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Component Pick and Place Scheduling for Surface Mount Device Placement Machine

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Abstract: This is a case study on improving the throughput of a pick and place surface mount device placement machine. These machines are designed to place electronic components onto a printed circuit board. The machines considered in this research are economical and medium speed machines that have four fixed feeder carriers, a fixed printed circuit board table, two vision cameras, a tool bank, a trash bin and a positioning arm head (i.e., a head that is moveable in both X and Y axes simultaneously) that is equipped with two pipettes. A nozzle (which is held by a pipette) is used to grasp the components for the pick and place operations. As nozzle change operations are very time consuming the constructive heuristic presented in this study gives priority to reducing the number of nozzle change operations in order to schedule the component pick and place operations when assembling printed circuit boards. Based on the average machine operation time provided by the machine manufacturer we compute the effectiveness of each pick and place operation type and assign a weighted value for each type of the operation. The nozzle pairs are ranked based on their effectiveness that indicates how many good pick and place operations can be performed by the nozzle pair. The heuristic begins by choosing the best nozzle pair to be applied. Computational results show that, on average, a weighted nozzle rank heuristic is superior to an ordered heuristic that was presented in the earlier research.

Key words: Scheduling, component placement sequencing, heuristic, printed circuit board assembly, nozzle optimisation

INTRODUCTION

A Printed Circuit Board (PCB) is a board that contains layers of circuitry that is used to connect components in order to make up an electronic device. Almost all electronic devices contain at least one PCB. Therefore, the PCB assembly industry plays an important role in the manufacture of almost every type of electronic product. To be more competitive in today's global marketplace, PCB assembly manufacturers are striving to respond to emerging trends which includes high quality, low-cost and just in-time delivery. In order to enhance their competitiveness, many PCB assembly manufacturers develop a computer integrated manufacturing system that is capable of producing an effective planning, scheduling and control procedure. Moreover, the need to automate printed circuit board assembly is increasing with the miniaturisation of component designs and the increasing density of components on PCB's (Moyer and Gupta, 1996a).

PCB assembly involves the placement of hundreds, or even thousands, of electronic components onto a PCB by an SMD (Surface Mount Device) placement machine. Many optimisation problems arise in the production planning for the assembly of PCBs such as grouping (i.e., assigning PCB types to product families and to machine groups) allocation (i.e., identifying which machine in the assembly line to assemble which components) and arrangement and sequencing (i.e., assigning component feeders to slots on the feeder carrier and sequencing the component's pick and place operations. Crama *et al*. (2002), Ji and Wan (2001) and McGinnis *et al*. (1992) had made further discussion on these points. These sub problems are tightly intertwined where each of them is very difficult to solve to optimality. For example, the quality of the component pick and place sequence is dependent on the feeder setup and vice versa (Bard *et al*., 1994). Indeed, the concurrent movement of many machine parts (such as turret rotation, feeder carrier and PCB table movement) requires a full examination of all feasible combinations of feeder setup and component retrieval sequence in order to determine the best feeder setup and component retrieval sequence for each feasible solution of the component pick and place sequence. In

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addition, there are many other issues that should be considered in optimising these sub problems such as the grouping of components in a sub-tour (i.e., what components should be picked and placed together in each tour if there is more than one pipette/nozzle per head) the speed difference between the movement of the PCB table the feeder carrier and the placement head the component transportation time simultaneous pickups, etc.

The literature is rich with work that has tackled this subject, especially investigating how to improve the efficiency of SMD placement machines (Ayob and Kendall, 2009; Duman and Or, 2007; Hardas *et al*., 2008). There are many types of SMD placement machine, including turret, multi-head and dual-delivery, etc. (Ayob and Kendall, 2008). Unfortunately, the technological characteristics of SMD placement machines influence the nature of some of the problem to be solved and the formulation of the associated models (Crama *et al*., 2002). As a result, many researchers solved the problem as a unique problem since the problem relies heavily on the machine characteristics (Ho and Ji, 2003). This causes difficulties in applying or comparing the various approaches from the literature.

For example, Ho and Ji (2003, 2004) considered both component placement scheduling and the feeder setup problem for a turret-type (2003) and a multi-head (2004) placement machine by introducing a Hybrid Genetic Algorithm (HGA). Their genetic algorithm represents a chromosome as two-link structures with the first link representing the sequence of the component placement whilst the second link represents the feeder setup. Initial chromosomes are generated using a nearest neighbour heuristic for the first link whilst the second link is randomly generated. An iterative swap procedure was applied to improve this initial chromosome. A 2-opt local search heuristic is then utilised to improve the second link. The total assembly time represents the evaluation function which is to be minimised. In solving a multi-head placement machine, Ho and Ji (2004) claimed that their approach outperformed a simple genetic algorithm used by Ong and Khoo (1999) in terms of the total travelling distance of placement head but no statistical analysis was reported.

To date, there has been relatively little research that has addressed the minimisation of the tool (or nozzle) change operations. Even the excellent survey by Crama *et al*. (2002) did not address this problem. A survey by McGinnis *et al*. (1992) and Ayob and Kendall (2008, 2009) concluded that there had been limited research which considered component specific nozzles although, Crama *et al*. (2002) proposed a heuristic hierarchical approach to the problem of optimising the throughput rate of a line of several placement machines by first assigning the nozzle to the machines and then performing the component allocations. This is a tool management issue in the context of flexible manufacturing rather than a single machine minimisation problem. A crucial problem in minimising tool management in a flexible manufacturing is to identify the sequence of parts are to be produced and deciding which tools to allocate to the machine so as to minimise the number of tool setups (Crama *et al*., 1994). Whereas, nozzle minimisation, in the context of single machine optimisation, involves searching for an effective nozzle assignment and sequencing/switching in order to improve the pick and place operations and to minimise the number of nozzle change operations to ultimately improve the machine throughput.

