MODELING & OPTIMIZATION FOR DISASSEMBLY PLANNING

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ABSTRACT

For the past two decades, increased efforts by both governments and the general public have been enforced through stricter legislations and more awareness to make manufacturing more environmentally conscious. Product refurbishing and component re-use are being applied on a wider scale worldwide. Disassembly, hence, has attracted more attention both in academia and the industry. Concepts and methods for disassembly planning should be further developed to support this new manufacturing environment. A semi-generative macro disassembly process planning approach based on the Traveling Salesperson formulation has been developed and is reported in this paper. Precedence graphs, which depict the precedence relationships between disassembly operations, are being utilized. The problem of generating optimal macro-level process plans is combinatorial in nature and proven NP-hard. Hence, a random-based hill-climbing heuristic based on Simulated Annealing is tailored for this problem. Finally, a realistic case study is presented to illustrate the working of the proposed methodology. The presented method produced good quality suboptimal solutions and is proven efficient in terms of computation time as demonstrated by the obtained results.

Keywords: Disassembly, Process Planning, Mathematical Programming, Non-traditional Optimization

1. INTRODUCTION

Short technology lifecycle and ever-changing customer needs shorten product life cycle [Ishii 1995]. This contributes to the increasing rate of products disposal at their end of life; these products are dumped to the environment causing different impacts [Chen 2001]. Many governments respond to the environmental problems caused by the industry by introducing and forcing new environmental legislations, which regulate waste management and recycling of products at its end-of life. Industries have to adapt with these new environmental regulations, which force the manufacturers to be held responsible of their products throughout the phases of its life cycle, including end-of-life phases. Product life cycle engineering (LCE) incorporates sustainability issues in product design at its early development stages [Hauschild et al. 2005]. LCE aims at optimizing the entire product life cycle including end-of-life phase through reusing, remanufacturing, or recycling retired products [Ishii 1995]. To facilitate these options product disassembly is needed at product end-of life.

Product disassembly is needed not only for end-of-life purposes, but also for product service and maintenance during product useful life. Because of this, product disassembly has been receiving more attention by both the industry and academia [Gungor and Gupta 1999]. Product disassembly can be defined as a systematic method for separating a product into its constituent parts, components, subassemblies or other grouping [Gupta and Taleb 1994]. Disassembly process has two main issues. First, is to determine to which level disassembly should be done. Disassembly level is usually based on the optimal economical and environmental benefits of product disassembly. For this paper, complete disassembly of the products is carried out; i.e., non-selective. Second is determining the optimal sequence of disassembly processes. Optimal sequence of the disassembly processes is the scope of this paper. Automated and hybrid disassembly systems lack the ability to handle the variations in the incoming flow of collected product. Hence, for the considered products range (household devices) where many variants exist for every model, manual assembly was advised. A case study of a coffee maker will be used to demonstrate the validity and effectiveness of the methodology.

2. CONCEPTUAL MODEL

Disassembly sequence planning is critical in minimizing resources invested and maximizing the level of automation of the disassembly process and the quality of parts recovered [Gungor and Gupta 2001]. Generally, an assembly that consists of many components can be decomposed via a multitude of sequences [Lambert 2003]. Although, the disassembly sequence planning literature has benefited from assembly sequence planning, there are several characteristic differences between the two processes. In other words, disassembly in most cases is not the reverse of assembly and hence, this invalidates the direct use of plans generated for assembly for the use of disassembly and vice versa [Gungor and Gupta 2001]. For a more detailed account of the main differences between the two process, see Lambert [2003].

Assembly plans are ordered sequences of operations that transform one configuration of parts into another. The amount and type of detail to be included in process planning is a critical design issue [Wolter 1991]; the more detail is included the more difficult the planning problem could be. Hence, it was suggested that planning be divided into two consecutive phases [ElMaraghy 1993]: macro planning concerned with high-level decisions such as identification of the planning tasks and their sequencing, followed by a more thorough micro planning, which would take into account the finer details of a disassembly plan such as setup (fixtures), tooling, end-effectors, trajectory planning, collision avoidance and generation of executable robot program files in case of robotic/flexible automated assembly- and the like.

