

A Nozzle Selection Heuristic to Optimise the Hybrid Pick and Place Machine

Masri Ayob and Graham Kendall

ASAP Research Group, School of Computer Science & IT, University of Nottingham, Nottingham NG8 1BB, UK
mxal@gxk@cs.nott.ac.uk

Abstract— In this paper we present a constructive heuristic to optimise the component pick and place operations of a hybrid pick and place machine, which is a new type of surface mount device placement machine. Since a nozzle change operation is very expensive (it significantly adds to the overall assembly time), the heuristic gives highest priority to minimising the number of nozzle changes. The ordered nozzle selection heuristic begins by choosing the best nozzle pair that is most effective for picking and placing components onto the printed circuit board (PCB). Next, we schedule all pairs of PCB points, that are expecting components from the chosen nozzle pair. Then, the nozzle pairs are re-ranked based on the availability of component feeders and the PCB points that need to be scheduled. Again, the best nozzle pair is chosen and the previous steps are repeated. When none of the selected nozzle pairs can pick and place two components in a sub tour, we schedule the one component sub tour. Finally, when all the available PCB points, have been scheduled, we then reoptimise the schedule by minimising the nozzles changes. Computational results are presented.

Keywords— *Component placement sequencing; tool selection; heuristic; optimisation; printed circuit board assembly.*

I. INTRODUCTION

SMD (surface mount device) placement machines are used to assemble components onto PCBs (printed circuit boards) have the ability to quickly place components. However, they present great challenges in optimising component placement sequences, feeder setups and component assignment, in order to improve the efficiency of the machine. When hundreds of electronic components of different shapes and sizes have to be placed at specific locations on a printed circuit board (PCB), finding an optimal robot travelling route is complicated and time consuming [1]. This problem is an NP-Hard problem and most practical instances are difficult to solve to optimality in a reasonable time [2]. In practice, a heuristic solution is highly desirable [1]. Heuristic algorithms can generate good solutions efficiently at a reasonable computational cost [3]. A lot of work has been done on improving the efficiency of SMD placement machines (see for example [1,2,3,4]) and Crama et al. [5] provides an exhaustive survey of some of the major optimisation problems arising in the area of production planning for the assembly of PCBs.

Crama et al. [5] classified the production planning problems into eight sub problems being assigning PCB types to product families and to machine groups, allocating component feeders to machines, partitioning component

locations on the PCB, indicating which components are going to be placed by each machine (for each PCB type), sequencing the PCB types, assigning component feeders to slots on the feeder carrier, sequencing the component's pick and place operations, component retrieving plans and a motion control specification. Normally, the decision as to which of the sub problems to be solved is based on which sub problem will minimise the assembly cycle time (Crama et al., [5]). However, the dilemma is that all the sub problems are intertwined and the question arises as to which one should be solved first. As a consequence, some researchers tackled the problem in an iterative manner, instead of a one-pass procedure through each of the sub problems. The technological characteristics of the SMD placement machine can also influence the nature of some of the problem to be solved and the formulation of the associated models ([5]).

However, to date, only a few researchers (in the context of a single SMD placement machine optimisation) have tackled the nozzle optimisation problem. For example, Magyar et al. [4] solved 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 of a multi headed placement machine by adopting a hierarchical problem solving approach. Magyar et al. [4] method was a trade-off between minimising the nozzle changes and minimising the number of placement groups (i.e. sub tours). Their system significantly improved the assembly cycle time when tested on real industrial problems.

When the SMD placement machine has more than one nozzle per head (or even a single nozzle per head), choosing an effective nozzle group (or a nozzle) is important since a nozzle change operation is time consuming. Optimising the pick and place operation without considering the tool switching operations, may not be efficient since it may cause many unnecessary nozzle switching that will significantly reduce the machine throughput. Hence, in this work, we develop a heuristic for nozzle group selection and component placement sequencing to optimise a new, hybrid SMD pick and place machine. This work extends our approach in [6] which introduced an adaptive scheduling approach using a greedy search that can concurrently generate a schedule for the subsequent PCB points using spare CPU time during pick and place operations. This paper extends that work by introducing a mechanical alignment procedure and a component type which can have more than one packaging, and which may require a different nozzle for picking and placing the same component type due to different packaging type.

