Cost-Based Evaluation for Product Selective Disassemblability

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Abstract Disassembly is required for product repairing, component reusing, and material recycling in the product lifecycle. Existing research in the area mainly focus on the complete disassembly for process planning algorithms, operation evaluations, and guidelines of product design. This paper introduces the evaluation of product selective disassembly planning. Cost measures are introduced in the evaluation of product disassemblability. Operating tools and tool changes are included in the analysis. A hybrid product representation is proposed to improve the existing method for the product selective disassembly analysis. The proposed method is verified using a case study.

1 Introduction

Product disassembly analysis at the early design stage will benefit the product with lower cost of product maintenance and end-of-life recycling operations. As the importance of product disassemblability in product repairing, component reusing, and material recycling [1], product disassembly has been investigated intensively [2]. Product disassembly can be classified into complete disassembly and selective disassembly. The complete disassembly separates an entire product into components, which can be processed as a reverse processing of the assembly. The selective disassembly takes some components from a product for the purpose of the product repair or the part replacement [3]. To replace failed parts from a

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product requires a process of the selective disassembly. There is no preplanned sequence available for the selective disassembly as the part failure is uncertainty in the product operation. The selective disassembly depends on the product status and operation conditions.

Product disassemblability is mainly decided in the product design stage. Existing research in the area mainly focuses on the complete disassembly in process planning algorithms, operation evaluations, and guidelines of design for disassembly. However, as the selective disassembly is planned based on the part selected for replacement or recycling, the plan has to be made based on the selected part, which cannot be planned in advance as in the case of completed disassembly in the design stage. The special attention has to be paid to product representation for selective disassembly planning. A well designed representation scheme can support the easy implementation of disassembly planning. An optimal disassembly plan needs the shortest operation to access the selected part with the least effort [4]. As the difference from the completed disassembly, selective disassembly plan has been challenges for the product representation and optimal sequence planning [5].

There are different methods for the generation and evaluation of disassembly plan such as optimization methods, design tools, or physical prototypes [6]. These methods provide different disassembly solutions with different measures for the optimal plan, such measures as shorter time used and fewer components moved. These different measures can be converted into the cost measure for the disassembly evaluation. Product disassembly cost includes the operation cost, tool cost, labor cost, and waiting for processing cost. Slavila and Decreuse used a fuzzy function as ‘criteria weight’ to evaluate the maintainability in product design [7]. Dong reviewed existing research and methods in disassembly modelling [8]. Desai surveyed disassembly algorithms and disassembly guidelines in product design [9]. However, there is a lack of effective methods in design analysis for selective disassembly with the consideration of operation constraints such as tools used and the tool operation. It is suggested that a systematic method should incorporate disassembly planning in product design for the quantitative evaluation. It is necessary to have an effective method to evaluate product selective disassemblability.

This research evaluates product disassembly based on the cost estimation. A cost-based method is developed to measure the product selective disassembly plan. The method uses a new hybrid product representation scheme, which simplifies product modelling to improve efficiency of disassembly planning. Operation and tool costs are included in the evaluation. Cost related to product structure constraints and tool changes in the operation is also considered. The analysis uses a combination of the automated process and user interactive process. A hybrid method simplifies the AND/OR graph to improve the matrix representation in the generation of disassembly plans. The disassembly plans are generated automatically based on the product representation. The plans are then used for the cost estimation to evaluate the product disassembly. In remaining parts of the paper, the research, and methods in the product disassembly planning and evaluation are introduced in Sect. 2. A cost-based method is proposed in Sect. 3 for the selective disassembly analysis and evaluation. The proposed system structure and implementation are discussed in Sect. 4. A case study is used to verify effectiveness of the proposed method in Sect. 5, followed by conclusions and further work discussed in Sect. 6.