The problem of macro-level disassembly planning is proven to be of combinatorial nature. For systematic algorithmic, graph theoretic and mathematical methods of the problem at hand, see de Fazio and Whitney [1987], whitney [2004], Homem de Mello and Sanderson [1991], and Henrioud and Bourjault [1991]. It is important to note that few attempts have been made in the literature to classify the different graphical representations and data structures used to model precedence relationships and sequences; for an example of these works, see Delchambre [1990]. In this paper, an implicit form of representations have been used, which is the precedence graph (figure 4).

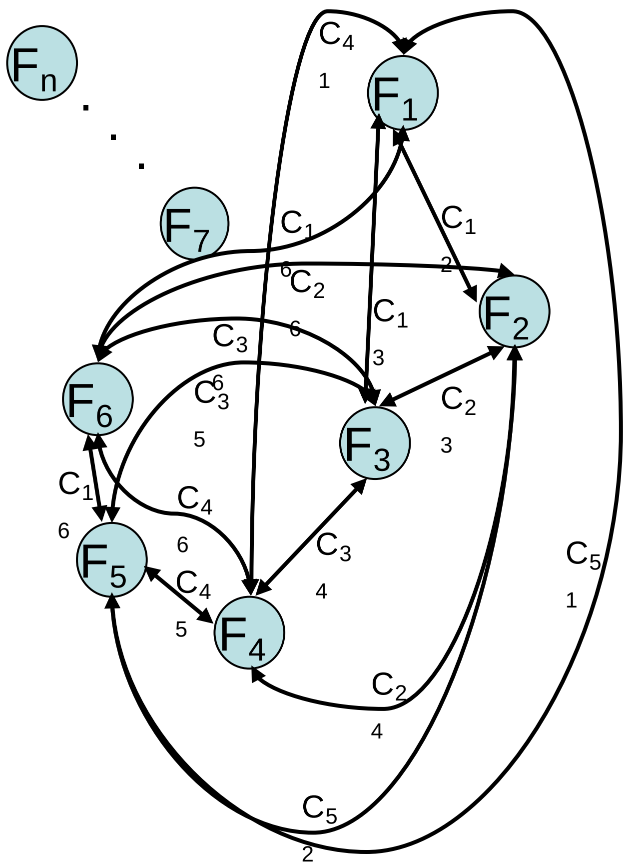

Figure 1. Problem is modeled as TSP problem, where n features $\{F_1, F_2, \ldots, F_n\}$ are to be sequenced

According to Kang *et al.* [2001], the sum of operation times in disassembly depends on tool change times because the pure operation time does not depend on its immediate preceding operations; hence, the non-dependent sequence disassembly time. Therefore, in the limit the optimum is the point where the changeover time is minimum. The problem of ordering n disassembly operations is formulated in this work as a Travelling Salesperson Problem (TSP), where each disassembly task is modelled as a city that has to be visited once and only once by a salesperson (see figure 1). The main constraint is precedence relations between disassembly operations. Sequence independent operation times are assumed.

Kroll and Hanft [1998] classified quantitatively a disassembly task according to task difficulty and performance. Their five categories included accessibility, positioning, force, base time and one last special category named *"special"* that covers circumstances not considered in their standard task model. In the proposed time objective function of the TSP model, it is required to find the optimal tour that would minimize the total distance travelled by the salesperson such that the optimal solution obtained contains no sub-tours. In this case, the total travel to be minimized is that of the disassembly tool such that all the tasks would be performed with a minimum total transient time between each two consecutive tasks. The time objective function, as mentioned earlier, is composed mainly of three different components: part orientation changes, tool changes, and tool traverse. Tool traverse in this case is quite indicative of accessibility. Rectilinear distances were taken. Currently, it is being investigated how to develop a CAD macro to measure the exact distances between successive features and avoid collision in the to-be-generated tool path. Setup change (part orientation) cost has been taken of the highest cost. A ration of 3:1 was used between the part orientation and the tool changeover cost components. As for the tool traverse, a speed of 0.1 unit distance/unit time was applied for the case study.

3. SOLUTION METHOD

In disassembly planning, the objective is to sequence a global set of operations of a given product, subject to a number of precedence constraints. This problem has already been proven to be NP-hard. Hence, a new search heuristic based on Simulated Annealing (SA) has been developed. SA is a hill-climbing search method suitable for solving combinatorial problems as well as continuous problems with multi-modal objective functions [Vidal 1993]. A search heuristic based on SA is tailored towards the problem at hand.