These new procedures more closely mirror the real-world which previous work has not addressed. This heuristic can be applied in on-line mode (or adaptive scheduling) that we proposed in [6]. Our previous work on optimisation of an SMD placement machine can be found in [7,8,9,10,11,12,13].

II. HYBRID PICK AND PLACE MACHINE

In this work we investigate the hybrid pick and place machine (specifically a new DIMA machine called Hybrid P&P HP-110 [14]). The Hybrid P&P is a type of multi headed placement machine (as classified in [7]). The HP-110 is an economical and medium speed machine that has four fixed feeder carriers (mounted on the four sides of the machine) that hold feeder banks, a fixed PCB table, two vision cameras, a tool bank, a trash bin and a positioning arm head that is equipped with two pipettes. Each pipette holds a nozzle (tool) that is used to grasp the components. Each feeder bank consists of several feeder slots where the component feeders are located. Several kinds of component feeders are available to handle the various types of component packaging; tape, sticks and trays. The feeders are used to provide the machine with a continuous supply of components. The tape feeder is an intelligent feeder that is equipped with a microprocessor that stores component data. The PCB table holds the PCB in a locked position during a pick-place operation. The head and arm (sometimes called the robot arm) is movable in the X-Y direction simultaneously. The nozzles (tools) are changed automatically, from a tool bank, as necessary. The tool bank contains thirteen slots that can hold twelve nozzles with one free slot for use during nozzle change operation.

A sub tour (we refer to a sub tour to differentiate with an overall tour, which is an operation to place all the required components onto a single board) means an operation taken by the robot arm to pick up and place a number of components (depending on the number of nozzles per head, i.e. at most two components for this machine) in a single trip. A sub tour starts with the robot arm moving (from the latest placement point) in the X and Y direction concurrently to pickup the appropriate component(s) (one or two (at most)) from the feeder(s) (assuming that the head is already equipped with a correct nozzle, otherwise a nozzle change is required). Simultaneous pickups (*SP*) can happen if the distance between the two pickup points (of the same sub tour) comes within a user's defined tolerance. Otherwise, the robot arm needs to move to the second pickup point to pick up the second component after picking up the first component. Next, the arm travels in the X and Y direction simultaneously and positions itself at the cameras for component recognition and alignment, if the component has to be recognised and aligned using camera (i.e. a vision's component recognition). If the left nozzle holds a small vision component and the right nozzle holds a large vision component, then a simultaneous vision (*SV*) can be done. That is the two components can be inspected simultaneously. Otherwise, the robot has to perform the two component visions sequentially, with the added overhead of the robot arm having to position the next pipette/nozzle at the larger vision camera and extra component recognition/alignment time. If a defective component is found, the robot moves to throw the rejected component into the trash

bin (located near the camera). Next, the robot arm travels in the X and Y direction simultaneously and positions itself at the point where the first component will be mounted. Finally, the robot arm moves down (Z-direction), mounts the component on the board before returning to its original position (moves up) and repeats these steps for the next location on the board that have to be mounted on the same sub tour. After completing a sub tour, the robot arm returns to the feeder location to begin another sub tour (if a nozzle change is not required). If both (left and right) nozzle hold the mechanical alignment components (MA), the robot arm can move directly to X-Y placement position on the PCB after pickups the components from the feeders without having to perform camera recognition operation. The robot arm carries out an on the fly alignment for mechanical alignment component. That is the component is aligned while the robot arm is moving. Fig. 1 is a sketch diagram of the Hybrid P&P machine.

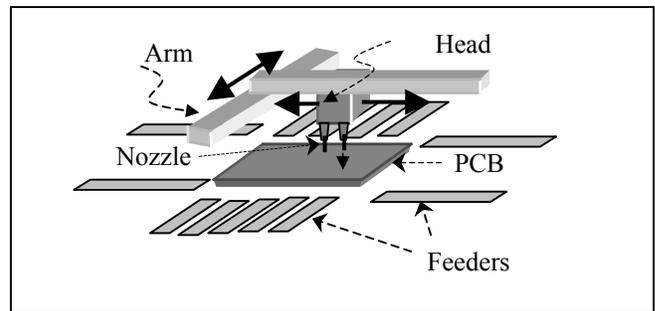


Fig. 1 The Hybrid P&P machine.

