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## Production Planning & Control: The Management of Operations

Publication details, including instructions for authors and subscription information:

<http://www.tandfonline.com/loi/tppc20>

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Published online: 15 Nov 2010.

To cite this article: Chao-Ton Su & Hsin-Pin Fu (1998) A simulated annealing heuristic for robotics assembly using the dynamic pick-and-place model, *Production Planning & Control: The Management of Operations*, 9:8, 795-802, DOI: [10.1080/095372898233560](https://doi.org/10.1080/095372898233560)

To link to this article: <http://dx.doi.org/10.1080/095372898233560>

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# A simulated annealing heuristic for robotics assembly using the dynamic pick-and-place model

CHAO-TON SU and HSIN-PIN FU

**Keywords** simulated annealing, FPP, DPP, robotics assembly, sequence, assignment

**Abstract.** Products assembled by robots are typical in present day manufacturing. The traditional type of automatic assembly is Fixed Picked and Place (FPP) mode. The development of the Dynamic Picked-and-Place (DPP) model is an important issue in robotics travel. Until now, to route robotics travel, the authors usually have utilized the fixed coordinate of insertion points and magazine of the Travelling Salesman Problems (TSP) method to sequence the insertion points. However, robotics travel routing should be based on a relative coordinate because the coordinates of insertion point and magazine are constantly changing. That is, the robotics, board and magazine are simultaneously moved at different speeds. This study presents a Simulated Annealing (SA)-based algorithm that can arrange the insertion sequence and assign the magazine slots to obtain a performance better than in the traditional approach.

## 1. Introduction

The industrial robot has been applied widely in manufacturing and is usually a high-production tool. In general, most products assembled by robots are electrical products high in unit value. Therefore, saved assembly cycle time being saved cost, it is important to reduce the assembly time to enhance productivity and competitiveness. The most general assembly cells consist of the robot, assembly table (board) and component slots (magazine). Three factors are highly correlated in their effects on overall assembly efficiency: (1) robot motion control; (2) the sequence for placing the individual component on the assembly board; and (3) the corresponding magazine slot assignment. To find the optimal robot travelling routes is complicated and time consuming, especially

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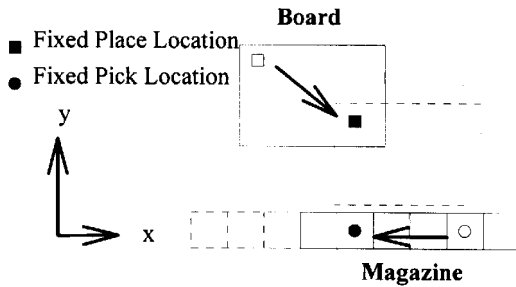


Figure 1. The layout of the FPP approach.

when many components need to be assembled. In practice, the heuristic solution is highly desirable.

Two types of robot assembly problems have been characterized based on different robot motions. They are: (1) fixed robot motion between fixed pick and place (FPP) points; and (2) robot motion with dynamic pick and place (DPP) points. In the FPP motion model, the magazine (or component slots) moves horizontally along an  $x$ -axis and the robot moves only vertically along a  $y$ -axis. The assembly board ( $x$ - $y$  table) moves freely in any direction so that the magazine can move required components to the fixed pick-up points. When the assembly board moves to a fixed placement location, the robot picks up and places the components among these two fixed points. Figure 1 shows the layout of the FPP approach. Few researchers have developed assembly sequence methods, instead focusing on the FPP mode (Randhawa *et al.* 1985, Cunningham and Browne 1986, Ball and Magazine 1988, Mettalla and Egbelu 1989, Egbelu *et al.* 1996). Because the FPP approach involves undesirable robot waiting time at the fixed pick-up and placement points, Su *et al.* (1995) developed robot moves with a flexible DPP approach using a heuristic method to eliminate the robot waiting time. Su *et al.* (1995) also show that the DPP approach is superior to the FPP approach in most cases where magazine slots are assigned randomly.