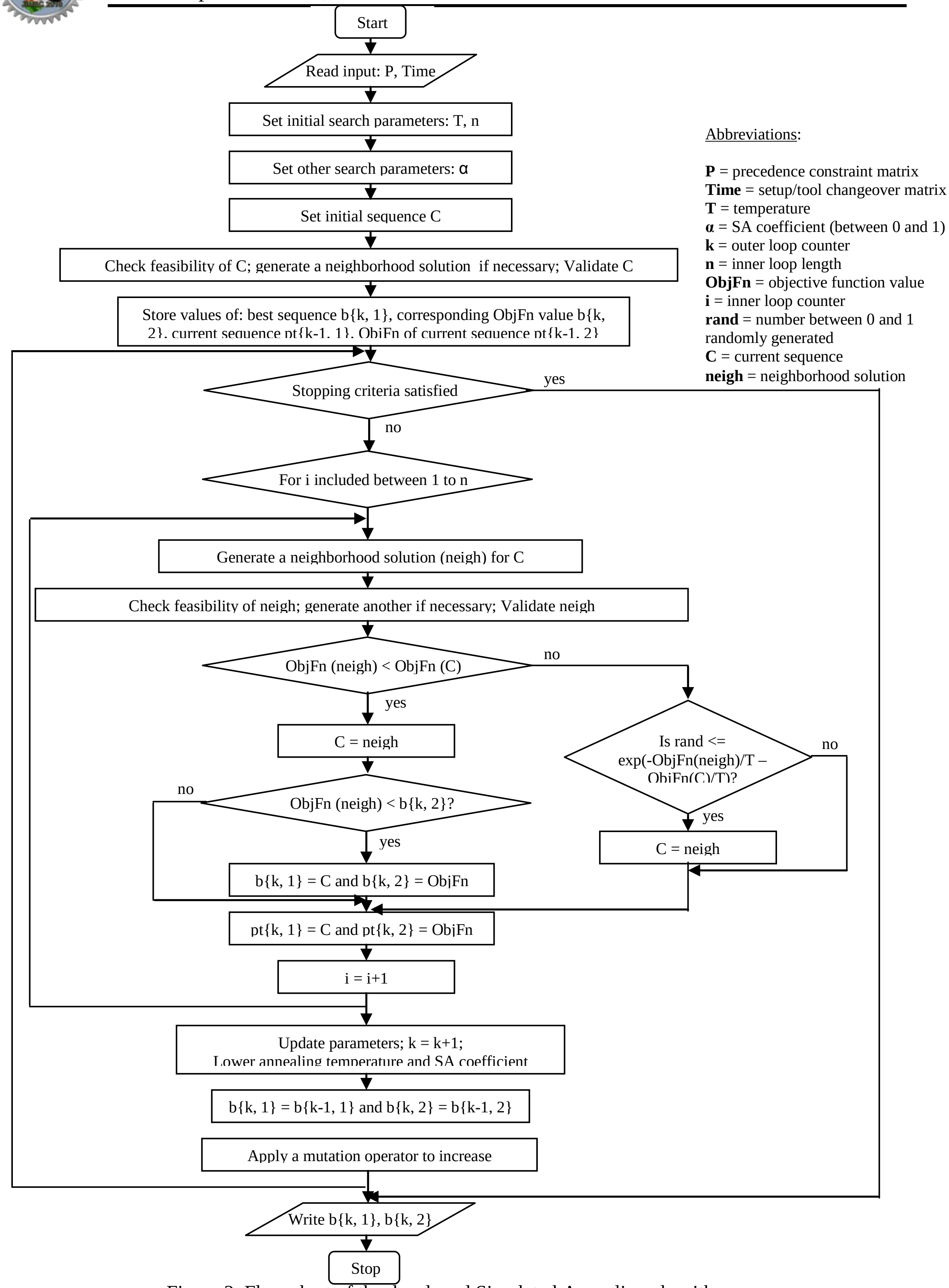

Figure 2. Flow chart of the developed Simulated Annealing algorithm

The proposed algorithm is detailed in figure 2; it is comprised of two nested loops, an outer loop where the annealing temperature (t) decreases and an inner one, which iterates a number of loops that decrease with t. In the inner loop new moves to neighboring solutions are accepted if they are of better quality to allow for hill climbing; lower quality solutions are also accepted with an exponential probability distribution. An algorithm is developed to validate the generated relaxed sequences against the precedence constraints and, then as needed, repair them if no valid feasible solutions are generated after a certain number of moves. The reason behind this validation process is that the solution space before the application of the constraints is factorial in size; it is also believed that the size of this part of the solution space is exponential in nature, which renders the search infeasible after applying the constraints. Therefore, it would be inefficient to wait until a feasible solution is generated randomly since the probability of its generation was shown to be poorly low. Also a Genetic Algorithms mutation operator is applied at the end of each outer loop to increase the chances of exploring more parts of the feasible solution space. The best solution found is always stored and updated. Generation of the objective function cost matrices for the different configurations of a given part was automated using an algorithm that exploited the symmetry property of the objective function matrices.

