A DECISION SUPPORT SYSTEM FOR MULTI-PLANT ASSEMBLY SEQUENCE PLANNING USING A PSO APPROACH

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Abstract: In a multi-plant collaborative manufacturing system in a global logistics chain, a product can be manufactured and assembled at different plants located at various locations. In this research, a decision support system for multi-plant assembly sequence planning is presented. The multi-plant assembly sequence planning model integrates two tasks, assembly sequence planning and plant assignment. In assembly sequence planning, the components and assembly operations are sequenced according to the operational constraints and precedence constraints to achieve assembly cost objectives. In plant assignment, the components and assembly operations are assigned to the suitable plants under the constraints of plant capabilities to achieve multi-plant cost objectives. A particle swarm optimization (PSO) solution approach is presented by encoding a particle using a position matrix defined by the numbers of components and plants. The PSO algorithm simultaneously performs assembly sequence planning and plant assignment with an objective of minimizing the total of assembly operational costs and multi-plant costs. The main contribution lies in the new multi-plant assembly sequence planning model and the new PSO solution method. The test results show that the presented method is feasible and efficient for solving the multi-plant assembly sequence planning problem. In this paper, an example product is tested and illustrated.

1 INTRODUCTION

In assembly sequence planning, the components and the assembly operations are to be arranged in an ordered sequence under the constraints of operational constraints and precedence constraints to achieve the assembly cost objectives. In traditional assembly sequence planning models, the components are assembled in a single plant with fixed resources of assembly operations and limited cost considerations.

In a multi-plant collaborative manufacturing system in a global logistics chain, a product can be manufactured and assembled at different plants located at various locations. Therefore, besides assembly sequence planning, the components need to be assigned to the suitable plants to complete the required assembly operations in a multi-plant manufacturing system.

In this research, a decision support system for multi-plant assembly sequence planning is presented. The multi-plant assembly sequence planning model performs two tasks, (1) assembly sequence planning, and (2) plant assignment. First, in assembly sequence planning, the components and the assembly operations are ordered in an assembly sequence by considering the assembly precedence constraints and assembly costs. Second, in plant assignment, each of the components is assigned to a suitable plant by considering the capabilities and the costs of the available plants. A complete decision support system is presented by integrating both assembly sequence planning and plant assignment.

In this research, a particle swarm optimization (PSO) algorithm is developed for finding the solutions with an objective of minimizing the fitness function formulated by the total cost. A new encoding scheme is developed by defining a particle with a position matrix represented by the number of components and the number of plants. The new encoding scheme is suitable for simultaneously performing assembly sequence planning and plant assignment. The presented models and algorithms are implemented and tested.

This paper is organized as follows. Section 2 presents a literature review. Section 3 describes the

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models for representation of multi-plant assembly sequences. Section 4 presents the PSO algorithm. Implementation and test results are presented in Section 5. Conclusions are discussed in Section 6.

2 LITERATURE REVIEW

In the related research, it can be summarized that assembly sequence planning can be performed with three stages: (1) assembly representation and modelling, (2) assembly sequence generation, and (3) assembly sequence evaluation and optimization. Lin and Chang (1993) presented an assembly precedence diagram (APD) which is a directed graph representing the precedence of the components and the associated assembly operations. In Abdullah *et al.* (2003), a review of assembly sequence planning methods was presented. Lai and Huang (2004) presented a systematic approach for automatic assembly sequence generation. Chen *et al*. (2004) presented optimizing assembly planning through a three-stage integrated approach. Su (2007) introduced a geometric constraint analysis method to generate assembly precedences and to evaluate feasible assembly sequences. Dong *et al.* (2007) presented an assembly tree hierarchy to analyze geometric and non-geometric information for assembly sequence planning.

With a given set of components, sequencing the components may become a combinatorial problem. From the solution aspect, the PSO (particle swarm optimization) algorithm has been shown to be effective and efficient in solving different optimization problems. The PSO has been successfully applied to many continuous and discrete optimizations (Kennedy and Eberhart, 1995, 1997). Banks *el al*. (2008) reviewed and summarized the related PSO research in the areas of hybridization, combinatorial problems, multiple objectives and constrained optimization areas.

In this research, a PSO algorithm with a new encoding scheme is developed for concurrently performing assembly sequence planning and plant assignment with an objective of minimizing the total of assembly operational costs and multi-plant costs.

