarily balanced since the same feeder setup was used for both feeder carriers of every machine (Tirpak et al., 2000). The assembly cycle time can be computed as a sum of the maximum durations of the pick-and-place cycles between the two heads (Tirpak et al., 2000).

Ahmadi et al. (1988, 1991) emphasised exploiting the concurrency operations in scheduling this machine. Their approach attempts to assign the components to the slots in order to balance the workload of both heads as well as minimising nozzle changes. Due to the extensive setup time of the feeders, they paid more attention to feeder setup/changeover time by assigning components to slots when producing many PCBs with many different board types. However, the recent advancement of the SMD placement machine technology has diminished the importance of feeder setup times (Bard et al., 1994). Some of the latest technology in placement machines (see for example Mydata, 2002; Dima, 2003) have smart feeder carrier(s) that can automatically detect the exact availability and location of each component type on the feeder slot, allows a feeder changeover while the machine is running and does not insist on a fixed feeder location (i.e. we can place the component feeders at any feeder slot).

Both Ahmadi et al. (1988, 1995) and Grotzinger (1992) recognised the criticality of improving the feeder movement in order to increase the machine throughput. They employed a hierarchical framework, comprising three optimisation problems, consisting of component allocation and partitioning, placement sequencing, and feeder setup.

Safai (1996) firstly balanced the assignment of the placement points to both heads. They eliminated head contention by assigning each nozzle that has no duplication in the tool bank, to only one of the heads. Their decision to assign the components to the nozzle of both heads is made using a greedy approach so as to minimise the total assembly cycle time including the nozzle change cost. They argued that the solution quality produced by their approach was superior to a solution produced by a human expert.

Tirpak et al. (2000) utilised an adaptive simulated annealing algorithm in solving three optimisation problems (feeder, nozzle and placement) for the Fuji NP-132 machine. At each iteration, a new candidate solution is generated. These solutions include a nozzle setup, a feeder setup and a placement sequence for the two heads. Cheapest insertion and nearest neighbour constructive heuristics produce a placement sequence. Feeder and nozzle setups are generated by a constraint satisfaction swapping heuristic. Results, from a Motorola factory, show a 3–12% improvement over the original assembly times.

Recently, Sun et al. (2005) employed a genetic algorithm to simultaneously solve the problem of component allocation and feeder setups in the context of a single machine problem. In order to maintain the consistency in evaluating the solution quality at each iteration, they solved the other problems (i.e. component pick-and-place sequencing, gantry scheduling etc.) as simply as possible. Indeed, Sun et al. (2005) argued that the simultaneous pickups and the number of pickups are crucial for assembly cycle time reduction and they do not rely on the component placement sequencing, gantry scheduling etc. Therefore, Sun et al. (2005) represented the fitness function of the chromosome (i.e. feeder setup) with the maximum workload of the two gantries. They estimated the gantry workload based on realistic moves and pickup times in order to balance the gantry workloads, whereas other works on multi-station or multi-head machines, only took a summation of a standard mounting time to balance the workload. They observed that the combination of roulette wheel selection and cycle crossover (CX) is more effective when compared to ranking-CX, roulette-PMX (roulette and partially mapped crossover) and ranking-PMX. Experimental results on real datasets showed that the proposed algorithm is capable of producing a solution of acceptable quality. However, as the GA is computationally expensive, the approach is more realistic when applied in off-line mode rather than on-line mode.

### *4.2. Models and heuristics for multi-station surface mount device placement machine*

Due to the constraints that each station in the multi-station SMD placement machine work concurrently and all stations share the common conveyor system, the synchronisation between conveyer step cycles is the most crucial factor for optimising machine throughput (Csaszar et al., 2000a). The assembly cycle time of the machine can be computed as the sum of the maximum completion time of stations in each conveyer step (Csaszar et al., 2000a). Based on the fact that the robotic arm can move simultaneously in $X$–$Y$ axes, Csaszar et al. (2000a) use a chebychev distance (refer to Section 4.3) for calculating the assembly cycle time where the assembly cycle time is proportional to the robot travelling distance. They observed that in most cases, the seek time (the time taken by the robot to travel between PCB and feeder carrier) is solely dependent on the *Y*-coordinate of the recent placement point.

Shih et al. (1996) employed a simple descent search algorithm to optimise the component pick-and-place operation of a multi-station SMD placement machine. They also employed an expert system approach that focussed on optimising nozzle switching rather than the component pick-and-place operation.

Subsequently, a genetic algorithm approach was utilised by Wang et al. (1999) to optimise the feeder setup for the Fuji QP-122, a multi-station SMD placement machine. A penalty function was employed to deal with the machine constraints. They found that the quality of solutions relies more on grouping a set of unique components in the same station, instead of ordering the components in the slots. Therefore PMX (partially matched crossover) crossover, that preserves the information of a group element, showed good performance. The elitist and tournament selection methods both perform well. By comparing with other optimisation methods, such as a human expert, vendor software, expert system and local search, they found that a genetic algorithm is suitable for solving the problem.