To obtain the shortest robot travel routing, the assembly sequence and magazine assignment are relatively important. The better the assembly sequence and magazine assignment, the shorter the moves of the assembly table and magazine. Two issues are thus involved: (1) how to arrange the insertion (assembly) sequence; and (2) how to assign the corresponding components to specific magazine slots. Su *et al.* (1995) dealt with robotics travel routing by the Travelling Salesman Problems (TSP) method (Karg and Thompson 1964) based on the fixed insertion point coordinates and random magazine assignments. Wang *et al.* (1997) indicated that reasonable allocation of the magazine slots instead of random assignment improves performance, and he developed a heuristic magazine assignment approach to opti-

mize the DPP method. The assembly cell of one board and one magazine (1B1M) is applied in Su and Wang's approaches. Wang (1996) also developed some layouts of assembly cell, e.g. 1B2M and 2B1M based on the DPP mode. Nevertheless, Wang's approach was still based on a fixed coordinate using the TSP method to obtain robotics travel routing. In fact, robotics travel routing should be based on relative coordinates not fixed coordinates because the coordinates of the insertion point and magazine change at all times, i.e. the robotics, board and magazine are simultaneously moved at different speeds. Su and Wang's approaches did not consider the simultaneous movement of robotics, board and magazine, and how this influences coordinates solving all the time during the assembly. Therefore, their approaches are not suitable for solving the robotics assembly problem. In this study, a Simulated Annealing (SA)-based algorithm is presented to obtain the shortest cycle time, arrange the insertion (assembly) sequence, and assign the corresponding components to specific magazine slots based on the DPP robot motion model. Simulation results demonstrate that the proposed approach can significantly reduce the assembly cycle time.

## 2. DPP background

In the DPP model, the assembly board and magazine move only horizontally along the  $X$ -axis; the robot moves vertically along the  $Y$ -axis, and the pick-up and placement points are dynamically allocated. Figure 2 shows the layout of the DPP model.

To describe the DPP model more clearly, the following notations are given:

$CT$	the cycle time to assemble all components
$N$	the number of insertion locations
$K$	the number of component types
$m(i)$	the magazine pick-up location of the $i$ -th assembly sequence
$b(i)$	the placement location of the $i$ -th assembly sequence

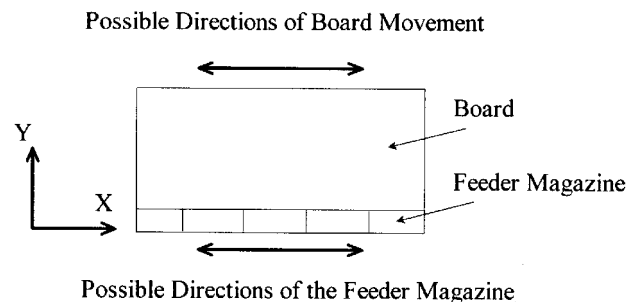


Figure 2. The layout of the DPP mode.

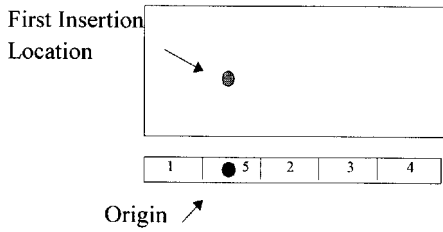


Figure 3. The initial setup location.

- $T_{R}(b(i), m(i))$  robot travel time from board location  $b(i)$  to magazine location  $m(i)$
- $T_{R}(m(i), b(i))$  robot travel time from magazine location  $m(i)$  to board location  $b(i)$
- $V_r$  the average speed of the robot
- $V_b$  the average speed of the assembly board
- $V_m$  the average speed of the magazine
- $T_P$  the time needed to pick up a component upon arrival
- $T_I$  the time needed to insert a component upon arrival
- $A(x_i, y_i)$  the coordinate of  $x$  and  $y$  at point  $A$
- $PQ$  the distance between points  $P$  and  $Q$

We assumed that the initial location of the robot is at the right upper coordinate of the first component pick-up point. Also, the initial location of board and magazine are at the  $x$  coordinate of the first insertion point (see figure 3). The robot returns to the initial location upon completion of the assembly process, ready to assemble the next product.