2 Related Research

A feasible disassembly plan has to be generated before any evaluation of product disassemblability can be performed. The proposed method consists of product representation-based selective disassembly planning, and the cost-based evaluation for the product disassemblability. This section reviews the existing research and methods in these two areas.

2.1 Product Representation and Disassembly Planning

Product representation decides the method and efficiency of product disassembly planning and optimization. The existing product representation methods mainly include graph representation, matrix representation, state representation, and Petri Net presentation.

Graph representation for disassembly planning AND/OR graph is a commonly used graph in the product disassembly analysis. It seems a natural way using AND/OR graph to represent the relation of product disassembly. Nodes in the graph denote components or subassemblies, hyperarcs represent product disassembly tasks. Two components or subassemblies are joined to yield an assembly. Each node in the AND/OR graph may have k ($k > 1$) disassemblies to form an OR-relation. If a process splits a node into sub-nodes, parts, or subassemblies, there will be m hyperarcs linking the node to its sub-nodes, which forms an AND-relation [10]. An AND/OR graph contains all possible disassembly options. Using AND/OR graphs, all sequences of a product disassembly can be generated with a complete search of the graph.

AND/OR graphs provide detailed relations of a product structure for the search of disassembly plans. It is advised that designers consider disassemblability from beginning of the product design using AND/OR graphs. Since a disassembly often happens after the product is made, the design stage normally only considers the product assembly. Some disassembly sequences may not exist in the corresponding AND/OR assembly graph. AND/OR graphs usually include unnecessary search space for the disassembly, which leads to the increasing computation in disassembly optimization. In addition, using AND/OR graphs, the disassembly precedence relationships are limited to simple AND and OR relationships. A product may contain complex AND/OR relationships. Therefore, there is much research to improve AND/OR graphs for the optimal disassembly planning [11].

Li suggested a hybrid graph that contains both undirected and directed edges to connect nodes [12]. This hybrid graph is called disassembly constraint graph. In the hybrid graph, nodes denote components or subassemblies, undirected edges represent geometrical relations or contact constraints between two components. The directed edges describe the precedence information for the priority of a part disassembly or non-contact constraint. The hybrid graph includes a reasoning mechanism to simplify the search space. The representation can represent both geometrical and precedence constraints for a product disassembly. It is usually a sub-graph of the AND/OR graph, which has a small search space for the disassembly planning.

Matrix representation for disassembly planning The matrix-based representation is the most commonly used method to explicitly describe information of products for the disassembly analysis. Matrices can represent constraints, process precedence and structure information of a product. Graph-based representation schemes are often converted into a matrix representation [13]. Different matrices have been defined to represent product information, such as part positions, connections, fasteners, and interferences [14]. Matrix-based representations can use decimal or binary values.

Decimal representation matrices often include logic, constraint, and precedence relationships of components without direction relationships of components. A relationship matrix can be derived from a directed graph for both component connections and precedence information [20]. It can separate fasteners and functional elements in a product. It is also necessary to know the physical link and layout interference of the functional elements. The physical link is the way of component connections. The layout interference reflects the precedence among functional components. Binary representation matrices often incorporate the direction information into one matrix. Other matrices can also use the binary representation such as interference matrix, connection matrix, disassembly sequence matrix, and contact matrix.

State representation for disassembly planning Using state representation, product disassembly relations are represented using a single disassembly graph based on the product connective state with binary variables. A true state indicates an established corresponding connection. Actions are transitions between states [15]. From the state representation, a large number of possible sequences may be derived. The selection of sequences is based on heuristic rules. As all possible disassembly sequences have to be searched to evaluate disassembly plans, the state representation method is not efficiency for the evaluation of product disassembly.

Petri Net representation for disassembly planning Petri Net provides a tool for discrete systems modelling [8]. A Petri Net-based disassembly model is regarded as a special case or variant of AND/OR graphs [12]. Using Petri Net method in product disassembly planning includes the development of disassembly precedence matrix, generation of disassembly Petri Net, and near-optimal search for disassembly plans. Petri Net representation schemes provide visual tools for showing processes of the product disassembly.