Csaszar et al. (2000b) employed a knowledge-based system to optimise the multi-station machine, which has a single head and a single nozzle per station. The system, designed to emulate human experts, divided the allocation problem into two subproblems; (1) the assignment of components to the stations, and (2) the arrangement of components within the stations (i.e. feeder setup). The expert system was split into four phases; (1) simulator pre-processing, (2) placement, (3) refining and (4) conversion. The system used an average of 16.14% fewer feeder slots than the vendor's software and throughput improved by 13.47–15.95%. By using a cost function comprising the number of placements together with the pick-and-place time they achieved better results than using just pick-and-place time.

In other work, Csaszar et al. (2000a) also optimised the same machine type by utilising a tabu search algorithm. Since the machine has many stations, they solved the problem of allocating components to the stations, feeder setups and component pick-and-place sequencing problem for each station. They partitioned the problem into two phases and solved them using a tabu search and a specific heuristic, respectively. Unfortunately, they do not explicitly explain how the original problems are solved using their proposed approach. Indeed, the results presented were insufficient to evaluate the effectiveness of their approach in solving the multi-station SMD placement machine.

To date, there are not many works which focus on optimising the multi-station SMD placement machine. This might be due to the complexity of the machine operation, which causes a great challenge in optimising the machine. In summary, some of the heuristics that have been applied to solve the multi-station SMD placement machines are expert systems (Csaszar et al., 2000b; Shih et al., 1996), genetic algorithms (Wang et al., 1999) and tabu search (Csaszar et al., 2000a).

### *4.3. Models and heuristics for turret-type surface mount device placement machine*

Many heuristics/meta-heuristics have successfully been applied for the optimisation of the turret-type placement machine; such as genetic algorithms (Ho and Ji, 2003; Khoo and Loh, 2000; Leu et al., 1993) and greedy approaches (Ellis et al., 2001; Klomp et al., 2000; Kumar and Luo, 2003).

Since the PCB table moves simultaneously and independently in *X*- and *Y*-directions, the chebychev distance (i.e. $\max(|\Delta x|,|\Delta y|)$ where $|\Delta x|$ and $|\Delta y|$ are the distances between two points in *X*-coordinate and *Y*-coordinate, respectively) can be used to determine PCB table movement time (Francis et al., 1992). The turret rotation time is dictated by the component with the slowest turret rotation rate (from those currently being held on the head), since larger and heavier components are more difficult to hold in place by the suction nozzle and must move more slowly (Ellis et al., 2001). Due to the various moving parts of the turret-type machine, which have different speeds, Leu et al. (1993) suggested that, the total assembly cycle time should be used as the objective function in optimising the throughput of the machine. In fact, this is also applicable to the other machine types since the throughput of the machine is a function of assembly cycle time.

The time taken to assemble each component using this machine is dictated by the maximum time of the PCB table movement, turret rotation or feeder movement (Leu et al., 1993). In fact, due to the various moving parts of the turret-type machine, Moyer and Gupta (1996b) argued that the coordination is a crucial factor. They highlighted that the following coordination is required between:

(a) Turret rotation and feeder positioning.
(b) PCB table movement and turret rotation.
(c) PCB table movement along *X*- and *Y*-axis.
(d) Component pickup and component placement.
(e) PCB table movement and feeder positioning.

Since turret rotation is an unavoidable movement, Leu et al. (1993) argued that the optimal solution is achieved if the assembly cycle time is only dictated by the turret rotation movement time. However, since the component pickup-and-placement operations only occur after each turret rotation (i.e. they are not concurrent with the turret movement), we suggest that the optimal solution is achieved if the assembly cycle time is only dictated by the turret rotation movement time plus the total time for component pickups/placements (where both the component pickup and placement operations should happen concurrently in the case of an optimal solution).

A two-link GA was devised by Leu et al. (1993) to simultaneously optimise the component pick-and-place sequence and feeder setup of the turret-type machine. Leu et al. (1993) defined a sequence of genes as a link. For a PCB (printed circuit board) having *N* components, they represented the placement/insertion sequence as a list of numbers between 1 and *N*. The first link represents the assembly sequence whilst the second link represents the feeder arrangement. Four genetic operators were applied to each link: crossover, inversion, rotation and mutation. Leu et al. (1993) used a total assembly cycle time as a fitness function, with the aim being to minimise the assembly cycle time. They argued that the solution found was almost optimal.

De Souza and Lijun (1994, 1995) incorporated a knowledge-based component placement system with a TSP algorithm to solve the component pick-and-place sequencing problem for a turret-type SMD placement machine. The algorithm first groups the components by type, then by a quantity threshold and finally by the device size. They found that their approach is more practical and superior to the software supplied by the machine vendor. They obtained a 24% improvement of the board travel distance after applying their approach to the machine generated sequence.

By formulating a feeder setup as a quadratic assignment problem (QAP), Moyer and Gupta (1996a) proposed two heuristic approaches to optimise the feeder setup. The first heuristic is a constructive heuristic that assigns component feeders to slots based on the switching between component types according to the predetermined component placement sequence. The second heuristic is an improvement heuristic that seeks better assignments by exchanging between pairs of slots. They aim to minimise the feeder travelling distance. They obtained better feeder setup, compared to Leu et al. (1993) in terms of feeder travelling distance. However, the approaches do not necessarily reduce the assembly cycle time since it is dependent on both the feeder setup and the component pick-and-place sequence. By focusing on reducing the feeder travelling distance, they only reduce the time required for feeders to supply the required components to the turret head. Of course this will help in minimising the assembly cycle time if the feeder movement time is dominating. Unfortunately, this is not the case since the PCB *X*–*Y* movement is the determining factor (in most cases) of the throughput rate of turret-type placement machine compared to the turret rotation time (see Gastel, 2002).