Some works that addressed the importance of nozzle minimisation in the context of single SMD placement machine minimisation are Chang and Terwilliger (1987), Magyar *et al*. (1999), Tirpak *et al*. (2000) and Jeevan *et al*. (2002). They considered the nozzle minimisation problem together with the problem of sequencing the pick and place operation and/or feeder setup.

Chang and Terwilliger (1987) proposed a rule-based approach to solve the component placement sequence problem. One of the rules aims to minimise the nozzle changes. Unfortunately, they did not present any results.

Magyar *et al*. (1999) tackled the problem of determining the sequence of component pickup and placement and scheduling the assignment of different nozzles to the robot head by adopting a hierarchical problem solving approach. Magyar *et al*. (1999) created the nozzle usage table to identify the nozzle layers. They considered the trade-off between minimising the nozzle changes and minimising the number of placement groups (or sub-tours). They argued that reducing the nozzle changes will increase the number of placement groups and vice versa. They found that nozzle changes are costly. Likewise additional sub-tours increase the camera costs. Their algorithm iteratively selects the sequence of nozzles changes (which starts with the minimum number of nozzle changes) and then increasing the number of nozzle change operations and determines the number of sub-tours in order to reduce the assembly cycle time. Their system significantly improved the assembly cycle time when tested on real industrial problems. On two of the tested PCBs they achieved savings of assembly cycle times by 7.50 and 5.71%. Therefore, this study addresses the specific problem of nozzle selection for sequencing component pick and place operations so as to increase the machines throughput. 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 just a single nozzle) is important since a nozzle change operation is very time consuming (Magyar *et al*., 1999; Jeevan *et al*., 2002). Optimising the pick and place operation, without considering tool switching operations may lead to a very inefficient schedule as it may cause many unnecessary nozzle changes which will significantly reduce the throughput of the machine. The problem of minimising the tool changes and minimising the pick and place operation are tightly intertwined and cannot be solved independently. The industrial partner (that is a machine manufacturer which provides the test bed for the research) agrees that these problems should not be solved separately. Hence, in this research, researchers develop a heuristic for nozzle selection and component pick and place sequencing to minimise the assembly cycle time.

The novelty and contribution of this research is in using a weighted nozzle rank approach where the nozzle pairs are ranked based on their effectiveness. Based on the average machine operation time given by the machine manufacturer, each pick and place operation type is weighted accordingly to reflect their effectiveness. The effectiveness of each nozzle pair is measured by adding the product of the weighted value of each pick and place operation type and the number of sub-tours. Many researchers only consider minimising the robot travelling distance (and/feeder carrier and PCB table movement) in order to improve the throughput of the machine (or particularly the component pick and place sequence) but ignore many important factors such as nozzle changes simultaneous pickup same feeder pickup, etc. Due to the increasing density of components on the PCBs, these factors (nozzle changes and simultaneous pickup, etc.) are becoming more crucial in determining the effectiveness of the component pick and place sequencing when compared with the robot travelling distance.

HYBRID PICK AND PLACE MACHINE

In this research, researchers study the hybrid pick and place machine (specifically a DIMA machine called the Hybrid P&P HP-110. The Hybrid P&P is a type of multi-head placement machine (Ayob and Kendall, 2008). 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 or gripper) 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 pick-place operations. The head and arm (sometimes called the robot arm) is movable in the X-Y direction simultaneously. The nozzles 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 (there has to be at least one slot so that the current nozzle can be dropped before another is picked up).

The operation of the machine begins by concurrently loading a PCB into the machine and reading the PCB and feeder setup information. Next, the head travels above the PCB to check the fiducial marks to ensure the proper positioning of the PCB. The fiducial marks are special points (typically 2-4 points) that are usually located at the corners of the PCB (Magyar *et al*., 1999). Then, the components are assembled onto the PCB guided by the scheduling and control 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 from the SMD placement machine and the next PCB is loaded. Before undergoing the solder reflow operation (a soldering process to adhere components on the PCB) the components are secured onto the PCB by using adhesive or solder paste.

A sub-tour (researchers refer to a sub-tour to differentiate from an overall tour which is an operation to place the required components onto a single board) is an operation taken by the robot arm (i.e., the arm and head) to pick up and place some components (depending on the number of pipettes/nozzles per head, i.e., at most two components for this machine) in a single trip. A sub-tour operation can be described.

It starts with the robot arm moving (from the latest placement point or for the first placement sub-tour the movement is from the last fiducial mark) in the X and Y direction concurrently to pickup the appropriate component (s) (one or two (at most)) from the feeder (s). This assumes that the head is already equipped with a correct nozzle, otherwise a nozzle change is required and a sub-tour begins when the robot arm performs a nozzle change and travels from the tool bank to the pickup points. Simultaneous Pickups (SP) can occur if the distance between the two pickup points (of the same sub-tour) is within a user-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 robot 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 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).

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) nozzles hold Mechanically Aligned components (MA) the robot arm can move directly to the placement positions on the PCB after picking up the components from the feeders without having to perform a 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. Figure 1 is a photograph of the HP-110 SMD placement machine (taken at the DIMA factory).