4. CASE STUDY

The product chosen is a household device. Mr. Coffee® is a popular brand of coffee makers. Figure 3 shows the coffee machine disassembled and in an exploded view. Part count for this example is 25 (see Table 1). The basic idea for the operation of the coffee maker is the use of electrical heating element (coil) which is assembled together with metal tube. The theory of operation of this device is as follows: the cold water contained in the water reservoir pass through the metal tube, the water reaches boiling due to the heat coming from the heating element; this forces the boiling water to climb up the metal tube to the top and then dripping through the grains inside the filter.

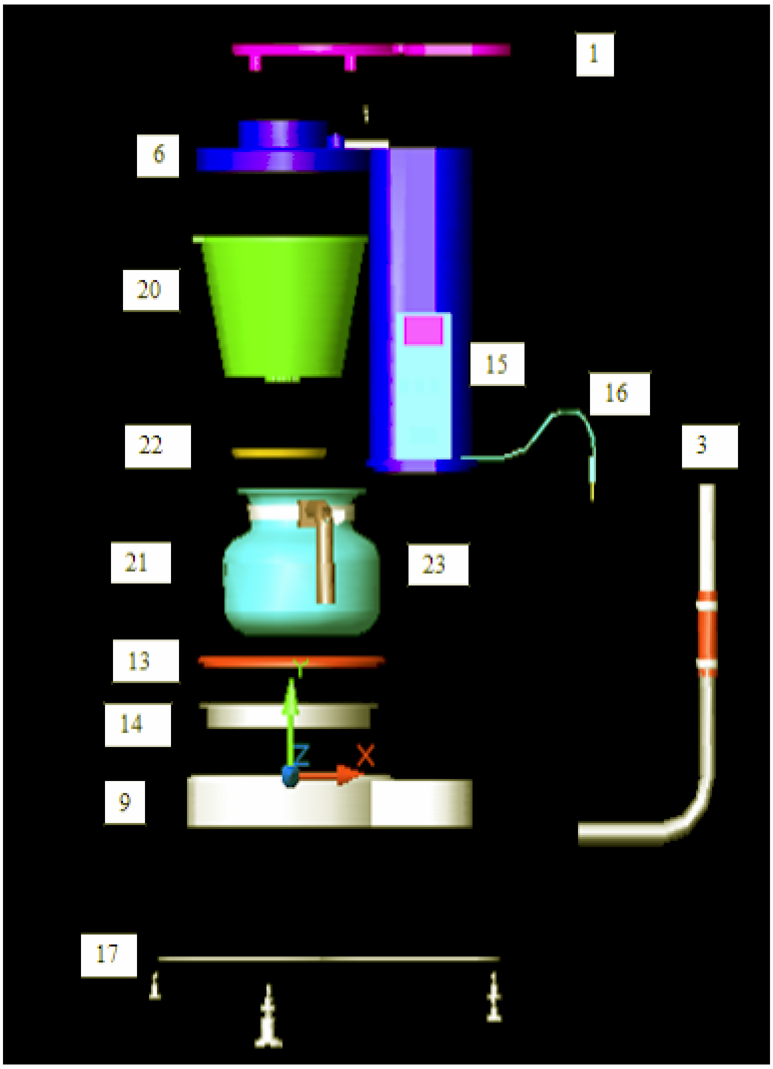

Figure 3. Exploded View of Coffee Maker

The purpose of the disassembly of the coffee maker could be either for part reuse or material recycling. In either case disassembly is required to obtain the parts for reuse or separating incompatible material. Since electrical wire cannot be used again because of safety reasons, hence, destructive disassembly for theses component is a valid option. All disassembly operations have been carried out manual. Complete disassembly was required (not selective). Non destructive disassembly was performed, except for the electrical wires and connectors as explained before. Setups used and preferred product orientations were selected based on the ergonomics and accessibility. No power tools were used. See figure 4 for the precedence diagram.