Figure 4 shows the basic layout of the DPP model. The insertion placement point is decided as follows: when the robot picks up the  $i$ -th component at point  $D(x_i, y_i)$  on the magazine and then moves to the insertion point

$C(x_i, y_i)$ , two insertion points are possible [figure 4(b)] due to the limitations of robot speed, board speed and the board's insertion point. It is assumed that point  $A(x_i, y_i)$  and point  $B(x_i, y_i)$  are two possible placement locations, and point  $C(x_i, y_i)$  is the relative coordinate location of the  $i$ -th component in the insertion sequence immediately after the robot finishes inserting the  $(i - 1)$ -th component. The coordinate of the point  $D(x_i, y_i)$  location should be determined during the preceding insertion. The placement location  $A(x_i, y_i)$  is used when the robot reaches that point from point  $D(x_i, y_i)$  after the board arrives at point  $A(x_i, y_i)$  from point  $C(x_i, y_i)$ . In other words, insertion takes place at point  $A(x_i, y_i)$  if the following is true:

$$T_{R}(b(i - 1), m(i)) + T_P + \overline{AD} / V_r \geq \overline{CA} / V_b \quad (1)$$

where  $T_{R}(b(i - 1), m(i))$  is determined during the preceding insertion operation and  $\overline{AD} / V_r = T_{R}(m(i), b(i))$ . The  $i$ -th insertion point moves from point  $C(x_i, y_i)$  to point  $A(x_i, y_i)$  and waits for the robot, which travels in the  $y$  direction for a distance of  $\overline{AD}$  only. Then, the placement coordinate location at point  $C(x_i, y_i)$  is set by

$$C(x_i) = D(x_i) \quad \text{and} \quad C(y_i) = A(y_i) \quad (2)$$

Otherwise, when the robot reaches point  $A(x_i, y_i)$  from point  $D(x_i, y_i)$  before the board arrives at point  $A(x_i, y_i)$  from point  $C(x_i, y_i)$ , the possible interception of the board movement by the robot occurs at point  $B(x_i, y_i)$ . That is, the robot intercepts the  $i$ -th insertion point  $A(x_i, y_i)$ , at point  $B(x_i, y_i)$  and the following relation holds:

$$T_{R}(b(i - 1), m(i)) + T_P + \overline{DB} / V_r = \overline{CB} / V_b \quad (3)$$

Equation (3) can also be expressed as

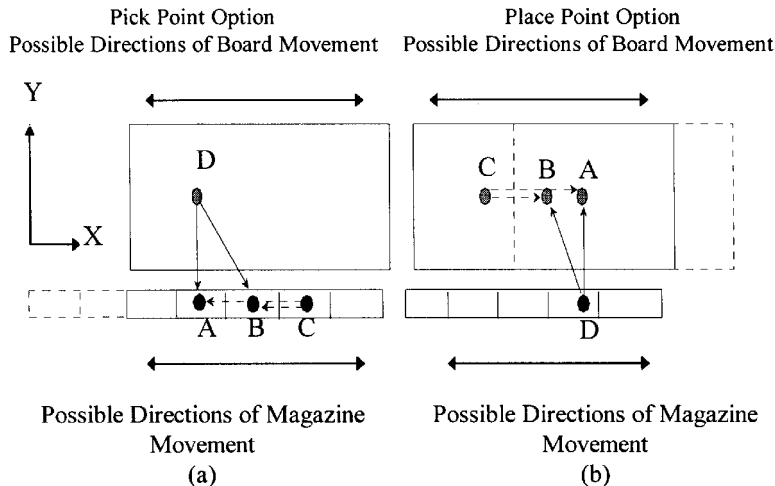


Figure 4. Possible movement of the DPP model.

$$TR(b(i-1), m(i)) + TP + \frac{[(D(x_i) - B(x_i))^2 + (D(y_i) - B(y_i))^2]^{1/2}}{Vr} = \frac{|B(x_i) - C(x_i)|}{Vb} \quad (4)$$

Also, the  $B(y_i)$  placement interception point by the robot at point  $B(x_i, y_i)$  is set by  $B(y_i) = A(y_i)$ .