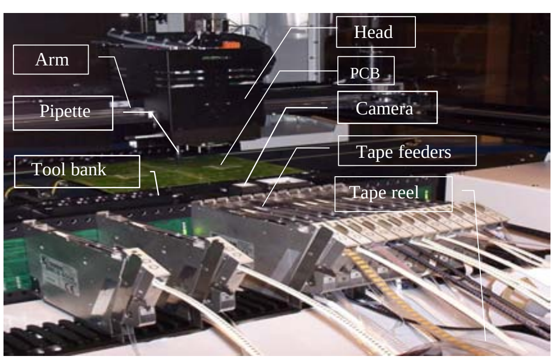

Fig. 1: The HP-110 SMD placement machine

PROBLEM STATEMENT AND ASSUMPTIONS

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. Researchers assume that the total number of required nozzles is less than the capacity of tool bank (<13 in this specific case which includes the nozzles currently in the placement head). This is a realistic assumption and in fact is adhered to on physical machines. Researchers further assume that all components have the same priority (no components have to be placed prior to the others) and handling time (the time for pickup, placement and transportation from pickup point to placement point is the same for all components). Usually, there is no pickup or placement priority unless researchers are dealing with small or large sized components that must be placed close to each other or there are multi-level components. In this case, we may need to place a smaller component first. If researchers placed the larger component first the nozzle may not be able to place the smaller one due to the restricted space. Similarly, researchers may need to place a small component first so that a larger component can be placed over the top (multi-level placement). However, since most of the components on the PCB are small in size this problem can easily be solved by assigning larger size components with a lower priority than the small size components and treat them as different boards.

This research addresses the scheduling problem for a single machine and a single board type and it focuses on the nozzle minimisation and component pick and place sequencing. So far, the PCB machine vendor's software is not capable of solving even the single machine optimisation problem effectively (Magyar *et al*., 1999).

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 may be able to accept more than one component packaging type. The component packaging type can be recognised and aligned without vision camera (using mechanical alignment on fly) using a small vision camera and/or a 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 researchers 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 a time saving. It is more economical (in terms of assembly cycle time) to have both Mechanically Aligned 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 performing component recognition and alignment.

The two pipettes on the placement head are fixed at positions such that a Simultaneous Pickup (SP) can happen if the distance between the two pickup points (of the same sub-tour) comes within a user defined tolerance. The SP sub-tour can also enhance the machine's throughput. The feeder also takes a long time (about 0.5 sec in this case) to transport a component from the component feeder to a pickup point. Therefore, researchers 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 further 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 situations, conditions and constraints described above that optimising the assembly cycle time of this machine is a challenging scheduling problem.

THE SCHEDULING MODEL OF THE HP-110

In this research, researchers propose a nozzle selection heuristic to optimise the HP-110. Researchers 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 of the HP-110 (Ayob and Kendall, 2004):

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 jth sub-tour index where $j \in \{1, 2, ..., B\}$
I(j) = The time taken for the robot arm to travel from feeder carrier/slot to PCB point and place the component (s) in the jth sub-tour
P(j) = The time taken for the robot arm to travel from PCB point (of the (j-1)th sub-tour) to feeder carrier/slot and pick the component (s) in the jth sub-tour
$\Phi_0(j)$ = The time taken for the robot arm to move from PCB point (of the (j-1)th sub-tour) to pickup the first component in the jth sub-tour from a component feeder
$\Phi_1(j)$ = The time taken for the robot arm to move from current feeder slot (pickup point) to the next feeder slot in the jth 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 jth 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 jth sub-tour
$C_0(j)$ = The time taken for the robot arm to travel from feeder carrier/slot to position the first pipette above the camera in the jth sub-tour
$C_1(j)$ = The time taken for the robot arm to position the next pipette above the camera in the jth 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 jth sub-tour where $\eta(j) \in \{0, 1, 2\}$
$\gamma(j)$ = A decision variable of simultaneous vision in the jth sub-tour where, $\gamma(j) = 0$ if exist simultaneous vision or 1 otherwise
$\omega(j)$ = A decision variable of simultaneous pickup in the jth 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 jth 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
$\psi(j)$ = 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:

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

Where:

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

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

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) (P(j)) and then travelling back to the placement point (on the PCB) and placing the component (s) (I(j)). This formulation is adopted from Ayob and Kendall (2004). In this formulation, researchers ignore the time of PCB loading, fiducial checking and PCB transfering (since these time are constant, only happen once for each board and there is nothing researchers can do to reduce this time). Researchers also ignore a simultaneous placement sub-tour because the chances of having the simultaneous placement is very small due to the nature of the problem.

The objective function (Eq. 1) could be applicable for various types of SMD placement machines such as a dual-delivery, sequential pick and place, multi-station and particularly the multi-head. However, the calculation of P(j) and I(j) are machine dependent due to the machine specifications and operational methods.

In this research, researchers use the average machine operation time given by DIMA to estimate the CT as an evaluation for the heuristic performance. To date, none of research in this field (as far as researchers are aware) 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 CT of many SMD placement machine types is dependent on many factors such as nozzle changes, simultaneous pickup and 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 operations 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 crucial factors are also considered. Moreover as the speed of the robot arm of the latest machines is very fast and the component density on the PCB is increasing (i.e., the distance among PCB points tends to be smaller) minimising the robot travelling distance is becoming a less significant factor for improving the throughput of the machine. 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 almost the same. 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, exact location of cameras, trash bin asnd tool bank, etc. is not necessary (as the machine is embedded with control software for accurate movements/operations). The average machine operation time (Table 1) is adequate for guiding the search for a better quality schedule. Moreover, including the machine speed, acceleration/deceleration rate, etc. might introduce a more complex formulation for the objective function. As a result, modelling the component pick and place sequencing problem as a travelling salesman problem, etc. by just minimising the robot travelling distance might not be effective. As such the exact location of PCB points are not crucially important in determining the component pick and place sequencing.