III. PROBLEM DESCRIPTION

As the HP-110 has a single head equipped with two pipettes which can hold two nozzles, a good selection of nozzle pair is important in order to minimise the number of nozzle changes to improve the efficiency of the machine. Moreover, the nozzle change operation is very time consuming (i.e. one tool change takes about 2 seconds in this case).

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. As the small vision camera is located to the left of the large vision camera, then we can have a simultaneous vision and alignment operation (*SV*) 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. It is more economical (in terms of assembly cycle time) to have

both mechanical alignment components in the sub tour (MA) rather than having both vision components since the MA sub tour eliminates the time for moving to the camera and perform component recognition and alignment.

The two pipettes on the placement head are fixed at positions such that a simultaneous pickups (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 sub tour can also enhance the machine's throughput.

The feeder also takes a long time (i.e. about 0.5 second in this case) to transport a component from the component feeder to a pickup point. Therefore we should avoid picking up from the same component feeder in a sub tour.

Having four fixed feeder carriers (mounted on the four sides of the machine) also provides a great challenge in optimising the pick and place operation of this machine, since a pickup from the same feeder bank in a sub tour is better (in term of assembly cycle time) than a pickup from different feeder banks. It is apparent from the various situation, conditions and constraints described above the optimising the assembly cycle time of this type of machine is a challenging scheduling problem.

IV. THE SCHEDULING MODEL

In this work, we propose a nozzle selection heuristic to optimise the HP-110. Based on the information supplied by DIMA, nozzle (tool) changes are very time consuming. Hence, our approach aims to minimise the nozzle changes in order to minimise the total assembly cycle time (CT). The CT is the total time taken by the machine to assemble all the components on a printed circuit board (PCB). Minimising the CT will directly increase the machine's throughput. The CT can be used to evaluate the quality of a schedule. The following notations are used to describe the scheduling model (most of them adopted from [6]):

- CT : the assembly cycle time to assemble all components;
- B : the total number of sub tours;
- λ : the time for picking up a component;
- θ : the time for placing a component;
- j : the j^{th} sub tour number where $j \in \{1, 2, \dots, B\}$;
- $I(j)$: the time taken for the robot arm to travel from feeder to PCB point and place the component(s) in the j^{th} sub tour;
- $P(j)$: the time taken for the robot arm to travel from PCB point to feeder and pick the component(s) in the j^{th} sub tour;
- $\Phi_0(j)$: the time taken for the robot arm to move from PCB point to pickup the first component in the j^{th} sub tour from a feeder;
- $\Phi_1(j)$: the time taken for the robot arm to move from current feeder to the next feeder in the j^{th} sub tour;
- $b_0(j)$: the time taken for the robot arm to travel from the camera (or pickup point for the mechanical alignment case) to the first PCB point in the j^{th} sub tour;
- $b_1(j)$: the time taken for the robot arm to travel from the first PCB point to the second PCB point in the j^{th} sub tour;
- $C_0(j)$: the time taken for the robot arm to travel from feeder to position the first pipette above the camera in the j^{th} sub tour;
- $C_1(j)$: the time taken for the robot arm to position the next pipette

above the camera in the j^{th} sub tour;

- $\rho(j)$: a decision variable to indicate either there is a second component for pickup and placement ($\rho(j)=1$), or 0 otherwise;
- $\tau(j)$: a decision variable for having one camera vision and one mechanical alignment component in a sub tour where $\tau(j)=0$ if true, or 1 otherwise;
- $\eta(j)$: the number of tool change required to pickup the component(s) in the j^{th} sub tour where $\eta(j) \in \{0, 1, 2\}$;
- $\gamma(j)$: a decision variable of simultaneous vision in the j^{th} sub tour where $\gamma(j)=0$ if exist simultaneous vision, or 1 otherwise;
- $\omega(j)$: a decision variable of simultaneous pickup in the j^{th} sub tour where $\omega(j)=0$ if exist simultaneous pickup, or 1 otherwise;
- $\sigma(j)$: a decision variable of having two mechanical alignment components in the j^{th} sub tour where $\sigma(j)=0$ if having two mechanical alignment components, or 1 otherwise;
- u : the time for the robot arm to move up/down;
- Ω : the tool changing time;
- α : the image acquisition and recognition time;
- ψ : a decision variable either both components are picked up from the same component feeder in a sub tour ($\psi=1$), or $\psi=0$ otherwise;
- ζ : the component feeder transportation time.