2.2 Cost-Based Evaluation of the Disassembly Plan

Cost is a common measure of product evaluation in product design, manufacturing, assembly, sale, product using, recycling, and disposal. The cost-based evaluation can be used to select an optimal plan from different disassembly solutions. Different methods have been proposed for using cost in the performance evaluation of disassembly plans, including intuitive evaluations, parametric techniques, variant-based models, and generative cost estimations [16]. The cost estimation can also use a bottom-up approach from a starting point of the least cost component aggregating to the total product cost [17]. Cost items included in evaluation models have the impact on efficiency and feasibility of the evaluation methods. The disassembly related time is a major part of the repair time. The statistical data can be used to form the cumulative distribution function based on available data for the cost calculation.

There are different methods for disassembly planning based on product representations [18, 19]. Operational research approaches are easy to be implemented based on the product representation. Other methods such as GA and ant colony are suitable to the disassembly sequences optimization from multi-sequences, or optimal disassembly sequence selections. We propose a heuristic rule-based recursive process with the cost measure for a feasibly selective disassembly plan optimized from alternatives of disassembly sequences.

3 Proposed Methods

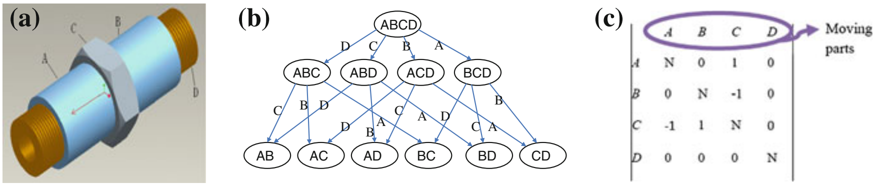
A hybrid method is proposed in this research to generate selective disassembly plans using a simplified graph and improved matrix representation. The plans are then used for the cost estimation to evaluate the product disassemblability. In the simplified graph, product disassemblies are represented by only left components after a disassembly. Disassembly sequences are established using levels of product tree structures. Nodes in the tree represent components remaining after disassemblies. The improved matrix is used to indicate the information of part constraints for the disassembly operation. In the matrix, operation constraints are limited into x, y, z directions of positive and negative linear motions. The cost estimation method is built based on the disassembly operation and tool costs.

3.1 Framework

There are two major functions in the proposed method: selective disassembly planning and cost-based evaluation. The disassembly planning determines operation sequences of a chosen part in a product for disassembly. The cost is used as a measure of the optimal disassembly, which is then simulated in a 3D virtual environment to verify the solution. Product graph and representation matrix are formed based on the product structure. For a certain operation of the chosen part, the disassembly cost is assumed as known data. In following discussion, we use the module to represent a subassembly. A module can be operated as a part or a group of parts in a disassembly. The cost is related to the operation time, and time for using tool and the tool changes. Therefore, the disassembly efficiency depends on parts' constraints and operations. The operation cost is decided by both parts' and tools' operations.

3.2 Details

Product representation Product structure is represented using a simplified tree graph and improved matrix. The simplified AND/OR tree graph only keeps the remaining parts in the product after each disassembly. The improved matrix contains both part relationships and constraints. The part relationship is from the existing product design. The constraint here is the spacial limit from surrounding parts for disassembled part moving. A constraint is the restriction of part's operation in the disassembly. The restriction limits a disassembly or increases the operation cost. Constraints may also decrease the complexity of an AND/OR tree graph and help to find disassembly sequences. For example, considering the example of parts' connections in Fig. 1a, there are four disassembly sequences shown in AND/OR tree graph of Fig. 1b, ABCD->ABC-D, ABCD->ABD-C, ABCD->ACD-B, and ABCD->BCD-A. However, based on the product structure, we can ignore the sequence ABCD->ABC-D and ABCD->ABD-C because parts C and D cannot be moved firstly as part C is blocked by parts A and B, and part D is blocked by part C. We use a matrix to represent these constraints shown in Fig. 1c. Numbers on the matrix diagonal are defined as 'N,' as there is no self-constraint applied for any part. Part A or B does not have any restriction from other parts; its state is thus set as 0 including B-A or A-B, D-A, and D-B. Using the linear motion assumption of the part operation, constraint values between parts can be set to be 1 and -1, which stands for constraints at positive and negative moving directions, respectively. The sum of values in each column of the constraint matrix is defined as 'constraint' of the selected part for disassembly to indicate its total number of constraints from other parts. For a part with three linear motion freedoms, the maximum constraint value will be 6 in both positive and negative