For each jth 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 ($2*\mu$), pickup the first component (λ) and if there is no simultaneous pickup and there is the second component to be picked up (P(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

Table 1: The average processing time of the HP-110 (given by the machine's manufacturer)

Operation	Time (msec)	Description (mm)
Pickup (λ)	10	-
Placement (θ)	10	-
Axis up/down (u)	50	-
Move to XY feeder ($\Phi_0(j)$)	350	200
Move to XY next feeder ($\Phi_1(j)$)	290/350+	150
Move XY to camera ($C_0(j)$)	350	200
Move next pipette to camera ($C_1(j)$)	225	45
Image acquisition and recognition (α)	175	-
Move to XY place ($b_0(j)$)	300/410*	150
Move to XY next place ($b_1(j)$)	175	10
Tool changing (Ω)	2000	-
The component feeder transportation (ζ)	500	-

*MA sub-tour; +: DF sub-tour

be picked up from the same component feeder ($\psi(j) = 1$) 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 ($\psi(j)*\zeta$) and $\Phi_1(j)$ factor is eliminated (since $\Phi_1(j)<\zeta$). If the jth sub-tour requires a nozzle change then the P(j) also includes the nozzle changing time ($\eta(j)*\Omega$).

The I (j) for the jth 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 a second component tobe placed ($\gamma(j) = 1$ 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 picking up from the same component feeder.

A WEIGHTED NOZZLE RANK FUNCTION

Researchers 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 Aligned components, MV as having one Mechanical and one Vision component, M as having only one Mechanical aligned in a sub-tour and V as one vision component in a sub-tour (for M and V there is only one component in a sub-tour). Each nozzle pair is associated with a set of counters that tracks 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 that also includes SC sub-tour (SFcounter), DF sub-tour (DFcounter) and one vision component sub-tours (Vcounter). 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.

Previously, in (Ayob and Kendall, 2004) the nozzle pair was ranked (named as an Ordered approach, R_0) starting with the maximum of MAcounter then SPcounter, Mcounter, MVcounter, SVcounter, SFcounter, DFcounter and Vcounter. This ranking procedure is capable of producing a good quality schedule (good nozzle selection). However, the drawback is this procedure may cause an unwanted nozzle change due to a bad nozzle pair selection. That is for example, researchers may choose a nozzle pair that has only one MA sub-tour since the other nozzle pairs cannot be chosen because of Macounter = 0 even though these nozzle pairs have many other sub-tours. Therefore, in this case, researchers pay for at least two nozzle changes due to a decision of having an MA sub-tour.

To overcome this problem, researchers propose two weighted nozzle rank procedures, $R_1(z)$ and $R_2(z)$ to intelligently choose the best nozzle pair to be applied in each sub-tour. The $R_1(z)$ function is computed based on the effectiveness of the sub-tour operation type and the appropriate counter values of the nozzle pair. The larger the counter values of the zth nozzle pair the more likely the nozzle pair is to be chosen. Researchers use a weighted parameter, δ_s, to represent the effectiveness of the sth sub-tour operation type. δ_s is calculated as follows:

$$\delta_s = \frac{E_s}{E_1} \tag{4}$$

where, E_1 and E_s are the efficiency of the most efficient sub-tour operation type (i.e., MA+SP sub-tour) and the sth sub-tour operation type, respectively. The E_s values are shown in Table 2 whilst the δ_s values are shown in Table 3.

Based on the average processing time of the HP-110 (Table 1), researchers calculate the time taken for completing a sub-tour by using Eq. 1-3. We then, compute the machine throughput in components per hour (cph) for each pickup and placement operation type.

The cph is represented as E_s and is shown in Table 2 which summarises the machine throughput without a nozzle change operation based on one or two components pickup and placement operations in a sub-tour. Table 2

Table 2: The throughput of the HP-110

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

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. As shown in Table 2, MA+SP is the most effective sub-tour whilst V is the worst sub-tour. The weighted nozzle rank function of the zth nozzle pair, $R_1(z)$ is:

$$R_1(z)=\sum_{s=1}^{S}\delta_s W_{zs} \quad (5)$$

where, W_{zs} is the sth counter of the zth nozzle pair and S = 14. The value of S should be 17 if researchers use 17 variables of counter to compute all the 17 types of sub-tour (Table 2). In order to simplify the logic problem, reduce the computational time and avoid introducing additional variables we use an approximation to compute W_{zs}. For example, W_{zs} of MA+SP sub-tour is computed by taking the minimum of (MAcounter and SPcounter) which may not be correct if all the mechanical alignment components for the nozzle pair does not allow for simultaneous pickup and the value of the Spcounter is only applicable to the camera vision components. In this example, researchers assume that if MAcounter>0 and SPcounter>0 then researchers have MA+SP sub-tours.

Researchers only compute 14 δ_s instead of 17 (researchers ignore δ_s for MA+SC, SV+SC and SC sub-tours). Moreover, researchers already count the same component feeder sub-tours (MA+SC, SV+SC and SC) when computing the same feeder bank sub-tours (MA+SF, SV+SF and SF). In fact, researchers are not searching for an exact solution (optimum solution) but aiming for a good solution that can be obtained in a reasonable time. Due to the complexity of the problem the optimum solution is extremely difficult to achieve (Moyer and Gupta, 1996b). The relationship between MAcounter, SPcounter, etc., δ_s, sub-tour operation type and the sth is shown in Table 3.