The objective function is to:

$$\text{Minimise } CT = \sum_{j=1}^B [P(j) + I(j)] \quad (1)$$

Where

$$P(j) = (\Phi_0(j) + \lambda + (2*u)) + (\rho(j)*\omega(j)*(max(\Phi_1(j), \psi*\zeta) + \lambda + (2*u))) + (\eta(j)*\Omega) \quad (2)$$

$$I(j) = ((2*u) + b_0(j) + \theta + \sigma(j)*(C_0(j) + \alpha)) + (\rho(j)*(\gamma(j)*\sigma(j)*\tau(j)*(C_1(j) + \alpha) + b_1(j) + \theta + (2*u))) \quad (3)$$

The CT is computed by adding the total time taken by the robot arm to travel from the PCB point to the feeder(s) and picking up the component(s) (i.e. $P(j)$), and then traveling back to the placement point (on the PCB) and placing the component(s) (i.e. $I(j)$). This formulation is different from the formulation in [6] where it includes the cost of same component feeder pickup and mechanical alignment component sub tour.

For each j^{th} sub tour, $P(j)$ is a summation of the time taken for the robot arm to travel from a PCB point to the first pickup point ($\Phi_0(j)$), move down/up ($2*u$), pickup the first component (λ); and if there is no simultaneous pickup and there is the second component to be picked up (i.e. $\rho(j)=1$ and $\omega(j)=1$), it includes the time taken for the robot arm to move from the current feeder to the next feeder ($\Phi_1(j)$), move down/up ($2*u$) and pick up the second component (λ). When both components need to be picked up from the same component feeder ($\psi=1$), then the time required to pick up the second component is usually dictated by the time taken by the feeder

to transport the second component from the component feeder to the pickup position ($\psi^* \zeta$) and $\Phi_1(j)$ factor is eliminated (since $\Phi_1(j) < \zeta$). If the j^{th} sub tour requires a nozzle change, then the $P(j)$ also includes the nozzle changing time ($\eta(j) * \Omega$).

The $I(j)$ for the j^{th} sub tour consists of the time taken for the robot arm to travel from the feeder to position the first pipette above the camera ($C_0(j)$), recognise the first component (α), travel from the camera to the first PCB point ($b_0(j)$), move down/up ($2*u$), and the time for placing the first component (θ); and if there is no simultaneous vision and there is the second component to be placed (i.e. $\gamma(j)=1$ and $\rho(j)=1$), it includes the time taken for the robot arm to position the next pipette above the camera ($C_1(j)$), to recognise the second component (α). If there is the second component to be placed, then the $I(j)$ also includes the time to travel from the first PCB point to the second PCB point ($b_1(j)$), move down/up ($2*u$), and the time for placing the second component (θ). However the recognition time of the second component and the time taken for the robot arm to position the next pipette above the camera can be eliminated if the machine can perform a simultaneous vision. The $C_0(j)$, $2*\alpha$ and $C_1(j)$ factors are eliminated when a sub tour involves two mechanical alignment components ($\sigma(j)=0$), whilst if a sub tour has one mechanical alignment and one vision components ($\tau(j)=0$), only $C_1(j)$ and α factors are eliminated. Therefore, the machine throughput can be increased by maximising the number of simultaneous vision sub tours, having both components mechanical's aligned in a sub tour, simultaneous pickup sub tour, minimising the number of nozzle changes and avoiding pickup from the same component feeder.

V. A NOZZLE SELECTION HEURISTIC

We denote SP as a simultaneous pickup, SV as a simultaneous vision, SF as a same feeder bank pickup, SC as a same component feeder pickup, DF as a different feeder bank pickup, MA as having two mechanical alignment components, MV as having one mechanical and one vision component, M as having only one mechanical alignment in a sub tour and V as a one vision component in a sub tour (i.e. for M and V , there is only one component in a sub tour).