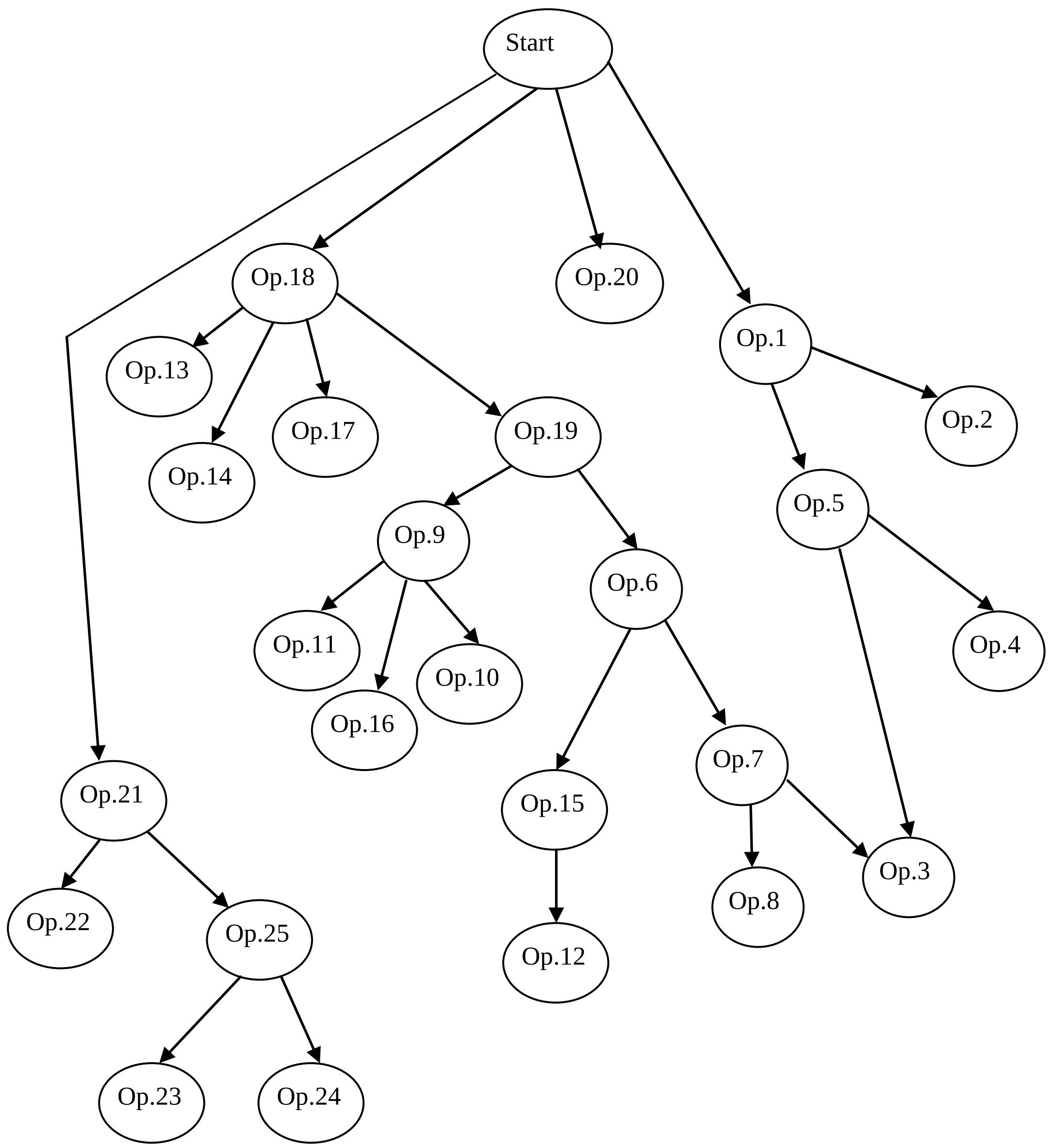

Figure 4. The precedence diagram

Disassembly operations with their respective required tooling, part orientations/setups and coordinates are given in Table 3 (see Appendix). It is worth noting that operations 18a and 18b are the same operation except that the screw driver's head used for each is different. Operation 18a is the scenario followed solving this case study. For table 2, tool 1 was no tool (i.e., by hand); tool 2 is screw driver (cross headed); tool 3 is screw driver (star headed); tool 4 is pliers and finally tool 5 is a wire cutter. For product orientation, "*V*" indicates a vertical product orientation, whereas "*H*" indicates a horizontal one. Note, when a disassembly operation involves the disassembly of more than one part, the farthest part is considered for the location info. That is to be more conservative. For the origin, see figure 3.