Table 3: The relationship of the counters

Sub-tour	Counter	δ_s
MA+SP	Min (MAcounter, Spcounter)	1.000
MA+SF	Min (MAcounter, SFcounter)	0.760
MV+SP	Min (MVcounter, SPcounter)	0.753
SV+SP	Min (SVcounter, SPcounter)	0.753
MA+DF	Min (MAcounter, DFcounter)	0.733
M	Mcounter	0.645
SP	SPcounter	0.608
SV+SF	Min (SVcounter, SFcounter)	0.608
MV+SF	Min (MVcounter, SFcounter)	0.608
SV+DF	Min (SVcounter, DFcounter)	0.591
MV+DF	Min (MVcounter, DFcounter)	0.591
SF	SFcounter	0.510
DF	DFcounter	0.498
V	Vcounter	0.453

To increase the gaps among δ_s, researchers employ another weighted nozzle rank function, $R_2(z)$ as follows:

$$R_2(z)=\sum_{s=1}^{S}(\delta_s)^2 W_{zs} \quad (6)$$

In Eq. 6, δ_s is squared in order to increase the chances of selecting a nozzle pair that has many good quality sub-tours. Without ignoring the lower efficient sub-tours, $R_2(z)$ heuristic is more likely to choose a nozzle pair that has many good quality sub-tours compared to $R_1(z)$ heuristic. However, $R_2(z)$ function does not just choose a nozzle pair that only has the most effective sub-tour as in Ordered (R_0) (Ayob and Kendall, 2004). Therefore, $R_2(z)$ heuristic might be more capable of producing a good quality schedule compared to an Ordered (Ayob and Kendall, 2004) and $R_1(z)$ function. However, in practice the efficiency of each method is really dependent on the problem itself.

NOZZLE SELECTION HEURISTIC

The idea of using a weighted nozzle rank approach in constructing pick and place schedules for HP-110 is motivated from the graph colouring heuristics (such as largest degree, saturation degree, largest weighted degree, etc.). These have already been successfully applied to some optimisation problems, especially timetabling. For example, in exam timetabling problem largest degree heuristic will first schedules those examinations that have the largest number of conflicts with other examinations. Hence, in the case study, it might be beneficial to have a good ranking procedure to schedule pick and place operations.

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 the set of available nozzles, C is the 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 available on the feeder bank and need to be scheduled. Q is decreased once the PCB point is scheduled.

Z is a decreasing ordered list of available nozzle pairs. There are three nozzle ranking procedures, these being an Ordered (R_0) and the two weighted nozzle rank procedures ($R_1(z)$ and $R_2(z)$) that were discussed in study. Z is generated using one of these procedures depending on which heuristic is to be applied. $z \in Z$ is the zth nozzle pair where $z \in \{0, 1, 2, ... D\}$ and D is a sum of available nozzle pairs. The zth 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 pth component package to be placed there by the zth nozzle pair, left and right, respectively. All the counters for the zth nozzle pair are denoted with z such as MAcounter (z) and SPcounter (z), etc.

A hybrid nozzle selection with a component pickup and placement sequencing heuristic, HybridNS which is a constructive heuristic is shown in Fig. 2 (mostly adopted from Ayob and Kendall (2004)).

The algorithm begins by initialising Q and all the counter values based on the available PCB points that need to be scheduled and the availability of component packages on the feeders. Researchers then sort the PCB points (that need to be scheduled) starting with the minimum of maximum (X, Y) coordinate (then with the minimum (X, Y) when duplication of maximum (X, Y) exists).

Next, researchers 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 exists 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 researchers 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, researchers 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 (Fig. 2). However, at this stage, researchers try to re-apply the used nozzle pair as much as possible. To do this, researchers rank the used nozzle pairs based on the number of sub-tours that have been scheduled using the nozzle pair. Next, researchers search for the best

1. Initialise Q and all counters; and then sort the PCB points as described above.
2. Create a 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, 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 and reduce the counter values accordingly.

   3.1.2 Else 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) accordingly. Similarly, schedule for SC and reduce SFcounter and Q accordingly.

   3.1.3 Else 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 Vcounter(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-optimise the nozzle changes.
6. Avoid same component feeder pickup in a sub-tour.
7. Re-optimise the nozzle changes (same as step 5).
8. Eliminate the infeasible sub-tour.
9. Simple re-optimise the nozzle changes.

Fig. 2: HybridNS with a component pickup and placement sequencing heuristic

nozzle pair (from the used nozzle pair list) to be applied. The obtained nozzle pair is compared to the first top nozzle pair, z = 0. Depending on the heuristic to be applied the best nozzle will be selected. For example, for the $R_1(z)$ heuristic, if $R_1(z)$ for the first top nozzle pair is greater than the obtained nozzle pair then the first top nozzle pair is chosen. Otherwise, another pair is chosen.

If none of the nozzle pair can perform step 3.1.1 in Fig. 2 then researchers try to schedule sub-tours for different feeder pickups (DF sub-tours) until no more DF sub-tours can be scheduled. Similarly, researches 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, researchers 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 (Table 3). For each sub-tour, the appropriate PCB points are selected once the pickup components are scheduled. The appropriate counter values of the nozzle pair and Q are decreased accordingly after the PCB points are scheduled.