In the same situation, to decide the pick-up coordinate location on a magazine is also necessary. It is similar to determining the placement locations on a board. Both points  $A(x_i, y_i)$  and  $B(x_i, y_i)$  are also possible pick-up locations, and  $C(x_i, y_i)$  is the relative coordinate location of the  $i$ -th insertion point in the pick-up sequence immediately after the robot finishes picking up the  $(i-1)$ -th component [figure 4(a)]. The point  $D(x_i, y_i)$  location has also been determined during the preceding insertion. The pick-up location  $A(x_i, y_i)$  is used when the robot reaches point  $A(x_i, y_i)$  from point  $D(x_i, y_i)$  after the magazine arrives at point  $A(x_i, y_i)$  from point  $C(x_i, y_i)$ . In other words, the pick-up takes place at point  $A(x_i, y_i)$  if the following is true:

$$TR(m(i-1), b(i)) + TI + \overline{DA}/Vr \geq \overline{CA}/Vm \quad (5)$$

the magazine indexes the  $i$ -th pick-up point,  $C(x_i, y_i)$ , to point  $A(x_i, y_i)$ . The pick-up coordinate location at point  $A(x_i, y_i)$  is given by

$$A(x_i) = D(x_{i-1}) \quad \text{and} \quad A(y_i) = C(y_i) \quad (6)$$

Otherwise, if the robot reaches point  $A(x_i, y_i)$  from point  $D(x_i, y_i)$  before the magazine arrives at point  $A(x_i, y_i)$  from point  $C(x_i, y_i)$ , then the robot intercepts to pick up the component at point  $B(x_i, y_i)$  and the following relational equation (7) holds:

$$TR(b(i-1), m(i)) + TI + \overline{DB}/Vr = \overline{CB}/Vm \quad (7)$$

where  $TR(b(i-1), m(i))$  is known and  $\overline{DB}/Vr = TR(b(i-1), m(i))$ . Equation (7) can also be expressed as

$$TR(b(i-1), m(i)) + TI + \frac{[(D(x_i) - B(x_i))^2 + (D(y_i) - B(y_i))^2]^{1/2}}{Vr} = \frac{|B(x_i) - C(x_i)|}{Vb} \quad (8)$$

and then the robot-magazine movement interception point is set  $B(y_i) = C(y_i)$ .

Equations (1), (3), (5) and (7) described above express both cases whether robot interception happens or not, while the robot begins its movement from the pick-up coordinate location to the place coordinate location  $D(x_i, y_i)$ , simultaneously the magazine begins to index

the proper component type to point  $A(x_i, y_i)$  or  $B(x_i, y_i)$ . In this study, we used the assembly cycle time ( $CT$ ) to evaluate the assembly efficiency. The shorter the assembly cycle time, the better the assembly efficiency. Equation (9) expresses total  $CT$  (not including  $TP$  and  $TI$ ) as a function of the total robot travelling distance divided by robot speed. If  $v_m$  and  $v_b$  are fast enough so that the assembly table and magazine can move to the points before the robot arrives, no robot interception of a moving board or magazine occurs in this optimal case. We achieve optimal assembly cycle time when equations (1) and (5) are true, and then the total cycle time in equation (9) also should be optimal.

$$CT = \sum_{i=1}^N TR(m(i), b(i)) + \sum_{i=1}^N TR(b(i), m(i+1)) \quad (9)$$

where  $m(N+1) = m(N)$ .

In fact, equations (1) and/or (5) may not hold in any case due to the speed limitation of  $v_m$  and  $v_b$ . To avoid the robot idling at  $A(x_i, y_i)$ , robot interception then occurs. Equations (3) and (7) represent the robot intercepts  $A(x_i, y_i)$  at  $B(x_i, y_i)$  such that no robot waiting time occurs, thus does the DPP model eliminate robot waiting time possible in the FPP model.