As an extension, Moyer and Gupta (1996b) applied the Acyclic Assembly Time (AAT) algorithm to simultaneously improve the quality of the component pick-and-place sequence and feeder setup. The aim of the AAT algorithm is to generate a placement sequence and feeder setup that exploits the unique characteristics of the turret-type machine. In the case where the PCB is still moving, to locate the proper placement point, the AAT model allowed the other mechanism to advance to the next position rather than keep idling. Again, Moyer and Gupta (1996b) argued that on average, their approach is superior to Leu et al. (1993) and De Souza and Lijun (1994).

By expanding the heuristic developed by Leipälä and Nevalainen (1989) (that was applied to solve a sequential pick-and-place machine), Sohn and Park (1996) simultaneously improve the component pick-and-place sequence and feeder setup of the turret-type machine. The component feeders were assigned to slots based on a frequency of use, and then a pick-and-place sequence is determined by also considering feeder setup.

Yeo et al. (1996) employed a rule-based approach to simultaneously solve the component placement sequencing and feeder setup problem of the Fuji

IV SMD placement machine. The Fuji IV can be optimised by meeting the following conditions (Yeo et al., 1996):

(a) A travelling distance, by the PCB table, for placement operations should be at most 20 mm in *X*- or *Y*-directions;
(b) A feeder movement to locate the component for the next pickup operation should be at most one slot distance.

Therefore, Yeo et al. (1996) arranged the components on the feeder slots based on the component placement sequence so that as many consecutive pickups as possible can happen at adjacent feeder slots. They aim to reduce the *X*–*Y* PCB table and feeder carrier movements in order to maximise the machine throughput. Four rules were developed, these being:

(a) Rule 1: Sequence the component placement operation in the shortest travelling route of the *X*–*Y* PCB table. They viewed a problem of minimising the *X*–*Y* PCB table distance as a TSP and solved the problem using a nearest neighbour heuristic.
(b) Rule 2: Arrange the component feeders to slots in such a way that a minimum pickup time can be achieved. The goal is to minimise the feeder translation movement. This rule allows for feeder duplication (that is the same component type can exist at various feeder locations).
(c) Rule 3: Mount identical components in one pass in order to take into account the limitation of feeder slots in the feeder carrier.
(d) Rule 4: Sequence the component placements starting from smaller sized to larger sized components in order to reduce the component processing time (at the rotary turret) and skewing of components due to inertia.

Solution qualities are measured using the total distance traversed by the *X*–*Y* PCB table and the actual machine cycle time per PCB. Computational results showed that the proposed approach outperformed the Fuji machine optimisation software in terms of the PCB table movement and the actual machine cycle time. Based on a typical production of 1000 PCBs per day, the approach could yield an improvement of about 7000 PCBs per month.

Klomp et al. (2000), considered a feeder and its corresponding cluster (that is, a set of locations served by a single feeder) as a node in a complete graph. Their results demonstrated that the gap between the solution found and the lower-bound was about 20% in the three machine case. This indicates that the movement of the PCB table and feeder rack are all within the turret rotation time and so can be disregarded as part of the optimisation process.

Khoo and Loh (2000) formulated the problem as a multi-objective optimisation problem and utilised a genetic algorithm (GA) to generate the pick-and-place sequences and feeder setup. Their results slightly improved on those of Leu et al. (1993).

Constructive heuristics, developed by Ellis et al. (2001), generated feeder setups and component placement sequences. The heuristics grouped components together that had similar PCB table speeds and turret rotation speeds. A surrogate function approximated penalties for feeder carriage movements, changes in turret rotation speed and changes in PCB table speed. After the initial feeder setup and placement sequences have been constructed, a 2-opt heuristic is used to search for placement time improvement. The time to generate the initial solutions was achieved in less than three minutes. However, although the final solution was close to the lower-bound, the time to generate improved solutions was high, and become worse as the problem size increased. For example, the initial solution can be produced in 2 seconds, while improvement requires 1586 seconds for the smallest PCB. Larger PCBs requires 164 seconds to generate an initial solution and 43,200 seconds to compute the improved solution.