After scheduling all the available PCB points, researchers then proceed to step 4 in Fig. 2 that will merge the single component sub-tours. Researchers create two lists; these being an Mlist and Vlist. The Mlist is a collection of M sub-tours whilst the Vlist is a collection of V sub-tours. Initially, we try to merge the M sub-tours (avoiding merging identical nozzles). Similarly, researchers then try to merge the V sub-tours. If there is one V sub-tour left and researchers still have M sub-tour (s), researchers try to merge V and M sub-tours in order to eliminate the V sub-tour since it represents a worse quality sub-tour. Actually, researchers try to avoid merging the V and M sub-tours since the quality of the obtained sub-tour the MV+SF or MV+DF is slightly worse than the M sub-tour (except the MV+SP sub-tour). If there are M sub-tours left to be merged then we try merging the M sub-tours with MA+SC, MA+DF, MA+SF, MV+DF or MV+SF sub-tours such that researchers can obtain two MA (i.e., MA+SP, MA+SF, MA+SC or MA+DF) sub- tours or at least, one MA (i.e., MA+SP, MA+SF, MA+SC or MA+DF.) sub-tour and one MV sub-tour if we merge with MV sub-tour. The V sub-tours that are left will be merged with the sub-tours that have the least used nozzle pair. Researchers begin with the worst sub-tour, i.e., the SC sub-tours then DF, etc.

In order to minimise the number of nozzle changes (step 5 in Fig. 2), researchers rearrange the sub-tours such that the nozzle changes only happen whenever necessary. Researchers begin by sorting the sub-tours such that the sub-tours which use the same nozzle pair are consecutively indexed. If researchers must do a nozzle change then researchers 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 $g \neq h$, $g<h$, $\{L_g, m\ R_g, L_h, R_h\} \in T$) by swapping the left and right nozzles of the later nozzle pair and the appropriate PCB points and component packages (i.e., the hth nozzle pair is converted to gth 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 researchers 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). If necessary, researchers try to swap the nozzles and components such that researchers can increase the number of sub-tours that are able to utilise the most used nozzle pair and eliminate the least used nozzle pair.

To further improve the schedule, if possible, researchers 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). However, reseachers avoid swapping SC (SV+SC, etc.) with SP (SV+SP, etc.) since we do not want to sacrifice the SP sub-tours. Researchers also avoid swapping a mechanical aligned component with a vision component.

Researchers then re-optimise the nozzle changes (step 7 in Fig. 2) as in step 5 in Fig. 2. This has to be performed since the previous step (step 6 in Fig. 2) might create a new nozzle pair. The step 8 in Fig. 2 will ensure that all used nozzle pairs are feasible. Not all the nozzles have a duplicate copy in the tool bank (i.e., most of the nozzles are unique). Therefore, if researchers have an identical left-right nozzle pair whilst the tool bank only has one copy of this nozzle then the nozzle pair is infeasible. Infeasible nozzle pairs might be created by steps 4-7 in Fig. 2. This step will swap the left or right nozzles of the infeasible pair with the appropriate pair to eliminate the infeasible nozzle pair.

Finally, researchers apply a simple re-optimise nozzle pair (step 9 in Fig. 2) that is guaranteed not to produce an infeasible nozzle pair (no new nozzle pair is generated).

EXPERIMENTAL SETUP AND RESULTS

As by Ayob and Kendall (2004), researchers use the average machine operation time given by DIMA to estimate the assembly Cycle Time (CT), in order to evaluate the quality of the component pick and place schedule (Table 1).

As this is an unexplored problem, researchers can only compare among the approaches (these being an

Ordered (R_0) and the two weighted nozzle rank procedures, $R_1(z)$ and $R_2(z)$) to demonstrate the performance of each heuristic. Researchers use two datasets in this research. The dataset 1 is the same dataset as use in Ayob and Kendall (2004) that contains 30 PCB points, 10 component types, 14 component packages, 9 nozzles in the tool bank and 2 feeder banks. The dataset DIMA is a simulated data provided by Dima which has 156 PCB points, 26 component types, 26 component packages, 9 nozzles in the tool bank and 2 feeder banks. The datasets are available at http://www.cs.nott.ac.uk/~gxk. In this study, researchers set a user-defined tolerance as 45 mm (user-defined tolerance = nozzle gap).

For each dataset, researchers perform 200 runs. Since, there is no random element in the heuristic any run will obtain the same result for the same dataset. Therefore, in this experiment, researchers need to modify the contents of these datasets to demonstrate their effectiveness. For each run, researchers randomly modify the specification of the component recognition and the nozzle assignment of each component package. At each run, at most four nozzles are randomly selected to be assigned to a component package. Therefore, each run is effectively a different problem instance. However, for each run the same problem instance is used to test the performance of the three nozzle ranking approaches, these being an R_0 and the two weighted nozzle rank heuristics, R_1 and R_2. Based on the Cycle Time (CT) of the schedule obtained by each approach researchers compute the component per hour (cph) to measure the machine throughput of each solution (denoted as M_0, M_1 and M_2 for components per hour for R_0, R_1 and R_2, respectively).

The relative change in M_1 over M_0, denoted as I_1 ($I_1 = (M_1-M_0)\times100/M_0$) and the relative change in M_2 over M_0, denoted as I_2 ($I_2 = (M_2-M_0)\times100/M_0$). Table 4 summaries the result of 200 runs. It shows that for dataset 1 (Table 4) 48 and 49% of the 200 runs reported improved solution quality when comparing M_1 and M_2 against M_0, respectively. For dataset DIMA (Table 5) researchers obtained improved solution quality of 65 and 70% of the 200 runs when comparing M_1 and M_2 against M_0, respectively. Figure 3 shows the distribution of the result when comparing M_1 and M_2 against M_0 for datas DIMA.