As mentioned above, the optimal condition (shortest  $CT$ ) happens when the robot travels in the Y direction and no robot interception occurs. In other words, the problem of increasing assembly efficiency can be converted to that of dealing with minimum overall robot interception distance.

### 3. Simulated annealing

The simulated annealing approach is a general combinatorial optimization technique used to solve difficult problems through controlled randomization. SA is a global technique that attempts to avoid local optimization traps by allowing occasional increases of criteria, and emulates the annealing process which attempts to force a system to its lowest energy-controlled cooling. The SA annealing process can be described follows: (1) the temperature is raised to a sufficient level; (2) the temperature is maintained at each level for sufficient time; and (3) the temperature is allowed to cool under controlled conditions until the desired energy is reached.

The initial temperature, the amount of time the system remains at this temperature, and the cooling temperature rate are referred to as the annealing schedule. If the system is cooled too fast, it may 'freeze' at an undesirable, high energy level. The freeze of a system at an undesirable energy state corresponds to the problem of undesirable local optimization.

The SA algorithm requires that we define: (1) a solution's configuration; (2) an objective (energy) function; (3) a generation mechanism; and (4) the annealing schedule. The most important issue in a SA algorithm is the annealing schedule consisting of: (1) the initial temperature; (2) a cooling function; (3) the number of iterations to be performed at each temperature; and (4) a stopping criterion to terminate the algorithm.

The general procedure for implementing a simulated algorithm is as follows:

- Step 1.* Set an initial temperature,  $T$ , and an initial solution  $x_0$ . Let  $f_0 = f(x_0)$  denoting the corresponding objective value. Set  $i = 0$ .
- Step 2.* Set  $i = i + 1$  and randomly generate a new solution  $x_i$ , and evaluate  $f_i = f(x_i)$ .
- Step 3.*  $\Delta Z = f_i - f_{i-1}$ . If  $\Delta Z < 0$  (downhill move) then go to step 5. Otherwise (uphill move) accept  $f_i$  as the new solution with probability  $e^{(-\Delta Z/T)}$ .
- Step 4.* If  $f_i$  was rejected in step 3 then set  $f_i = f_{i-1}$ .
- Step 5.* If the current objective value,  $f_i$ , is satisfied then 'freeze'. Otherwise, adjust the current temperature  $T$  according to the annealing schedule and go to step 2.

Detailed descriptions of the SA approach and its applications can be found in Rutrnbar (1989), Sridhar and Rajendran (1993), Koulmas *et al.* (1994), Schmidt and Jackmen (1995), and Chen *et al.* (1995).

#### 4. Simulated annealing in the DPP approach

To describe the proposed heuristic for the DPP model, the following notations are first given:

$T$	the initial temperature.
$M$	the number of iterations for each temperature level.
$CT_i$	the $i$ -th fitness function (finish assembly cycle time)
$KN$	the iteration number of temperature decreased
$NN$	the number of swap in insertion points and slots on each iteration
$TT C_i$	the $i$ -th optimal solution
$RP_i$	the $i$ -th energy probability in the $i$ -th iteration
$AP_i$	the $i$ -th random probability in the $i$ -th iteration
$R$	the rate by which the temperature is decreased
$X_i$	the $i$ -th iteration solution
$f_i(P_i, S_i)$	the $i$ -th solution in the insertion sequence $P_i$ and magazine assignment $S_i$
$\Delta Z$	the difference of $CT_i - TT C_{i-1}$

Next, the proposed procedure is presented in the following:

- Step 1.* Set  $T = 100$ ,  $I = 0$  and  $M = 0$ , and set an initial solution  $x_0 = f_0(P_0, S_0)$ .
- Step 2.* Set  $i = i + 1$ .
- If  $T > 5$  then  $NN = 3$ .
- If  $T \geq 0.1$  and  $T \leq 5$  then  $NN = 2$ .
- If  $T < 0.1$  then  $NN = 1$ .