3 REPRESENTATION MODELS

3.1 Assembly Precedence Graph (APG)

An assembly precedence graph (APG) is modelled for representing the components and the assembly operations.

$$APG \text{ is a directed graph } G = (C, A), \tag{1}$$

where $C = \{c_1, \ldots, c_n\}$ = the set of components,
c_i = (*component node*) = a component, $i = 1, \ldots, n$,
$A = \{a_1, \ldots, a_m\}$ = the set of operation arcs between component nodes,

As shown in Figure 1, the example product A is a mobile phone with 13 main components. The APG of the product A is shown in Figure 2.

3.2 Assembly Precedence Matrix (APM)

An APG is transformed into an assembly precedence matrix (APM) for use in the PSO.

$$APM = \begin{array}{c} \\ c_{i=1} \\ c_{i=2} \\ \vdots \\ c_{i=n} \end{array} \begin{array}{c} \begin{array}{cccc} c_{j=1} & c_{j=2} & \cdots & c_{j=n} \end{array} \\ \begin{bmatrix} b_{11} & b_{12} & \cdots & b_{1n} \\ b_{21} & & \cdots & \\ \vdots & \vdots & b_{ij} & \vdots \\ b_{n1} & b_{n2} & \cdots & b_{nn} \end{bmatrix} \end{array}, \tag{2}$$

where c_i and c_j are components,
b_{ij} = 1 represents that component c_j must be assembled before component c_i.

APM for the example product A =

	01	02	03	04	05	06	07	08	09	10	11	12	13
01	0	1	1	1	1	1	1	1	1	1	1	1	1
02	0	0	0	1	0	0	1	1	0	0	1	1	1
03	0	0	0	0	1	0	1	1	0	0	1	1	1
04	0	0	0	0	0	0	1	1	0	0	1	1	1
05	0	0	0	0	0	0	1	1	0	0	1	1	1
06	0	0	0	0	0	0	0	1	0	0	1	1	1
07	0	0	0	0	0	0	0	1	0	0	1	1	1
08	0	0	0	0	0	0	0	0	0	0	1	1	1
09	0	0	0	0	0	0	0	1	0	0	1	1	1
10	0	0	0	0	0	0	0	1	0	0	1	1	1
11	0	0	0	0	0	0	0	0	0	0	0	0	1
12	0	0	0	0	0	0	0	0	0	0	0	0	1
13	0	0	0	0	0	0	0	0	0	0	0	0	0

3.3 Plant Capability Table (PCT)

A plant capability table (PCT) is developed for use in the plant selection and assignment. The general form of a PCT is shown in Table 1. In the table, a value of $t_{ij} = 1$ indicates that the component c_i can be assembled in the plant f_j. The PCT of the product A is shown in Table 2.

4 SOLUTION USING PARTICLE SWARM OPTIMIZATION (PSO)

A PSO algorithm is presented for simultaneously performing assembly sequence planning and plant assignment. The PSO algorithm is an evolutionary computation method introduced by Kennedy and Eberhard (1995, 1997). In PSO, each particle moves around in the multi-dimensional space with a position and a velocity. The velocity and position are constantly updated by the particle's own experience and the experience of the whole swarm. Given a problem, a particle can be encoded to represent a solution. Each solution, called a particle, flies in the search space towards the optimal position.

A particle is defined by its position and velocity. The position of a particle i in the D-dimension search space can be represented as $X_i=[x_{i1}, x_{i2}, \ldots, x_{id}, \ldots, x_{iD}]$. The velocity of the particle i in the D-dimension search space can be represented as $V_i=[v_{i1}, v_{i2}, \ldots, v_{id}, \ldots, v_{iD}]$. Each particle has its own best position $P_i=[p_{i1}, p_{i2}, \ldots, p_{id}, \ldots, p_{iD}]$ representing the particle's personal best objective (*pbest*) at time t. The global best particle is denoted as p_g and the best position of the entire swarm (*gbest*) is denoted as $P_g=[p_{g1}, p_{g2}, \ldots, p_{gd}, \ldots, p_{gD}]$ at time t. To search for the optimal solution, each particle adjusts its velocity according to the velocity updating equation and position updating equation.