Table 4 and 5 also show that on average R_2 slightly outperformed R_0 by about 1.54 and 2.77% for dataset B and dataset DIMA, respectively. Whilst, R_1 is slightly superior to R_0 by about 1.39 and 2.43% for dataset 1 and dataset DIMA, respectively. From this experiment, the best improvement obtained by R_1 gains R_0 are 32.43% for dataset 1 and 16.79% for dataset DIMA whilst R_2 gains 32.43% for dataset 1 and 18.88% for dataset DIMA over R_0. On the contrary, the worst result obtained by R_1 against R_0 are -18.77% for dataset 1 and -9.54% for dataset DIMA whilst R_2 obtained -15.78% for dataset 1 and -9.54% for dataset DIMA over R_0.

This indicates that each of the approaches have their own strengths and weaknesses. For example, R_0 nozzle ranking approach may perform best when the dataset has many mechanical aligned components that may incur many MA+SP, MA+SF, MA+DF or MA+SC sub-tours which are among the few best sub-tours. R_0 nozzle ranking approach also chooses those sub-tours compared to the other sub-tours. Therefore, as a result R_0 nozzle ranking approach might be capable of producing a schedule which has many good quality sub-tours compared to R_1 and R_2 nozzle ranking approaches. However, due to a decision of first searching for a nozzle pair that has MA+SP sub-tours then MA+SF sub-tours, etc. R_0 nozzle ranking approach only considers the counters of the highest quality sub-tour for each nozzle pair, without considering the value of the counters of the lower quality sub-tours. This might lead to selecting a bad nozzle pair that may cause unnecessary nozzle changes. When this case happen R_0

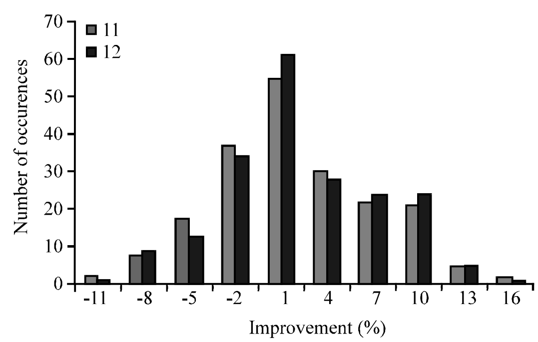

Fig. 3: A frequency distribution of the I_1 and I_2 for dataset DIMA

Table 4: The summary of 200 runs comparing M1 and M2 against M0 (dataset 1)

Counters	Minimum (%)	Average (%)	Maximum (%)	Improvement>0 (%)	Improvement = 0 (%)	Improvement<0 (%)
I_1	-18.77	1.39	32.43	48.0	8.5	43.50
I_2	-15.78	1.54	32.43	49.0	8.0	43.00

Table 5: The summary of 200 runs comparing M1 and M2 against M0 (dataset DIMA)

Counters	Minimum (%)	Average (%)	Maximum (%)	Improvement>0 (%)	Improvement = 0 (%)	Improvement<0 (%)
I_1	-9.54	2.43	16.79	65	2.5	32.5
I_2	-9.54	2.77	18.88	70	1.5	28.5

nozzle ranking approach might produce a bad quality schedule even though the generated schedule contains many good quality sub-tours since there are unnecessary nozzle changes which drastically reduces the throughput of the machine. This explains why sometimes R_2 and R_1 gain 32.43% over R_0 and sometimes the R_0 heuristic is better than the other two heuristics. There is a tradeoff between having many good quality sub-tours and minimising the tool change operations. Therefore, R_1 and R_2 heuristics are introduced to overcome the problem. Compared to R_1, R_2 heuristic places more emphasis on selecting a tool pair which has many good quality sub-tours without ignoring the existence of the lower quality sub-tours. As a result, on average, R_2 heuristic is capable of producing a better quality schedule compared to R_1 and R_0 nozzle ranking heuristics.

Based on the experiments on a Pentium 4, 1.5 Ghz, 256 MB RAM computer, researchers obtained a complete schedule in about 0.3 sec (for dataset 1) after the PCB data was downloaded into the machine. To investigate the scalability of the result, researchers carried out another experiment that varied the value of N (number of PCB points) whilst the other parameter values (i.e., number of component types, board size, feeder setup and component packaging assignment) were fixed. The following N values were chosen; 30, 60, 90, 120, 240, 480, 960, 1920, 2880, 3840, 5760, 7680 and 10000. The maximum value of N = 10000 was chosen due to the fact that, currently, it is very rare to have >10000 components on a PCB. Figure 4 shows the result of this experiment. Researchers can observe from Fig. 4 that, for all cases, the computation time increases with an increase in N. Figure 4 shows that for a small value of N (i.e., N<3000) the computation time linearly increases with an increase in N (for all heuristics). However, for larger values of N (i.e., N>3000), it appears exponential but still appears manageable as the value of N is never likely to be very large due to the problem domain.

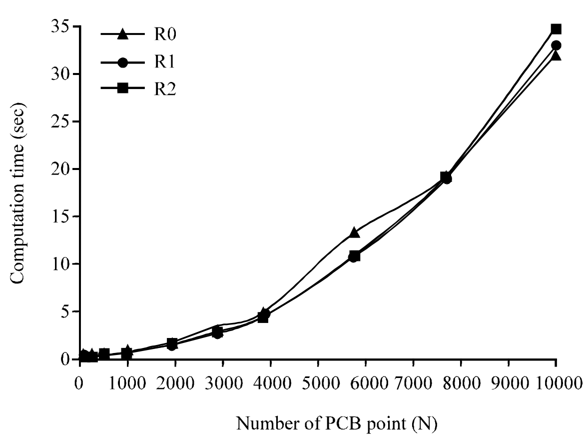

Fig. 4: The computation time of the R_0, R_1 and R_2 nozzle ranking approaches which varies N parameter value

CONCLUSION

Three nozzle rank procedures have been presented. These are an Ordered (R_0) and two weighted nozzle rank procedures ($R_1(z)$ and $R_2(z)$). The nozzle is ranked based on the effectiveness of the sub-tour operation type and the appropriate counter values of the nozzle pair. The larger the counter values of the nozzle pair, the more likely the nozzle pair is to be chosen. However, there is a tradeoff between having many good quality sub-tours and minimising the number of tool change operations. By using weighted nozzle rank procedures, researchers overcome the tradeoff issue. As, this is an unexplored problem, researchers can only compare among the approaches and datasets. On average, reseachers found that R_2 heuristic is capable of producing a better quality schedule compared to R_1 and R_0 nozzle ranking heuristics.