Kumar and Luo (2003) viewed the placement sequencing problem on a Fuji FCP-IV, as a "*generalised TSP*" where not only the overall travel time depends on the travel sequence (as in the standard TSP), but the distances between any pair of nodes is sequence dependent. For example, if the 4th pipette is used for the 1st pickup in a subtour, then the robot travelling distance for the other pickups are not just dependent on the distance among pickup points, but also includes, which pipette is used to hold the current pickup nozzle and which pipette is used to pickup the previous component. Kumar and Luo (2003) also addressed the fact that the feeder carrier movement is considerably slower and, therefore, the whole process is dependent upon this movement although the movement of the PCB table and feeder carriage, and the rotation of the turret, take place at the same time. They show that an optimal tour for the distance matrix provides an optimal placement sequence (for a given slot assignment) such that it visits all components of the same part number consecutively. If switching components is required, the feeder carriage should be moved to the adjacent feeder slots in order to obtain the optimal solution. Consistent improvement of over 25% in overall assembly time was achieved, compared to the solution generated by the SMD placement machine optimiser at Lexmark, Inc. For some cases, the rotation of the turret, which takes fixed time, determines the travel time, and thus implies that their optimisation algorithm will be more efficient on machines with faster turret rotation or with smaller rotation angles. However, Kumar and Luo (2003) overlooked the feeder transportation time (i.e. time taken by the feeder to transport the next component to the pickup position). If the feeder transportation time is longer than the turret rotation time, then the optimal solution does not hold if all components of the same part number are placed consecutively. Moreover, in some SMD placement machines, the feeder transportation is longer than the time taken for the feeder carrier to move to the adjacent feeder slot.

Ho and Ji (2003) introduced a hybrid genetic algorithm (HGA) integrated with three heuristics to solve the component placement scheduling and feeder setup problems for a turret-type SMD placement machine. Their genetic algorithm represents a chromosome as two-link structures. As in (Leu et al., 1993), the first link represents the sequence of the component placement whilst the second link represents the feeder setup. The initial chromosomes (i.e. initial solutions) are generated using a nearest neighbour heuristic for the first link whilst the second link is randomly generated. During the initialisation stage, each chromosome is improved using an iterated swap procedure and a 2-opt local search. The iterated swap procedure is performed on the first link of each initial chromosome generated by the nearest neighbour heuristic as well as each offspring produced by the genetic operators. A 2-opt local search heuristic is applied to the second link in order to improve the feeder setup of each initial chromosome or offspring generated by the genetic operators. The fitness function represents the total assembly time. Roulette wheel selection is used to select chromosomes to undergo genetic operations. The HGA used a modified order crossover operator and two mutation operators; a heuristic mutation and inversion mutation. Ho and Ji (2003) argued that the HGA is superior to a simple GA used by Leu et al. (1993). They obtained better initial solutions, better final solutions with smaller population sizes and fewer iterations compared to Leu et al. (1993).

Other works which report improving the turret-type SMD placement machine include Ellis et al. (2002), Ng (1998, 2000) and Ong and Tan (2002).

### 4.4. Models and heuristics for multi-head surface mount device placement machine

A lot of work has been carried out optimising the component pick-and-place sequence of the multi-head SMD placement machine such as Altinkemer et al. (2000), Ayob and Kendall (2003a,b, 2004), Burke et al. (2001), Crama et al. (1990, 1997), Ho and Ji (2004), Jeevan et al. (2002), Van Laarhoven and Zijm (1993), Lee et al. (1999) and Magyar et al. (1999).

Van Laarhoven and Zijm (1993) used a hierarchical approach to sequentially solve the optimisation problems of a set of placement machines. These are (i) an assignment of nozzles to the head/pipettes on each machine, (ii) an assignment of the components to the machines, (iii) an assignment of component feeders to the feeder slots (for each machine) i.e. feeder setup, (iv) for each machine, a partition (cluster) of the set of components/placement points to indicate which components/placement points have to be placed by the machine in each sub tour, where at most three components are involved (as the machine has three nozzles), (v) for each machine, a sequence of component clusters (or subtours) to perform an overall tour and determine the optimal sequence for placing the components within the cluster. The optimisation problems are solved sequentially by adapting a simulated annealing approach. They argued that, on average, the approach performs well in balancing the workload over the machines.

To solve this machine optimisation problem, Lee et al. (1999) employed dynamic programming and a nearest neighbour TSP to design heuristics. Their approach started with the construction of feeder reel-groups, then the assignment of those feeder reel-groups and, finally, the sequencing of pick-and-place movements. They chose a nozzle for each feeder reel in an effort to reduce the number of nozzle changes. Next, they assigned the reels to heads so that each has about the same workload. As nozzle changes are expensive, and the number required is proportional to the number of nozzles used, Lee et al. (1999) first determined the order of nozzle changes before optimising the pick/place movements. Their simulation results showed an average saving of 18% in PCB assembly time over the heuristic algorithm supplied by Yamaha.

Magyar et al. (1999) tackled the problem of determining the sequence of component pickup-and-placement; scheduling the assignment of different nozzles (tool) to the robot head; and feeder setup by adopting a hierarchical problem solving approach. They studied the problem of a GSM machine (Universal, 1999) that is a multi-head SMD placement machine that has one placement head equipped with four pipettes and each of them can handle one component. Firstly they solved the feeder setup problem by using a greedy local search that searched for maximising the number of gang-pickups (i.e. a simultaneous pickup where many components are picked up at a given time). The output of the feeder setup is given as an input for a nozzle optimisation procedure whilst the output of the nozzle optimisation procedure, served as input to the component pick-and-place procedure that also employed a greedy local search heuristic. Their system significantly improved the assembly cycle time when tested on real industrial products.