The insertion points and component slots swapped  $NN$  times, respectively, then obtain the new solution  $x_i = f_i(P_i, S_i)$ .

Calculate the  $CT_i$  of  $x_i$ .

- Step 3.* Set  $M = M + 1$ .

If  $M \geq 30$  then  $T = T \times R(0.9)$ ,  $M = 0$  and  $KN = KN + 1$ .

- Step 4.* If  $CT_i < TT C_{i-1}$  then go to step 5, else  $\Delta Z = CT_i - TT C_{i-1}$  and  $RP_i = e^{(-\Delta Z/T)}$ . Select a probability for  $AP_i$ . If  $RP_i < AP_i$  then  $TT C_i = TT C_{i-1}$  and go to step 6.

- Step 5.* Set  $TT C_i = CT_i$  and  $x_i = f_i(P_i, S_i)$ .

- Step 6.* If  $KN \geq 15$  then 'freeze', else go to step 2.

#### 5. Simulation results

A numerical example from Wang *et al.* (1997) is presented in this section which demonstrates the proposed heuristic's effectiveness. Seven factors are selected in the study. Table 1 lists control factors and their experimental design levels. A total of 32 ( $2^5$ ) combination runs (table 2) are designed. For each combination, 30 sets of assembly locations and their component types are randomly generated by computer for simulation so that the averaged result is more objective.

For example, to obtain one set of robotics travel times in the case of  $N$  assembly points and  $K$  component types, we decide robot, board and magazine speeds, and randomly generate  $N$  placement locations on the board and  $K$  corresponding component types. Based on the DPP motion, to obtain one set of data takes about 5 min to run the program in BASIC language on a pentium-100

Table 1. Factors and their experimental design levels.

Factors	Levels (low/high)
Number of assembly points ( $N$ )	20/30
Number of component types ( $K$ )	10/15
Length of board ( $BL$ )	20/40 (unit distance)
Width of board ( $BW$ )	15/25 (unit distance)
Speed of robot ( $v_r$ )	6/12 (unit distance/unit time)
Speed of board ( $v_b$ )	3/5.5 (unit distance/unit time)
Speed of magazine ( $v_m$ )	2.5/4.5 (unit distance/unit time)

Table 2. Thirty-two combinaitns of five factors.

Combination	<i>B L</i>		<i>B W</i>		<i>V<sub>r</sub></i>		<i>V<sub>b</sub></i>		<i>V<sub>m</sub></i>	
	20	40	15	25	6	12	3	5.5	2.5	4.5
1	*		*		*		*		*	
2	*		*		*		*			*
3	*		*		*		*	*	*	
4	*		*		*			*		*
5	*		*			*	*		*	
6	*		*			*	*			*
7	*		*			*		*	*	
8	*		*			*		*		*
9	*			*	*		*		*	
10	*			*	*		*			*
11	*			*	*			*	*	
12	*			*	*			*		*
13	*			*		*	*		*	
14	*			*		*	*			*
15	*			*		*		*	*	
16	*			*		*		*		*
17		*	*		*		*		*	
18		*	*		*		*			*
19		*	*		*			*	*	
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25		*		*	*		*		*	
26		*		*	*		*			*
27		*		*	*			*	*	
28		*		*	*			*		*
29		*		*		*	*		*	
30		*		*		*	*			*
31		*		*		*		*	*	
32		*		*		*		*		*

PC using the SA approach. Thus, the shortest robotics assembly cycle time, the insertion sequence, and the assignment of corresponding components to specific magazine slots can be determined. One combination is the average of 30 data sets obtained in the same way through the SA approach.

The swapped principle of insertion point and component slots in the SA approach is that the higher temperature implies a greater swapping number. The initial temperature is set at 100 °C and progressively decreased according to the cooling schedule until frozen. If the *CT* of continuous 450 ( $M \times KN$ ) iterations is not decreased, then 'freeze' and a solution is obtained. Figure 5 shows an example of simulated annealing data (20 assembly points and 10 components). We can see how the annealing process works by the cooling schedule to freeze.