Let P be a set of available component packages on the feeder bank that are required by the current PCB, a component package $p \in P$, T is a set of available nozzle, C is a set of PCB points that have to be scheduled (having components available on the feeder bank) and Q is a sum of PCB points that have component's available on the feeder bank and need to be scheduled. Q is decreased once the PCB point is scheduled.

Each nozzle pair is associated with some counters that count the number of MA sub tours ($MAcounter$), SP sub tours ($SPcounter$), M sub tours ($Mcounter$), MV sub tours ($MVcounter$), SV sub tours ($SVcounter$), SF sub tours ($SFcounter$), two components sub tours ($STcounter$) and one component sub tours ($Scounter$). Z is a decreasing ordered list of available nozzle pairs based on the maximum of $MAcounter$, then $SPcounter$, $Mcounter$, $MVcounter$, $SVcounter$, $SFcounter$, $STcounter$ and $Scounter$. These counters only count based on the availability of PCB points that need to be scheduled which have the component packages

available on the feeder and have not been scheduled yet. $z \in Z$ is the z^{th} nozzle pair where $z \in \{0, 1, 2, \dots, D\}$ and D is a sum of available nozzle pairs. The z^{th} nozzle pair has a left nozzle ($L_z \in T$) and a right nozzle ($R_z \in T$). The $p_{Lz} \in P$ and $p_{Rz} \in P$ are the component packages that can be picked up by L_z and R_z nozzle, respectively. $c_{pLz} \in C$ and $c_{pRz} \in C$ are a set of PCB points that are expecting the p^{th} component package to be placed there by the z^{th} nozzle pair, left and right, respectively. All the counters for the z^{th} nozzle pair are denoted with z , such as $MAcounter(z)$, $SPcounter(z)$, etc.

The nozzle selection heuristic, ordered NS, which is a constructive heuristic, is shown in Fig. 2. The algorithm begins by sorting the PCB points starting with the minimum of maximum (X,Y) coordinate (then with the minimum (X,Y) when duplication of maximum (X,Y) exists). This approach was introduced in [10].

1. Sort the PCB points as in [10].
2. Create nozzle pair list, Z and choose $z=0$ where $z \in Z$.
3. If $Q > 0$;
REPEAT
 - 3.1 Using the same nozzle pair:
 - 3.1.1 If possible, start schedule for $MA+SP$ sub tours by choosing pairs of $p_{L0} \in P$ and $p_{R0} \in P$, and then $c_{pL0} \in C$ and $c_{pR0} \in C$. Reduce $MAcounter(z_0)$, $SPcounter(z_0)$, $SFcounter$, $STcounter$, $Mcounter$ and Q accordingly. Similarly, schedule for $MA+SF$, $SV+SP$, $MV+SP$, $MA+DF$, M , SP , $SV+SF$, $MV+SF$, $SV+DF$, $MV+DF$ and SF sub tours.
 - 3.1.2 If none of the nozzle pair can perform Step 3.1.1, then schedule for DF sub tours by choosing pairs of $p_{L0} \in P$ and $p_{R0} \in P$, and then $c_{pL0} \in C$ and $c_{pR0} \in C$. Reduce $DFcounter(z_0)$ and $STcounter$ accordingly. Similarly, schedule for SC and reduce $SFcounter$, $STcounter$ and Q accordingly.
 - 3.1.3 If none of the nozzle pair can perform Step 3.1.1 and 3.1.2, then schedule for V sub tours by choosing $p_{L0} \in P$ or $p_{R0} \in P$, and then $c_{pL0} \in C$ or $c_{pR0} \in C$. Reduce $Scounter(z_0)$ and Q accordingly.
 - 3.2 Nozzle changing:
If $Q > 0$ then re-generate the Z list and choose the best nozzle pair, $z=0$ where $z \in Z$.
- UNTIL $Q=0$.
4. Merge the single component sub tours.
5. Re-optimize the nozzle changes.
6. Avoid same component feeder pickup in a sub tour.