Since the head and arm can move simultaneously in the $X$- and $Y$-axis, Altinkemer et al. (2000) used the chebychev distance to calculate maximum distance movements in either the $X$- or $Y$-direction. Two cases were considered. When the feeder carrier is moveable, the feeder of the component type that will be used next can move towards the tool bank while the head is mounting another component type. Therefore, the distance between the feeder carrier (pickup point) and the points on the PCB (placement point) can be measured from a fixed pickup point (i.e. the point next to the tool bank) to the appropriate placement points. The simultaneous movement enables each component type to have the same origin and destination points, allowing the formulation to be an independent capacitated vehicle routing problem (VRP). Since the distance between a point on the PCB and feeder is not dependent on where the component is located among feeders, the feeder setup problem does not have to be integrated with the pick-and-place sequencing decisions. Of course, in this case, the distance between a point on the PCB and feeder carrier is not dependent on where the component is located among feeders. However, a delay will occur if the feeder carrier is not capable of bringing the required component to the pickup point next to the tool bank before the robot arm arrives at the pickup point for each pickup operation. That is, the robot arm has to wait for the component feeder to bring the appropriate component so that it is next to the tool bank. This factor suggests that the arrangement of components on the feeder slots (i.e. feeder setup) also affects the pick-and-place operation. Similarly, a delay can also occur if the PCB table is not capable of positioning the required PCB point before the robot arm arrives at the fixed placement location. Therefore, modelling this problem as an independent capacitated VRP, by just considering the distance between the points on the PCB and a fixed point next to the tool bank, might not be an effective way of improving machine throughput. For the case where the feeder carrier is not moveable, the problem is first solved as a VRP for each component type at every possible feeder slot location. Then this feasible solution is used as the cost of assigning the component type to the particular feeder location. They argue that their integrated algorithm provides a feasible solution with an error gap less than or equal to the maximum error gap of the VRP costs.

Burke et al. (2001) introduced a three phase heuristic that deals with the assembly of multiple printed circuit board types with different batch sizes on a single machine without set-ups between board types. Experimental results show this approach to be promising.

Jeevan et al. (2002) employed a GA to optimise the component pickup-and-placement of the multi-head SMD placement machine. They represent the distance of a TSP tour (i.e. a total pickup and placement distance) as a fitness function. However, they do not explicitly discuss their mathematical model and chromosome representation in the paper.

Recently, Ho and Ji (2004) applied the same approach that was introduced in (Ho and Ji, 2003) to solve the component placement scheduling and feeder setup problems for a multi-head placement machine. In solving a multi-head placement machine, Ho and Ji (2004) claimed that their approach also outperformed a simple GA used by Ong and Khoo (1999) in terms of the total travelling distance of placement head.

More recently, Grunow et al. (2004) distinguished the optimisation problem of the multi-head SMD placement machine into four subproblems. These are (i) the allocation of component feeders to feeder carrier slots (i.e. feeder setup); (ii) the assignment of placement points to the various subtours of the placement head; (iii) the sequence order of the placement operations within a subtour and (iv) the sequence order of the subtours in an overall tour. These subproblems are solved using a three-stage procedure. In the first stage, the subproblem (i) is solved by applying a greedy algorithm to arrange component feeders adjacent to each other based on the strength of the neighbourhood relations. The second stage solved the subproblems (ii), (iii) and (iv) by modelling them as a vehicle-routing problem. Given the feeder setup obtained from the first stage, Grunow et al. (2004) sequence the component pick-and-place operations using different adaptation of savings heuristic (Clarke and Wright, 1964). The final stage improves the feeder setup and the component pick-and-place sequence by using a random descent 2-opt swapping procedures. Since the optimal solution is unknown, due to the problem complexity, they derived a lower bound based on the kinematical properties of the machine type. Due to the concurrency movements of the machine and the fact that revolving head rotation is an unavoidable movement, the revolving head rotational cycle time (i.e. the time taken by the revolving head to index the adjacent pipette/nozzle for subsequent placement operation) constitutes a lower bound of the pick-and-place operation of the machine. However, Grunow et al. (2004) do not explicitly discuss how they compute the lower bound. The issue of different component types which require different nozzle types has not been addressed. If this issue is considered, the question arises as to how many steps the revolving head needs to rotate to position the correct nozzle for picking up a component from the feeder and similarly for placing a component. That is, do they use a constant rotational cycle time (which they should do) to compute the lower bound of the pick-and-place operations? The subproblem of assigning the nozzles to the rotary head (i.e. where to locate the nozzle at the rotary head) which is not considered in Grunow et al. (2004) is left for future work. This will then closely models the real-world problem. However, experimental results showed that the heuristics proposed by Grunow et al. (2004) are very efficient and can produce a high quality solution which is close to the theoretical lower bound (e.g. for smaller size PCB's, they obtained an average deviation from the lower bound of 2.32%).