$$v_{id}^{new} = w_i \cdot v_{id}^{old} + c_1 \cdot r_1 \cdot (p_{id} - x_{id}) + c_2 \cdot r_2 \cdot (p_{gd} - x_{id}), \quad (3)$$

where d =1, …, D, i =1, …, E (number of particles),
v_{id}^{new}: the new velocity of i in the current iteration t,
v_{id}^{old}: the velocity of i in the previous iteration (t - 1),
c_1 and c_2: constants called acceleration coefficients,
w_i: the inertia weight,
r_1 and r_2: two independent random numbers with a uniform distribution [0, 1],
p_{id}: the best position of each individual particle i,
p_{gd}: the best position of the entire swarm.

$$x_{id}^{new} = x_{id}^{old} + v_{id}^{new}, \quad (4)$$

where x_{id}^{new} is the new position in the current iteration t, x_{id}^{old} is in the previous iteration (t - 1).

4.1 Encoding Scheme

In the developed encoding scheme, a particle represents a feasible multi-plant assembly sequence. A heuristic sequencing and assignment rule for encoding and decoding is introduced as follows.

The position of particle i is represented by a position matrix, denoted as X_{ijk}, j = 1, …, (M+1), k = 1, …, N, where N is the number of components and M is the number of plants. In the heuristic sequencing rule, the values in the first row S of R_{s1}, R_{s2}, …, R_{sN} represent the ranked order values of the N components in an assembly sequence.

In each column, the values from row F_1 to row F_M represent the ranked assignment values for plant assignment of a component. In the heuristic assignment rule, the component C_k is assigned to the plant with the smallest value in the column of R_{1k}, R_{2k}, …, R_{Mk}.

$$X_{ijk} = \begin{array}{c} \\ S \\ F_1 \\ F_2 \\ \vdots \\ F_j \\ \vdots \\ F_M \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & C_2 & \cdots \; C_k & \cdots & C_N \end{array} \\ \begin{bmatrix} R_{s1} & R_{s2} & \cdots & R_{sk} & \cdots & R_{sN} \\ R_{11} & R_{12} & \cdots & R_{1k} & \cdots & R_{1N} \\ R_{21} & R_{22} & \cdots & R_{2k} & \cdots & R_{2N} \\ & & & & & \\ & & \vdots & R_{jk} & & \vdots \\ & & & & & \\ R_{M1} & R_{M2} & \cdots & R_{Mk} & \cdots & R_{MN} \end{bmatrix} \end{array} \quad (5)$$

where i = 1, …, E, where F_j is a plant, j =1, …, M, and C_k is a component, k =1, …, N,
R_{sk} represents the ranked order value of a component k,
R_{jk} represents the ranked assignment value for component k assigned to plant j.

In the heuristic rule for assembly sequencing, the values in [R_{s1}, R_{s2}, …, R_{sk}, …, R_{sN}] are sorted in an ascending order. The ranked order values represent the ordered position of component C_k in the assembly sequence. For example, if the values of row S are [4.5 1.1 3.2 7.6 5.3], then the ordered positions of (C_1, C_2, C_3, C_4, C_5) are (third, first, second, fifth, fourth). The assembly sequence is determined as (C_2, C_3, C_1, C_5, C_4).

In the heuristic rule for plant assignment, in each column of C_k, the component C_k is assigned to the plant with the smallest ranked assignment value in R_{jk}, for j = 1, …, M. For example, if there are four plants, the values of column C_2 are $[3.1 \;\; 5.8 \;\; 1.5 \;\; 6.9]^T$, then the smallest value is 1.5 of plant F_3. Therefore, the component C_2 is assigned to plant F_3.

4.2 Fitness Function

The cost functions include two major items. The assembly operational costs are mainly related to assembly sequencing, whereas the multi-plant costs are primarily related to the plant assignment.

(1) Assembly operation cost (*AOC*): The assembly operation cost is the basic operational cost for performing an assembly operation.
(2) Assembly tool change cost (*ATC*): To perform the assembly operation, proper tools are required. If two tools are different, then an assembly tool change cost is required.
(3) Assembly setup change cost (*ASC*): If two consecutive setups are different, then an assembly setup change cost is required.
(4) General transportation cost (*GTC*): Proper transportation cost for moving and handling between different plants needs to be defined.

The total cost function (*TC*) can be formulated as follows (unit: dollars).

$$TC = AOC + ATC + ASC + GTC \quad (6)$$

In the PSO evaluation, the objective is to minimize the fitness function as follows.

$$\text{Min } Fitness = TC, \quad (7)$$

Fitness: the fitness function value of a particle.