Fig. 2 An ordered nozzle selection heuristic algorithm

Next, we create a list of decreasing ordered nozzle pairs, Z . The first top nozzle pair, $z=0$ where $z \in Z$ is chosen for the next pickups and placements. If there exist component(s) that need to be scheduled ($Q > 0$), then the algorithm tries to schedule pairs of components that are possible for both simultaneous pickups and mechanical alignment ($MA+SP$) by the current nozzle's pair (i.e. if $SPcounter > 0$ and $MAcounter > 0$). After scheduling all the $MA+SP$ sub tours, then we try to

schedule pairs of components that allow both mechanical alignment and same feeder pickup in a sub tour (MA+SF) without changing the nozzle pair until no more MA+SF sub tours can be scheduled. Similarly, we continue to schedule $SV+SP$, followed by $MV+SP$, $MA+DF$, M , SP , $SV+SF$, $MV+SF$, $SV+DF$, $MV+DF$ and finally SF sub tours. Next, based on the PCB points that are left to be scheduled and the availabilities of component packages on the feeders, the Z list is regenerated. Again, the first top nozzle pair is chosen and the above processes are repeated (i.e. repeat Step 3.1.1 in Fig. 2). If none of the nozzle pair can perform Step 3.1.1 in Fig. 2, then we try to schedule sub tours for different feeder pickups (DF sub tours) until no more DF sub tours can be scheduled. Similarly, we then schedule the SC sub tours. When none of the nozzle pair can perform Step 3.1.1 and 3.1.2 in Fig. 2, we then try to schedule sub tours for single pickups (V sub tours) until no more V sub tours can be scheduled. The sequence of sub tours is determined based on the importance of the sub tour increasing the machine throughput (refer to TABLE 2). For each sub tour, the appropriate PCB points are selected once the pickup components are scheduled. The appropriate counters of the nozzle pair are decreased accordingly after the PCB points are scheduled.

After scheduling all the available PCB points, we then proceed to Step 4 in Fig. 2 that will merge the single component sub tours.

In order to minimise the number of nozzle changes (Step 5 in Fig. 2), we rearrange the sub tours such that the nozzle changes only happen whenever necessary. We begin by sorting the sub tours such that the sub tours which use the same nozzle pair are consecutively indexed. If we must do a nozzle change, then we try to change only one nozzle if possible. This procedure also eliminates a reverse nozzle pair (i.e. $L_g = R_h$ and $R_g = L_h$ where $g \neq h$, $g < h$, $\{L_g, R_g, L_h, R_h\} \in T$) by swapping the left and right nozzles of the later nozzle pair and the appropriate PCB points and component packages (i.e. the h^{th} nozzle pair is converted to g^{th} nozzle pair). If one of the nozzles of the new pair is already used in the previous sub tour, but in a different side (i.e. $L_g = R_h$ or $R_g = L_h$ where $g \neq h$, $g < h$, $\{L_g, R_g, L_h, R_h\} \in T$), then we swap the left and right nozzles of the new nozzle pair and the appropriate PCB points and component packages (such that $L_g = L_h$ or $R_g = R_h$ whichever applicable).

Finally, to further improve the schedule, if possible and necessary, we swap a component package in a same component feeder (SC) sub tour with a component package in the other sub tour in order to avoid same component feeder pickups (Step 6 in Fig. 2).

VI. EXPERIMENTAL SETUP AND RESULTS

To evaluate the performance of our heuristic, we use the average machine operation's time given by DIMA to estimate the CT. We cannot compare the result with any other work since this is an unexplored problem. The average machine operation time is shown in TABLE I.

We use the same PCB points dataset as in [6] but a slightly different component specifications, nozzle specification and feeder arrangement since this work considers a component

type having different packaging and the association of the nozzle is not with component type but with component packaging type. Our data set contains 30 PCB points, 10 component types, 14 component packages, 9 nozzles in the tool bank and 2 feeder banks. A data set is available at <http://www.cs.nott.ac.uk/~gsk>. In this work, we set a user's defined tolerance as 45mm (user's defined tolerance=nozzle gap). We assume the feeder setup is determined.

TABLE I. THE AVERAGE PROCESSING TIME OF THE HP-110

Operation	Time(ms)	Description
Pickup (λ)	10	
Placement (θ)	10	
Axis up/down (u)	50	
Move to XY feeder ($\Phi_o(j)$)	350	200mm
Move to XY next feeder ($\Phi_i(j)$)	290/350*	150mm
Move XY to camera ($C_o(j)$)	350	200mm
Move next pipette to camera ($C_i(j)$)	225	45mm
Image acquisition and recognition (a)	175	
Move to XY place ($b_o(j)$)	300/410*	150mm
Move to XY next place ($b_i(j)$)	175	10mm
Tool changing (Ω)	2000	
The component feeder transportation(ζ)	500	

Note: * for MA sub tour ; * for DF sub tour.