Our previous works in (Ayob and Kendall, 2003a,b, 2004, 2005b,c,d) also investigated improving the pick-and-place operation of the multi-head SMD placement machines. In Ayob and Kendall (2003a,b, 2005b) we modelled the multi-head machine (of the first type, referred to in Section 3.4) that has a stationary feeder carrier, a fixed PCB table and a positioning arm head that is equipped with four or eight pipettes. There are many factors involved in determining the efficiency of pick-place operations of multi-head SMD placement machines such as the grouping of PCB points (also referred to as placement points) to a subtour, nozzle assignment, pickup and placement sequencing etc. These pose a number of scheduling problems in optimising the multi-head SMD placement machine. These are:

(a) Assigning PCB points to a subtour. As the head (robot arm) is equipped with many pipette/nozzles, the problem is to determine the sets of PCB points that will be visited by the robot arm (i.e. to pick-and-place a component) in the same subtour.
(b) Assigning the pickup/placement pipettes. The issue is to determine which pipette should be used to pickup/place a component such that we minimise the pickup/placement time. If we consider a nozzle size selection, where different nozzle sizes are required to handle different types of component packaging (which more closely mirror the real-world machine problem), we also have to minimise the nozzle change operation in optimising the component pick-and-place sequencing problem. This is a crucial factor since the nozzle change operation is very time consuming (Crama et al., 1990; Jeevan et al., 2002; Magyar et al., 1999; Safai, 1996; Shih et al., 1996). For example, the HP-110 takes about two seconds for nozzle changeover. We must also ensure that the PCB points will receive the correct component type. As the pipettes are located at a fixed position at the end of pickup/placement heads, the cost of picking up (or placing) the next component is also dependent on the pipette/nozzle to be used, the current location of the head and the current pipette/nozzle used to pick up (or place) the current component.

In general, a good pickup pipette/nozzle assignment may allow many simultaneous pickup and simultaneous vision (that can also enhance the machine throughput) and may also reduce the number of nozzle changes.

(c) Sequencing the component pickups. The problem is to determine the sequence of picking up components in a subtour to optimise the pickups. This subproblem can be modelled as a TSP problem but with a different initial and ending city (i.e. placement and pickup points in this case) without ignoring the component specific nozzle and ensuring that the PCB points will receive the correct component type. However, as argued by Kumar and Luo (2003), the pick-and-place sequencing problem on an SMD placement machine can be viewed as a "*generalised TSP*" where not only the overall travel time depends on the travel sequence (as in the standard TSP), but also the distances between any pair of nodes is sequence dependent.
(d) Sequencing the placement operation. The problem is to determine the sequence of placing components in a subtour to optimise the placement operations. As discussed above (see subproblem c), this subproblem can also be viewed as a "*generalised TSP*".
(e) Sequencing the subtours. The aim is to optimise the sequence of subtours in order to minimise the overall cycle time.

The subproblems (a), (c), (d) and (e) were also addressed by Grunow et al. (2004).

In Ayob and Kendall (2003a), we proposed a methodology for an adaptive scheduling approach to sequence the pickup-and-placement of components by utilising the advancement of the new machine technology that allows the machine to continuously work without interruption even though there are some components missing, misallocated or being reloaded. We generated an initial schedule using a greedy constructive heuristic by only considering the available placement points. The initial solution can immediately be used to assemble components for the first PCB. While the placement machine is assembling components, we propose to employ the CPU free time (whilst the robot arm is moving) to improve the initial schedule by using a randomised 2-opt descent search technique. Thus, the subsequent PCB's may use the improved schedule. Our experimental result on two data sets show that we gain 36.60% and 43.29% (respectively) improvement on assembly cycle time over the initial schedule.

In Ayob and Kendall (2003b), we extend the work in (Ayob and Kendall, 2003a) by introducing a Monte Carlo based hyper-heuristic. By applying a hyper-heuristic (Burke et al., 2003a,b,c, 2005) approach, we do not have to concern ourselves with the trade-off between the optimisation of the important factors as this will be catered for within the hyper-heuristic. The Monte Carlo hyper-heuristic manages a set of low level heuristics based on our Monte Carlo acceptance criteria. The Monte Carlo acceptance criteria always accepts an improved solution and probabilistically accepts worse solutions, in order to escape from a local minimum. We developed three hyper-heuristics: Linear Monte Carlo (LMC), Exponential Monte Carlo (EMC) and Exponential Monte Carlo with counter (EMCQ). EMCQ will exponentially increase the acceptance probability if we have been unable to find a better solution for a long time (i.e. too long being trapped in local optima). However, EMCQ will exponentially reduce the acceptance probability as the search time increases. As EMC and EMCQ approaches do not require parameter tuning (all the parameters are automatically controlled based on the solution quality (with the exploration time and the duration of being trapped in local optima in the case of EMCQ)), these methods are simple and robust heuristic technique. Results showed that the EMCQ is a fast and robust heuristic that is also capable of producing good quality schedules.

In Ayob and Kendall (2005b), we extend the study, on the same problem, by employing a VNS (variable neighbourhood search) approach. We developed a variable neighbourhood Monte Carlo Search (VNMS), which employs a variable neighbourhood search (Avanthay et al., 2003; Hansen and Mladenović, 1997, 2001; Hansen et al., 2001) technique with an Exponential Monte Carlo with counter (EMCQ) acceptance criterion. The novelty of the VNMS approach (in the context of VNS) are the concept of three stages of neighbourhood search, using an EMCQ acceptance criterion at the VNS level and the shaking procedure that is only applied when the local searchers cannot find an improved solution. Results show that VNMS is capable of producing good quality and stable results (for smaller datasets) in solving the component pick-and-place sequencing on multi-head SMD placement machine. The proposed framework of

VNMS might be suitable for solving other types of SMD placement machines or even problems from other domains. However, the local searchers are problem specific.