Ten SA runs were performed for the disassembly of the coffee maker. The near optimal operation sequences are given in Table 2. The mean and standard deviation of the objective function values are 8.8 and 1.95 time units respectively.

Table 1. Bill of Materials for the Coffee Maker

#	Part Name	Quantity	#	Part Name	Quantity
01	Top cover's screws	1	16	Electrical cord	1
02	Top cover	3	17	Bottom cover	1
03	Hot water pipe	1	18	Bottom cover's screws	6
04	Small metal plate	1	19	Water reservoir's screws	3
05	Metal plate's screws	2	20	Coffee filter case	1
06	Water reservoir	1	21	Pot	1
07	Clips	4	22	Pot's lid	1
08	Connection hoses	4	23	Pot's handle	1
09	Base	1	24	Pot's ring	1
10	Electrical wires	2	25	Handle's screw	1
11	Electrical connector	2			
12	Thermo switch	1			
13	Heating plate	1			
14	Support ring	1			
15	Control unit	1			

Table 2. Planning runs results for the coffee maker case study

#	Plan Sequences	Objective Function Value (Time Units)
1st Run	21 1 18 5 19 4 9 6 25 16 7 3 20 24 17 8 23 14 15 10 2 13 22 12 11	10.76
2nd Run	21 18 1 19 9 5 25 16 10 6 23 11 7 8 4 22 3 15 12 2 24 17 14 20 13	5.96
3rd Run	20 18 19 9 10 6 16 7 1 5 4 21 17 15 12 8 11 25 24 23 14 3 22 2 13	7.44
4th Run	19 9 6 1 18 16 5 21 14 7 10 2 4 15 13 22 12 25 24 20 8 3 23 17 11	10.38
5th Run	**20 18 1 5 19 6 2 21 14 9 25 24 23 15 17 7 3 13 22 8 12 11 10 16 4**	**5.84**
6th Run	19 1 21 20 6 25 5 18 9 2 17 14 22 13 10 11 23 15 4 24 16 7 8 12 3	10.00
7th Run‡	1 5 18 21 19 6 9 7 25 14 24 23 3 13 22 2 4 15 17 20 11 16 10 12 8	11.68
8th Run	18 21 19 1 20 9 25 6 7 5 17 14 2 24 23 13 3 22 16 15 11 8 12 10 4	9.44
9th Run	18 1 21 19 9 25 5 24 6 23 7 8 3 17 4 14 15 22 11 10 16 13 2 20 12	7.22
10th Run	18 1 21 5 19 9 6 7 25 16 3 20 24 8 23 17 10 2 4 14 22 13 15 11 12	9.42
	Mean	8.8
	Standard Deviation	1.95

‡ *Solution in bold face is the best one obtained.*

For this case study, it can be concluded from the small difference in magnitude (2.96 time units) between the best objective function values obtained and the averages, as well as the small values of the standard deviation that the results obtained were consistent. In many cases, more than one solution is obtained with close value of the objective function. The search algorithm parameters were tested to arrive at the best working ranges. Figure 5 is exemplary; it demonstrates the output and convergence for one of the runs.