Based on the average processing time of the HP-110 and the time taken for one sub tour, we calculate the machine throughput in components per hour (cph) for each pickup and placement operation type. TABLE II summarises the machine throughput without a nozzle change operation based on one or two components pickup and placement operations. TABLE II shows the effectiveness of each pickup and placement operation type. It gives a significant clue as to how to devise a good strategy in constructing a good pickup and placement schedule.

TABLE II. THE THROUGHPUT OF THE HP-110.

Pickup and placement operation type	Time (ms)	cph
MA+SP	1265	5691
MA+SF	1665	4324
MV+SP	1680	4285
SV + SP	1680	4285
MA+DF	1725	4173
MA+SC	1875	3840
M	980	3673
SP	2080	3461
SV + SF	2080	3461
MV+SF	2080	3461
SV+DF	2140	3364
MV+DF	2140	3364
SV+SC	2290	3144
SF	2480	2903
DF	2540	2834
SC	2690	2676
V	1395	2580

TABLE III shows an example of the result obtained by the ordered NS before applying Step 4, 5 and 6 in Fig. 2, whilst TABLE IV shows an improved schedule. The schedule in TABLE III caused 4 nozzle changes with CT= 36060ms (for assembling 30 components) and producing 2995cph whilst an improved schedule (result in TABLE IV) also caused 4 nozzle

changes with CT=35320ms and producing 3057cph. Results show that the machine's throughput is improved from 2995cph to 3057cph (2.07% improvement).

The Schedule in TABLE III has four single sub tours, these being the 8th, 12th, 13th and 16th sub tours, which will be merged by the merging procedure. The nozzles, packages and PCB points in sub tour 14 and 15 (TABLE III) are swapped left-right by the re-optimize nozzle change procedure. Finally to avoid pickups from the same component feeder, the component in the 9th sub tour (TABLE III) is swapped with the other sub tour.

TABLE III. THE RESULT OBTAINED (WITHOUT STEP 4, 5 AND 6)

Sub tour	Left nozzle	Right nozzle	Left PCB ID	Right PCB ID	Left package	Right package	Operation type	$\eta(j)$
0	2	4	1	18	C	A	MA+SF	0
1	2	4	8	12	C	A	MA+SF	0
2	2	4	14	19	C	A	MA+SF	0
3	2	4	20	22	C	A	MA+SF	0
4	2	4	4	3	G	D	SV+SF	0
5	2	4	6	2	G	D	SV+SF	0
6	2	4	30	24	G	D	SV+SF	0
7	2	4	21	13	G	J	SV+DF	0
8	2	4	NONE	23	NONE	J	V	0
9	8	16	5	9	E	E	MA+SC	2
10	8	16	25	16	M	O	SV+SP	0
11	8	16	15	29	M	O	SV+SP	0
12	8	16	27	NONE	E	NONE	M	0
13	8	16	28	NONE	M	NONE	M	0
14	1	64	10	17	B	L	MA+DF	2
15	1	64	7	26	B	L	MA+DF	0
16	1	64	11	NONE	B	NONE	M	0

TABLE IV. THE FINAL SCHEDULE

Sub tour	Left nozzle	Right nozzle	Left PCB ID	Right PCB ID	Left package	Right package	Operation type	$\eta(j)$
0	2	4	1	18	C	A	MA+SF	0
1	2	4	8	12	C	A	MA+SF	0
2	2	4	14	19	C	A	MA+SF	0
3	2	4	20	22	C	A	MA+SF	0
4	2	4	4	3	G	D	SV+SF	0
5	2	4	6	2	G	D	SV+SF	0
6	2	4	30	24	G	D	SV+SF	0
7	2	4	21	13	G	J	SV+DF	0
8	8	4	27	23	E	J	MV+SF	1
9	8	16	5	9	E	E	MA+SC	1
10	8	16	25	16	M	O	SV+SP	0
11	8	16	15	29	M	O	SV+SP	0
12	8	1	28	11	M	B	MA+DF	1
13	64	1	17	10	L	B	MA+DF	1
14	64	1	26	7	L	B	MA+DF	0

Based on our experiment on a Pentium 4, 1.5Ghz, 256 MB RAM computer, we obtained a complete schedule in about 0.3 seconds after the PCB data was downloaded into the machine. Therefore the machine can start the pickup and placement operation at 0.3 seconds after the PCB data is downloaded into the machine or, perhaps, immediately after the board (i.e. PCB) is ready (clamped on the PCB table) if the board loading time is more than 0.3 seconds.