	A	B	C	D
A	N	0	1	0
B	0	N	-1	0
C	-1	1	N	0
D	0	0	0	N

Fig. 1 **a** Product example, **b** simplified AND/OR graph, **c** constraint matrix

directions. For the sample shown in Fig. 1a, there is only one linear motion freedom. The movement from part C to A is assumed in the positive direction. Thus, the states of C-A and C–B are set as 1 and −1, respectively. Therefore, the constraint value of part C in Fig. 1c is 2. Once a constraint is removed, the chosen part in this direction will be free to move. This is a dynamic processing based on the moving part and remaining parts. For example, when part A or B is moved, part C can be moved in positive or negative direction. The constraint value of part C will be decreased by 1 accordingly.

Constraint detection and disassembly sequence generation The operation direction decision finds part's degree of freedom (DOF) to decide movable directions of the selected part for disassembly. It is to find constraints for each part to be moved. For a selected part, the sum of values of its column in the matrix is the total constraints in movable directions. To build the matrix, the value is set for each part's movable direction between the selected part and its connected parts as 1 or −1. The values in matrix diagonal are set as 'N'. The matrix is used for the input information of the disassembly sequence generation. The matrix is updated along with the disassembly process. For example, for the structure shown in Fig. 1a, when part A is removed, the constraint of C-A becomes 0. Therefore, its value in the matrix will be updated to 0 accordingly. The total constraints of part C will be 1 in the updated constraint matrix. A counter is used to calculate the current constraint of a moving part.

Assumptions for cost calculation and disassembly operation Product disassembly time consists of operation preparation time, disassembly time, and post-processing time. Direct time of moving parts and related cost are only considered in this research. The cost is calculated based on the unit time cost. Therefore, the total cost of a part disassembly operation is defined as the sum of part's moving cost and constraint release cost. The moving cost depends on paths of the moving part. The product constraint matrix is used to generate possible moving paths for a part disassembly operation. If the chosen part is required moving only in one direction, the operation is assumed to take 1 unit time and its movement cost is set as 1 unit dollar. Otherwise, the movement time will be timed by n, and the related cost will be $n when there are n moving directions required. The constraint cost is the current constraint value of a selected movable part. For example, the moving time of part C shown in Fig. 2a is 1 unit time, and constraint release time of part C is also 1 as part B will limit the operation of part C in one direction. We therefore