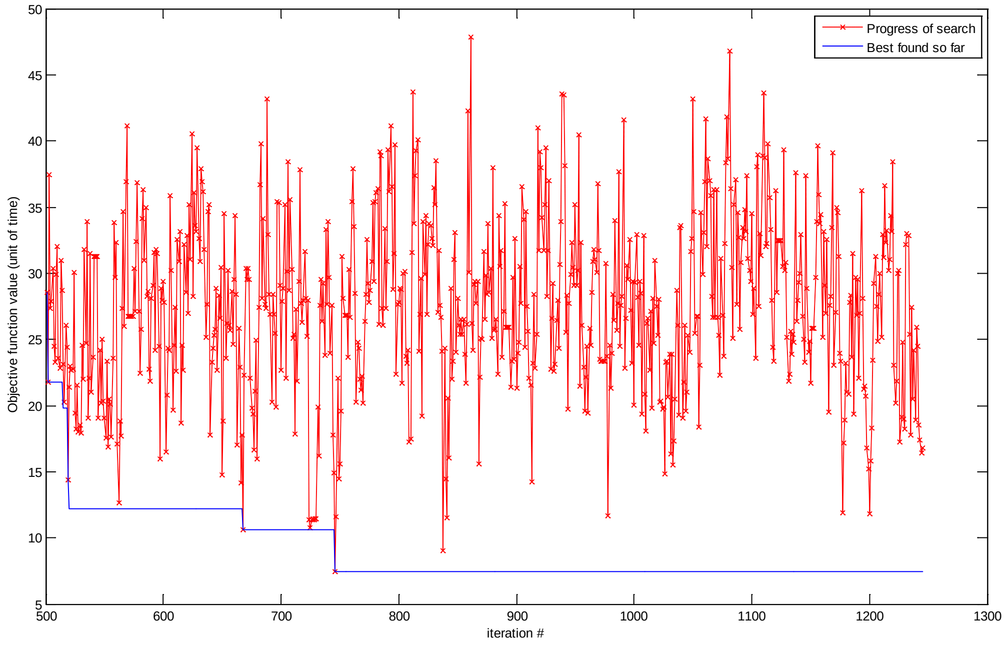

Figure 5 Conversion curve for one of the 10 SA runs performed

5. CONCLUDING REMARKS

A practical semi-generative macro-level planning approach suitable for disassembly has been developed. The macro-level disassembly process plan is formulated as a sequence of operations corresponding to a set of features in the part. The interactions between the product's different disassembly operations are modeled using Operations Precedence Graphs. A random-based heuristic is developed to obtain optimal or near-optimal solutions for the proposed TSP model. A validation scheme is developed and used to maintain the specified precedence relationships.

For the developed objective function of the TSP model, three cost components have been proposed: time required to change disassembly orientation, tool changeover time and tool traverse time. The last component (tool traverse) here is a measure of accessibility of the part to be disassembled. The proposed method is applied to a household device. Ten macro-level disassembly process plans are generated. Although this re-planning is normally done off-line, the developed heuristic has the advantage of being fast (few seconds on average per run on a 1.4GHz Dual Core with 3 GB RAM and 3 MB L2 cache memory); hence, multiple runs are possible to arrive at alternate solutions efficiently. Moreover, converting the code deployed on MATLAB™ (an interpreter) into an executable could further reduce the algorithm execution time. For future work, a hybrid heuristic with Genetic

Algorithms may be developed to transform the point search into a population search, and hence more than one sub-optimal solution could be obtained from a single run.

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APPENDIX

Table 3. Disassembly operations data for Coffee Maker

operation I.D. #	Operation Description	Disassembly time (s)	Setup (Product orientation)	Tool used	Location (x,y,z)
1	Unscrew top cover's screws	9	V	2	4,35,4
2	Removing top cover	6	V	1	5,35,5
3	Removing hot water pipe	5	V	1	3,30,2
4	Removing Small metal plate	3	V	1	-5,32,5
5	Unscrewing Metal plate's screws	9	V	2	-5,32,4
6	Releasing Water reservoir	6	H	1	5,30,5
7	unclamping Clips	4	H	4	3,22,2
8	Pulling Connection hoses	2	H	4	3,24,2
9	Releasing Base	5	H	1	5,0,5
10	Disconnect Electrical wires	9	H	5	3,-2,3
11	Disconnect Electrical connector	8	H	4	3,-2,3
12	Removing Thermo switch	6	H	1	4,17,3
13	Removing Heating plate	7	V	1	5,2,5
14	Removing Support ring	2	V	1	5,1,5
15	Releasing Control unit	5	V	1	4,16,3
16	Disconnecting Electrical cord	5	H	5	5,4,2
17	Removing Bottom cover	6	V	1	5,-3,5
18[a]	Unscrewing Bottom cover's screws	3	V	3	4,-3,4
18[b]	Unscrewing Bottom cover's screws	16	V	2	0,-3,0
19	Unscrewing Water reservoir's screws	13	V	2	4,6,2
20	Releasing Coffee filter case	6	V	1	0,27,5
21	Releasing Pot	2	V	1	0,22,5
22	Removing Pot's lid	2	V	1	0,23,5
23	Removing Pot's handle	4	H	1	0,20,5
24	Removing Pot's ring	12	V	1	0,20,3
25	Unscrewing Handle's screw	11	H	2	0,20,4