4.3 The PSO Algorithm for Multi-plant Assembly Sequence Planning

The flowchart is shown in Figure 3.

Step 1. Setup parameters.
(1) Set iteration $t = 0$.
(2) T_{Number}: the iteration (generation) number.
(3) P_{Size}: the number of particles.

Step 2. Initialize a population of particles $i = 1, \ldots, E$,with random positions and velocities.
(1) A particle i is defined by a multi-dimensional position matrix of $(N)*(M+1)$.
(2) The position of particle i is defined by X_{ijk}.
(3) The velocity of particle i is defined by V_{ijk}.

Step 3. Evaluate the fitness function.
(1) $t = t + 1$.
(2) $Fitness = TC$.

Step 4. Update the velocity of each particle i.

$$v_{id}^{new} = w_i \cdot v_{id}^{old} + c_1 \cdot r_1 \cdot (p_{id} - x_{id}) + c_2 \cdot r_2 \cdot (p_{gd} - x_{id}),$$

v_{id}^{new} is the new velocity in the current iteration t,

v_{id}^{old} is the velocity in the previous iteration (t-1),

Step 5. Move the position of each particle i.

$$x_{id}^{new} = x_{id}^{old} + v_{id}^{new},$$

where x_{id}^{new} is the new position in the iteration t,

x_{id}^{old} is the position in the iteration (t - 1).

Step 6. Check the feasibility of the solution and the number of iteration t.
(1) The precedence is checked by APM.
(2) The plant capability is checked by PCT.
(3) If ($t > T_{Number}$), then go to Step 7, else go to Step 2.

Step 7. Decode the best particle position and interpret the solution.

5 IMPLEMENTATION AND TEST RESULTS

In the presented decision support system, the models were implemented and tested by developing software on a personal computer with a 3.0 GHz CPU and 1 GB memory. The example product A as illustrated in Figure 1 is modelled and tested. The product A is a mobile phone with 13 main components. There are 4 available plants. The APG of the product A is shown in Figure 2. The APM of the product A is listed in the section 3 as described earlier. The PCT of the product A is shown in Table 2. The numerical values of the PSO parameters are tested with an experiment using a Taguchi's orthogonal array to find the best combination of parameters of $T_{Number} = 80$, $P_{Size} = 20$, $w_i = 0.9$, and $(c_1, c_2) = (2, 2)$.

Figure 4 shows that the computation converges after 32 generations with a cost of 258 (unit: dollars) and a computer time of 0.0312 (unit: seconds). The position matrix of the final solution is shown in Table 3. As shown in Table 4, the position matrix of the solution particle is decoded into assembly sequence and plant assignment information. The assembly sequence can be listed as C_{13}-C_{12}-C_{11}-C_8-C_6-C_9-C_{10}-C_7-C_4-C_2-C_5-C_3-C_1. The plant assignment information shows that the components C_{13}-C_{12}-C_{11} are assigned to plant F_2. The components C_8-C_6-C_9-C_{10}-C_7 are assigned to plant F_3. The components C_4-C_2-C_5-C_3 are assigned to plant F_2. Finally, the component C_1 is assigned to plant F_3 to complete the final product. As observed from the illustrative example, it shows that the developed model and algorithm present a feasible and efficient solution method.

6 CONCLUSIONS

In this research, a decision support system with a new multi-plant assembly planning model is presented to perform two tasks, assembly sequence planning and plant assignment. A PSO algorithm is developed for simultaneously optimizing assembly sequence planning and plant assignment. First, an assembly precedence graph (APG) is built. The assembly precedence matrix (APM) is modeled for checking feasibility of the sequences. The plant capability information is modeled in the plant capability table (PCT). Next, a PSO algorithm is presented to search for the solutions. A new PSO encoding scheme is developed for assembly component sequencing and plant assignment. A particle is represented as a position matrix defined by the number of components and the number of plants. The fitness function is formulated by integrating assembly operation cost, assembly tool change cost, assembly setup change cost, and general transportation cost. The test results show that the PSO method converges fast to reach a minimized cost objective. It can be generally concluded that the developed models and the PSO algorithm are feasible and efficient for solving multi-plant assembly sequence planning. Future research should be concerned with detailed analysis of the parameters and investigation of the problem complexity to reduce computational time.