Researchers have addressed the importance of choosing a proper nozzle group in maximising the machine throughput since a nozzle change operation is time consuming. Hence, researchers proposed a HybridNS. These heuristics give highest priority to minimising the number of nozzle changes in sequencing the pick and place operations.

Researchers also found the order of significant factors to be considered for generating a good quality schedule for the hybrid pick and place machine is as follows, starting with the most significant:

- Minimise the nozzle changes
- Maximise the multi-pickup of Mechanical Aligned component (MA sub-tour)
- Maximise the simultaneous pickup
- Maximise the simultaneous vision pickup and
- Maximise the same feeder bank pickup (pickup both components from the same feeder bank)

This research was conducted based on a simulation dataset given by DIMA machine expert and the randomly generated datasets (based on the problem description by DIMA machine expert). In order to test the proposed approach on the real-world machine, some modifications might be required to ensure correct communication between the scheduler and other software on the SMD placement machine. The proposed approach might be applicable to other SMD placement machines which have similar characteristics.

The proposed approaches in this study were only focused on a constructive heuristic that is machine specific. However, a general solution framework might be applicable in solving other machine types.

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REFERENCES

Ayob, M. and G. Kendall, 2004. A nozzle selection heuristic to optimise the hybrid pick and place machine. Proceedings of the 2004 IEEE Conference on Cybernetics and Intelligent Systems, December 1-3, 2004, Singapore, pp: 1259-1264.

Ayob, M. and G. Kendall, 2008. A survey of surface mount device placement machine optimisation: Machine classification. Eur. J. Oper. Res., 186: 893-914.

Ayob, M. and G. Kendall, 2009. The optimisation of the single surface mount device placement machine in printed circuit board assembly: A survey. Int. J. Syst. Sci., 40: 553-569.

Bard, J.F., R.W. Clayton and T.A. Feo, 1994. Machine setup and component placement in printed circuit board assembly. Int. J. Flexible Manuf. Syst., 6: 5-31.

Chang, T.C. and J. Terwilliger, 1987. Rule-based system for printed wiring assembly process planning. Int. J. Prod. Res., 25: 1465-1482.

Crama, Y., A.W.J. Kolen, A.G. Oerlemans and F.C.R. Spieksma, 1994. Minimizing the number of tool switches on a flexible machine. Int. J. Flexible Manuf. Syst., 6: 33-54.

Crama, Y., J. Van De Klundert and F.C.R. Spieksma, 2002. Production planning problems in printed circuit board assembly. Discrete Applied Math., 123: 339-361.

Duman, E. and I. Or, 2007. The quadratic assignment problem in the context of the printed circuit board assembly process. Comput. Oper. Res., 34: 163-179.

Hardas, C.S., T.L. Doolen and D.H. Jensen, 2008. Development of a genetic algorithm for component placement sequence optimization in printed circuit board assembly. Comput. Ind. Eng., 55: 165-182.

Ho, W. and P. Ji, 2003. Component scheduling for chip shooter machines: A hybrid genetic algorithm approach. Comput. Oper. Res., 30: 2175-2189.

Ho, W. and P. Ji, 2004. A hybrid genetic algorithm for component sequencing and feeder arrangement. J. Intell. Manuf., 15: 307-315.

Jeevan, K., A. Parthiban, K.N. Seetharamu, I.A. Azid and G.A. Quadir, 2002. Optimization of PCB component placement using genetic algorithms. J. Electron. Manuf., 11: 69-79.

Ji, P. and Y.F. Wan, 2001. Planning for printed circuit board assembly: The state-of-art review. Int. J. Comput. Appli. Technol., 14: 136-144.

Magyar, G., M. Johnsson and O. Nevalainen, 1999. On solving single machine optimization problems in electronics assembly. J. Electron. Manuf., 9: 249-267.

McGinnis, L.F., J.C. Ammons, M. Carlyle, L. Cranmer and G.W. Depuy *et al.*, 1992. Automated process planning for printed circuit card assembly. IIE Trans., 24: 18-30.

Moyer, L.K. and S.M. Gupta, 1996a. SMT feeder slot assignment for predetermined component placement paths. J. Electron. Manuf., 6: 173-192.

Moyer, L.K. and S.M. Gupta, 1996b. Simultaneous component sequencing and feeder assignment for high speed chip shooter machines. J. Electron. Manuf., 6: 271-305.

Ong, N.S. and L.P. Khoo, 1999. Genetic algorithm approach in PCB assembly. Integr. Manuf. Syst., 10: 256-265.

Tirpak, T.M., P.C. Nelson and A.J. Aswani, 2000. Optimization of revolver head SMT machines using adaptive simulated annealing (ASA). Proceedings of the 26th IEEE/CPMT International Electronics Manufacturing Technology Symposium, October 2-3, 2000, Santa Clara, CA., pp: 214-220.