Simulation results are shown in figures 6–9. Each unit on the abscissa for these figures stands for a combination in table 2. According to these figures, we find that the performance of the SA approach is superior to Wang's approach. The average assembly times of 32 combina-

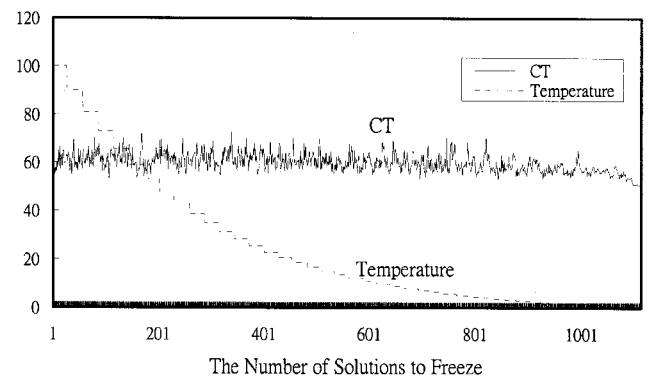


Figure 5. An example of freezing in SA ( $N = 20$ ,  $K = 10$ ).

tions for the SA and Wang's approach are shown in table 3. In the case of 30 assembly points and 15 component types, the average cycle times of the SA algorithm and Wang's algorithm are 78.46 time units and 88.71 time units, respectively. The reduction of average cycle time is 10.25 time units and the percentage of reduction is

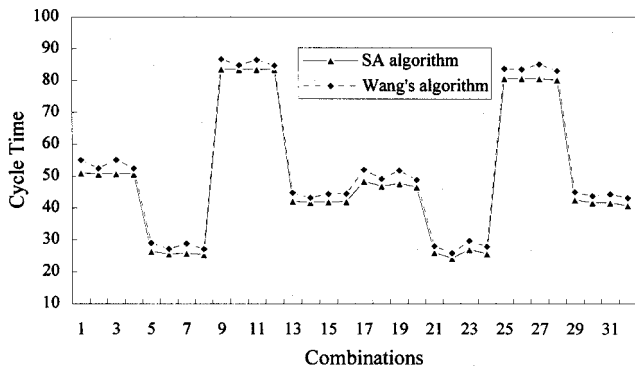


Figure 6. Simulation results for the case of 20 assembly points and 10 component types.

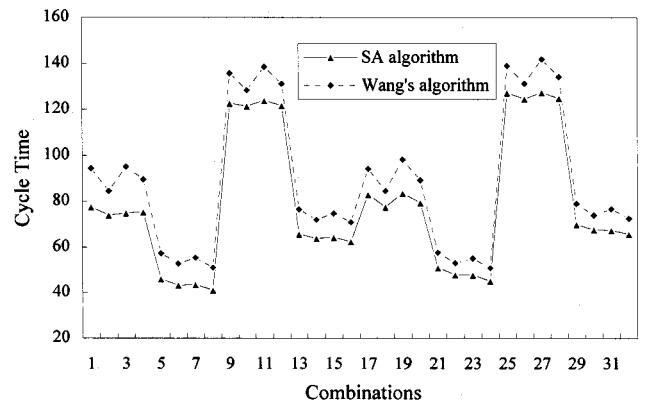


Figure 9. Simulation results for the case of 30 assembly points and 15 component types.

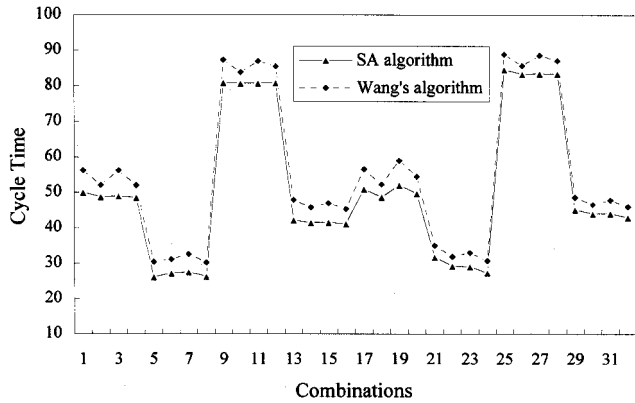


Figure 7. Simulation results for the case of 20 assembly points and 15 component types.