VII. CONCLUSION

We have presented a constructive heuristic that aims to minimise the assembly cycle time of a hybrid pick and place machine. We have addressed the importance of choosing a proper nozzle group in maximising the machine throughput since a nozzle change operation is time consuming. As this is a new type of machine we cannot compare with previous work but the results are very promising.

ACKNOWLEDGMENT

This work was supported by Public Services Department of Malaysia (financer), National University of Malaysia (financer) and DIMA SMT Systems (our company collaborator).

REFERENCES

- [1] Su, C. -T and Fu, H. -P., A Simulated Annealing heuristic for robotics assembly using the dynamic pick-and-place model, *Prod. Planning and Control*, 1998, 9(8), 795-802.
- [2] Ellis, K.P, Vittes, F.J. and Kobza, J.E., Optimizing the Performance of a Surface Mount Placement Machine, *IEEE Transactions on Electronic Packaging Manufacturing*, 24(3), July 2001, 160-170.
- [3] Wang, W., Nelson, P.C. and Tirpak, T.M., Optimization of high-speed multistation SMT placement machines using evolutionary algorithms, *IEEE Transactions on Electronics Packaging Manufacturing*, 22(2), April 1999, pp. 137-146.
- [4] Magyar, G., Johnsson, M. And Nevalainen, O. (1999). On solving single machine optimization problems in electronics assembly. *Journal of Electronics Manufacturing*, 9(4), 249-267.
- [5] Crama, Y., Klundert, J. van de and Spijksma, F. C. R., Production planning problems in printed circuit board assembly, *Discrete Applied Mathematics*, Volume 123, Issues1-3, 15 November 2002, 339-361.
- [6] Ayob, M. and Kendall, G., An Adaptive Constructive Heuristic to Optimise the Hybrid Pick and Place Machine. Submitted to *IEEE Transaction of Automation Science and Engineering*, 2004.
- [7] Ayob, M. Cowling, P. and Kendall, G., Optimisation for surface mount placement machines, *Proc. of the IEEE ICIT'02*, Bangkok, 11-14 Dec. 2002, 498-503.
- [8] Ayob, M. and Kendall, G., A new dynamic point specification approach to optimise surface mount placement machine in printed circuit board assembly. *Proc. of the IEEE ICIT'02*, Bangkok, 498-503, 11-14 Dec. 2002, 486-491.
- [9] Ayob, M. and Kendall, G., Real-time scheduling for multi headed placement machine. *Proc. of the 5th IEEE International Symposium on Assembly and Task Planning*, ISATP'03, Besançon, France, 9-11 July 2003, 128-133.
- [10] Ayob, M. and Kendall, G., An investigation of an adaptive scheduling for multi headed placement machines. *Proc. of the 1st Multidisciplinary International Conference on Scheduling: Theory and Applications*, MISTA 2003, Nottingham, UK, 13-16 Aug 2003, 363-380.
- [11] Ayob, M. and Kendall, G., A monte carlo hyper-heuristic to optimise component placement sequencing for multi head placement machine. *Proc. of the International Conference on Intelligent Technologies*, InTech'03, Chiang Mai, Thailand, 17-19 Dec 2003, 132-141.
- [12] Ayob M. and Kendall G., A triple objective function with a chebychev dynamic point specification approach to optimise the SMD placement machine. *European Journal of Operational Research*, forthcoming, 2004.
- [13] Ayob, M. and Kendall, G., A Variable Neighbourhood Monte Carlo Search For Component Placement Sequencing Of Multi Headed Placement Machine in Printed Circuit Board Assembly, submitted to *Journal of Intelligent Manufacturing*, 2004.
- [14] Hybrid P&P HP-110, User Manual Version 1.2, DIMA SMT Systems, ©2003.