The work in (Ayob and Kendall, 2004, 2005c,d) are devoted to modelling a real world SMD placement machine that is the hybrid pick-and-place machine (specifically a new DIMA machine called Hybrid P & P HP-110), a multi-head SMD placement machine. Ayob and Kendall (2004, 2005c,d) have collaborated with DIMA SMT System. This has provided an understanding of their HP-110 machine with regard to the specification and its operational method. The machine has four fixed feeder carriers (mounted on the four sides of the machine), a stationary PCB table, two vision cameras, a tool bank, a trash bin and a positioning arm head that is equipped with two pipettes. As the HP-110 has a single head equipped with two pipettes which can hold two nozzles, a good selection of nozzle pairs is important in order to minimise the number of nozzle changes to improve the efficiency of the machine. These works (Ayob and Kendall, 2004, 2005c,d) address the scheduling problem for a single machine and a single board type and we focus on the nozzle selection and the component pick-and-place sequencing.

There are various types of component packaging and each packaging type is associated with a certain nozzle type. Each component packaging type can be associated with more than one nozzle type, and vice-versa. The problem is more complicated when one component type can have more than one type of packaging. This means that each PCB point on the board can be placed with more than one component packaging type. The component packaging type can be recognised and aligned without vision camera (i.e. using mechanical alignment on fly), using small vision camera and/or large vision camera, depending on the component packaging specification. For the HP-110, the small vision camera is located to the left of the large vision camera. As such, for this machine, we can have a simultaneous vision and alignment operation if the left nozzle holds a small vision component and the right nozzle holds a large vision component. That is, the two components can be inspected simultaneously which leads to time saving. For the HP-110, it is more economical (in terms of assembly cycle time) to have both mechanical alignment components in the subtour (*MA*) rather than having both vision components since the *MA* subtour eliminates the time for moving to the camera and perform component recognition and alignment.

For the HP-110, the two pipettes on the placement head are fixed at positions such that a simultaneous pickup (*SP*) operation can happen if the distance between the two pickup points (of the same sub tour) comes within a user's defined tolerance. The *SP* subtour can also enhance the throughput of the machine.

For the HP-110, the feeder also takes a long time (i.e. about 0.5 seconds in this case) to transport a component from the component feeder to a pickup point. That is, once a component has been picked up from a feeder, we must wait about 0.5 seconds while another component is moved into position. Therefore we should avoid picking up from the same component feeder in a subtour. In addition, a pickup from the same feeder bank in a subtour is better (in term of assembly cycle time) than a pickup from different feeder banks.

In (Ayob and Kendall, 2004, 2005c,d), we use the average machine operation time given by DIMA to estimate the assembly cycle time as an evaluation for our heuristic performance. This is different from the evaluation function used in (Ayob and Kendall, 2003a,b, 2005b) (in which we only considered minimising the robot travelling distance and/or feeder carrier and PCB table movement). In fact, to date, none of work in this field uses the average machine operation time to evaluate the machine throughput. Many researchers are only concerned with minimising the robot travelling distance (and/or feeder carrier and PCB table movement) in order to improve the machine throughput (or particularly, the component pick-and-place sequence). The assembly cycle time of many SMD placement machine types is dependent on many factors such as nozzle changes, simultaneous pickup, simultaneous vision etc. (these factors are very machine dependent). Ignoring these factors in solving component pick-and-place sequencing might not be a good strategy. For example, solving the component pick-and-place sequencing by minimising the robot travelling distance without considering the nozzle change operation might incur many unnecessary nozzle changes, which is very inefficient. Of course, they might be able to produce a good quality solution. However, they may obtain a much better solution if the other factors are also considered. Moreover, as the speed of the robot arm (i.e. the arm and head) of the latest machines is very fast and the component density on the PCB increases (i.e. the distance among PCB points tends to be smaller), minimising the robot travelling distance is becoming a less significant factor for improving machine throughput. Indeed, due the acceleration/deceleration rate of the robot arm, the time taken for the robot arm to move short or longer distances might be fairly equal. Therefore, it is ineffective to just minimise the robot travelling distance in order to improve the machine throughput. For the purpose of optimising the component pick-and-place operation, exact information about the machine speed, acceleration/deceleration rate etc. is not necessary (as the machine is embedded with a control software for accurate movements/operations). The average machine operation time is adequate in guiding the search towards a better quality schedule. Moreover, including the machine speed, acceleration/deceleration rate etc. might introduce a more complex formulation for the objective function.

The work in Ayob and Kendall (2005c) proposed an on-line constructive heuristic that gives the highest priority to minimising the number of nozzle changes, then maximising simultaneous vision operations, simultaneous pickups and same feeder bank pickups. Ayob and Kendall (2005c) utilised a greedy search that can concurrently generate a schedule for the subsequent PCB points using spare CPU time during pick-and-place operations.