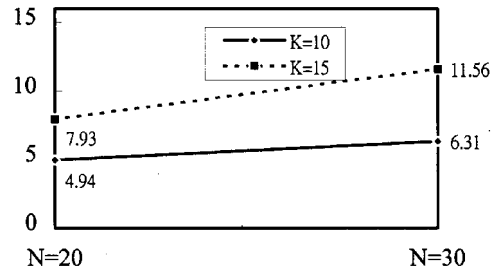


Figure 10. A comparison of the reduction percentage between  $N$  and  $\kappa$ .

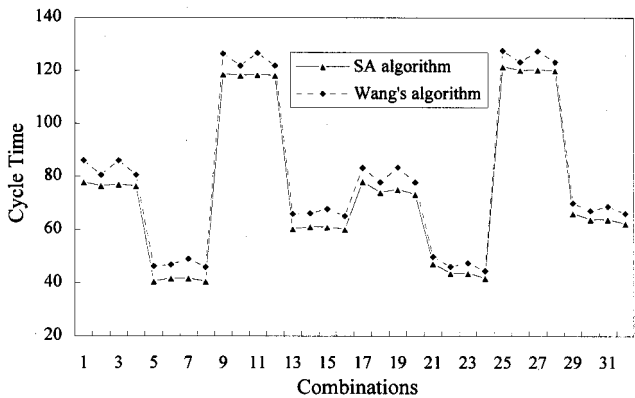


Figure 8. Simulation results for the case of 30 assembly points and 10 component types.

11.56%. In other words, if there is a product where  $N = 30$  and  $\kappa = 15$  and it is assembled by robotics, the production rate of the SA approach is 11.56% higher than Wang's. This is a significant improvement in terms of product due date or reduction of product cycle time. Moreover, figure 10 shows that the greater the insertion points and/or number of parts, the better the

Table 3. A comparison of cycle times.

Cases	Average $CT$ of Wang's approach	Average $CT$ of SA algorithm	$CT$ of reduction	Percentage of reduction
$N = 20, \kappa = 10$	52.25	49.67	2.58	4.94
$N = 20, \kappa = 15$	55.07	50.70	4.37	7.93
$N = 30, \kappa = 10$	80.19	75.13	5.06	6.31
$N = 30, \kappa = 15$	88.71	78.46	10.25	11.56

performance. If a product has more insertion points and/or component types than in the case of  $N = 30$  and  $\kappa = 15$ , it will enjoy a significant advantage of more than 11.5%.

### 6. Conclusions

The robotics assembly problem is a NP-complete problem. The development of the DPP model is an important



issue for robotics assembly. The robotics travel routing is based on the TSP method; however, the TSP method focuses on the fixed location solution and only considers the movement of robotics, but not the movement of boards and magazines. During the robotics assembly, the location of insertion points and magazine slots changes all the time according to the simultaneous movement of robotics, board and magazine. To aim directly at the problem of robotics travel routing with changing coordinates, a SA-based approach has been presented in this study to solve the problem. The simulation results demonstrate that the SA approach is more efficient than Wang's approach in all tested cases. Also, the more insertion points and/or number of parts, the better the performance.

The SA algorithm is a stochastic heuristic approach to avoiding the trap in local optimal. This study demonstrates that the SA approach is more suitable for solving the problem of occasionally changed coordinates than other existing approaches. The proposed approach can also be applied to the FPP model. Although the proposed approach takes some time program (each data set takes about 5 min to run in a pentium-133 PC), however, the saving of cycle time using the SA algorithm is still a significant improvement.

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