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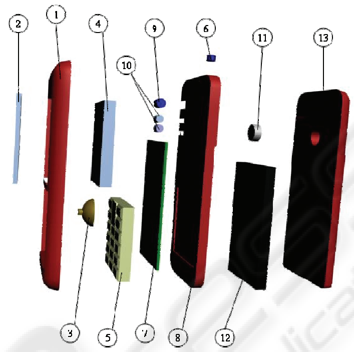


Component	Name
1	Top case
2	Screen cover
3	Main button set
4	LCD panel
5	Keyboard
6	Top button
7	Printed circuit board
8	Frame
9	Right button (Camera)
10	Right button(Sound)
11	Camera lens set
12	Battery
13	Bottom case

Figure 1: The example product A is a mobile phone with 13 main components.

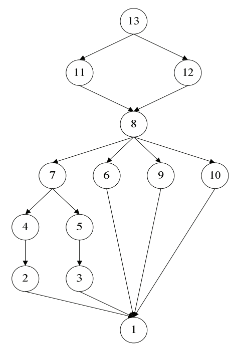


Figure 2: The APG of the example product A.

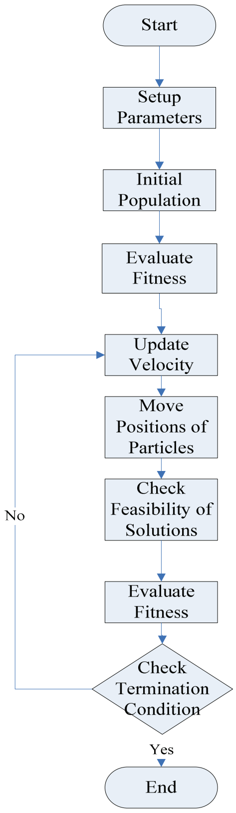
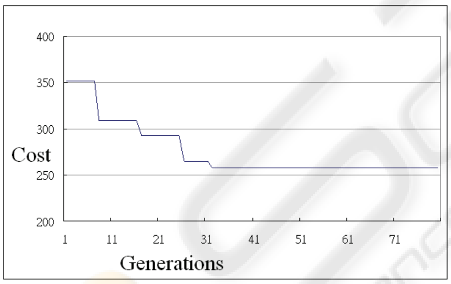


Figure 3: The flowchart of the PSO algorithm.



Cost (dollars)	258
Iterations (Generations)	32
Computer time (seconds)	0.0312

Figure 4: The test result of the PSO for product A.

Table 1: General format of PCT.

Plant f_j / Component p_i	1	2	…	m
1	t_{11}	t_{12}		t_{1m}
2	t_{21}	t_{22}	t_{ij}	t_{2m}
n	t_{n1}	t_{n2}		t_{nm}
t_{ij} = 1 indicates that p_i can be assembled in f_j, t_{ij} = 0 indicates that p_i cannot be assembled in f_j.				

Table 2: The PCT of the product A.

Plant f_i / Component p_i	F_1	F_2	F_3	F_4
1	0	0	1	1
2	1	1	0	0
3	1	1	0	0
4	1	1	0	0
5	1	1	0	0
6	0	0	1	1
7	0	0	1	0
8	0	0	1	0
9	0	0	1	1
10	0	0	1	1
11	0	1	0	0
12	0	1	0	0
13	1	1	1	1

Table 3: The solution position matrix for product A.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
S	6.17	4.68	4.84	4.67	4.75	4.52	4.67	4.29	4.57	4.59	4.12	4.12	3.03
F_1	14.37	6.71	7.33	4.97	5.25	14.66	11.73	12.35	10.88	12.32	14.67	14.52	4.47
F_2	13.76	4.54	0.43	3.6	3.76	17.65	13.56	15.83	11.67	13.21	4.18	3.9	2.39
F_3	3.96	13.61	14.79	12.73	19.74	2.82	5.87	9.91	3.89	3.39	13.05	14.6	3.13
F_4	4.57	11.12	13.75	14.53	15.74	3.58	13.33	14.5	5.6	5.04	15.4	13.82	6.01

Table 4: The solution of the multi-plant assembly sequence for product A.

Assembly sequence	1	2	3	4	5	6	7
Component	13	12	11	8	6	9	10
Assigned plant	F_2	F_2	F_2	F_3	F_3	F_3	F_3

Assembly sequence	8	9	10	11	12	13
Component	7	4	2	5	3	1
Assigned plant	F_3	F_2	F_2	F_2	F_2	F_3