The subsequent work (Ayob and Kendall, 2004, 2005d) extends the work (Ayob and Kendall, 2005c) by introducing a mechanical alignment procedure and considering component types which can have more than one packaging, and may require a different nozzle for picking and placing the same component type due to the different packaging types that are encountered. The latter procedure more closely mirrors the real-world which previous work (Ayob and Kendall, 2005c) has not addressed. Indeed, the heuristic can also be applied in on-line mode that we proposed in Ayob and Kendall (2005c).

Based on our experience on solving the theoretical machine problem (Ayob and Kendall, 2003a,b, 2005b) and the real machine problem (Ayob and Kendall, 2004, 2005c,d), we found that, there is a gap between solving the real and theoretical machine problems. In solving a real machine problem, we use the average machine operation time to estimate the assembly cycle time as an evaluation for our heuristic performance instead of just using the robot travelling time (modelled as TSP problem). It is more realistic since the assembly cycle time is not only dependent on the robot travelling time but also relies on other factors such as nozzle change operations, feeder transportation time, simultaneous pickups, mechanical alignment pickups and simultaneous vision operations These issues have rarely (if ever) been addressed by previous researchers.

### *4.5. Models and heuristics for sequential pick-and-place surface mount device placement machine*

Ball and Magazine (1988) formulated the placement sequence problem as a type of directed postman problem. They show that the balance and connect heuristic can be applied to this problem.

Leipälä and Nevalainen (1989) treated the component insertion sequence as a three-dimensional asymmetric travelling salesman problem whilst the feeder setup was formulated as a quadratic assignment problem.

A linear programming approach has been applied by Kumar and Li (1995) to model the optimisation of feeder setup and component placement sequence for sequential pick-and-place SMD placement machines. They solved the problem by determining an assignment of pickup slots and a component assembly sequence for each individual nozzle. Various heuristics such as nearest neighbour, nearest insertion, furthest insertion, and random generation are used to construct an initial assembly sequence, and other heuristics such as 2-opt and 3-opt improve upon the initial solution. Simulation results show a consistent assembly time saving of 25% over the current approach used in the factory.

Ahmadi and Mamer (1999) have modelled the problem of sequencing the part types for placement and the problem of scheduling the movement between points on the PCB as a collection of interdependent travelling salesman problems. The computational results show that the approximation of the problem by a sequence of TSPs was able to produce significant increases in throughput.

Ong and Khoo (1999) employed a GA approach to simultaneously solve the component pick-and-place sequencing and feeder setup problems. The objective function, which represents a fitness function, was to minimise the travelling distance of the placement head. They applied a two-link GA proposed by Leu et al. (1993) to optimise the sequential pick-and-place SMD placement machine. They also addressed the advantage of allowing feeder duplication.

As the board and feeder carrier are simultaneously moved at different speeds during assembly, Fu and Su (2000), Hop and Tabucanon (2001a,b), Su et al. (1995), Wang et al. (1995, 1998) believe that robotic travel routing should be based on relative coordinates to obtain a better solution. In the dynamic pick and place (DPP) model, introduced by Su et al. (1995), the robot moves vertically along the *Y*-axis (in the optimal condition), while the PCB table and feeder rack move horizontally along the *X*-axis. The pickup and placement point are dynamically allocated. The optimal condition occurs when the robot travels only in the *Y*-direction, and no movement in the *X*-direction is observed (Wang et al., 1998). They modelled the sequential pick-and-place SMD placement machine. A more detailed review of these works is discussed in Ayob and Kendall (2005a).

## 5. Conclusions

This paper presented a survey of surface mount device (SMD) placement machine optimisations. In particular, the survey associated the models, assembly machine technologies and heuristic methods. We also addressed the optimisation issues of each SMD placement machine categories. We attempted to classify the SMD placement machine based on the specification and operational methods. The SMD placement machines may be arranged into five categories: dual-delivery, multi-station, turret-type, multi-head and sequential pick-and-place.

GA (genetic algorithm) approaches have been applied to optimise all types of SMD placement machines. Knowledge-based systems are also applicable for solving some type of SMD placement machine such as turret-type and multi-station. Tabu search, simulated annealing and integer programming are rarely used in solving SMD placement machine. As far as we concerned, none of the research in this field reported on applying variable neighbourhood search, hyper-heuristic and on-line scheduling approaches (except our work in Ayob and Kendall, 2003a,b, 2005b,c). This is, as yet, a largely unexplored research area in this field. Due to the complexity of the problem, which involves many machine constraints, much of the research in optimising the SMD placement machine utilised a greedy search heuristic which is very problem specific.

As the optimisation of the SMD placement machine is very machine specific, this work strongly suggests that researchers clearly define the machine characteristics and operational methods. For an evaluation and comparable purposes, this work also suggest that researchers clearly define their objective function which is usually not very clearly stated in many of the reported works in this field. It is more precise to formulate the main objective function in terms of optimising the assembly cycle time, CT, instead of optimising the head travel distance, PCB travel distance, feeder carrier travel distance, etc. since the machine throughput is a function of the CT. Moreover, due to concurrency operations, optimising one of the movements does not guarantee optimisation of machine throughput. Indeed, many other determining factors are involved in determining the efficiency of the SMD placement machine such as nozzle optimisation, component feeder transportation etc.

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