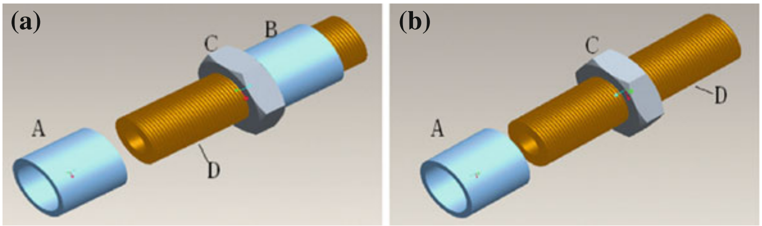


Fig. 2 Different part moving conditions

assign the total operation time of the disassembly of part C as 2, which results from its constraint release time 1 plus its movement time 1. For the position of part C shown in Fig. 2b, the total movement time is only 1 as there is no constraint for part C to move. The cost estimation of a part disassembly is mainly based on the operation constraint. However, the tool used for disassembly operations may be different for different parts. Using different tools will affect the disassembly time. For example, an adjustable spanner is more flexible than a fix-sized handle tool, but it will take more time to adjust if different sized parts to be operated. The analysis will thus include both tool change and operation time for final disassembly cost estimation. When the tool is changed in an operation, there will be an extra cost added. The tool change time is assumed as 1 unit time, and its cost is 1 unit dollar for each change in the operation. That is, if there is a tool change required in a disassembly operation, the total cost will be added by 1 unit dollar. Therefore, the operation cost related to a disassembly is calculated using following equation: $C = (Wp \times Tpart\ moving + Wr \times Trelease\ constraint + Wt \times Ttool\ operation + Wc \times Tchange)$, where Wi is the cost of each item in each unit time. The criteria in the cost-based evaluation include part constraints and tool operations in the disassembly. The weight and items can be adjusted based on the data collected in the real applications.

4 Implementation

Proposed methods include the product representation, disassembly sequence planning and cost evaluation. The connection of different steps in a disassembly plan is represented using '->.' Once a part is disassembled, the part's number will be deleted from the next sequencing process.

The selective disassembly analysis consists of three processes. The first process is the operation analysis to decide moving paths of the chosen part for disassembly. The disassembly operation is simulated in a 3D visual interface. The second process is the cost calculation of the generated disassembly sequences. The third process is the optimization of disassembly sequences based on the cost measure. For example, for the disassembly sequence generation of a selected part A as shown in Fig. 3, the process will start searching the part constraint information to generate the sequence by releasing the constraint for the part removing step by step until Part A is approached. If part A is a father node, all parts under part A are processed as a subassembly in a module which will be disassembled together with part A.

For the completion of a disassembly sequence, if a subassembly with more than one part is disassembled, the parts in the disassembly model will be stored in a temporary data set for the following process. It is an iterative process to check the part state in the process. The alternative disassembly sequences are evaluated based on the cost measure. An optimal solution will be a disassembly with the minimum cost.

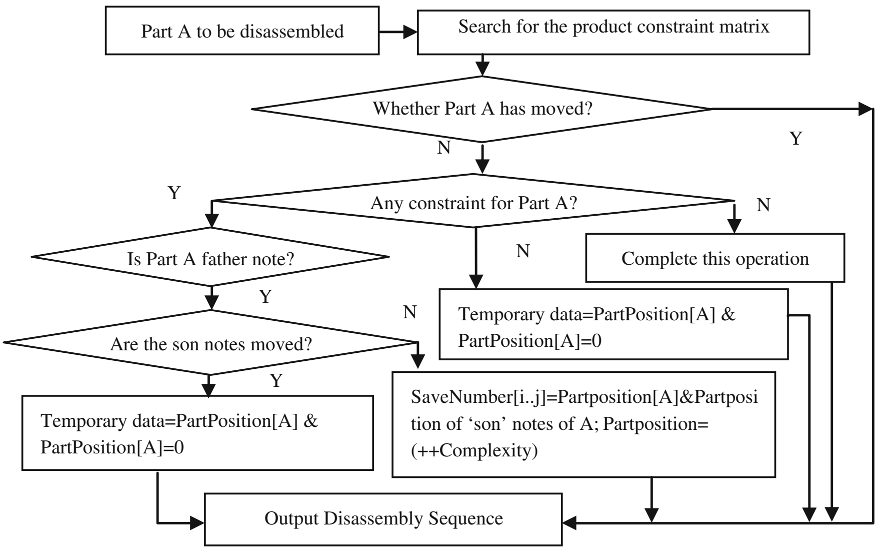


Fig. 3 Flowchart of the selective disassembly sequence generation

5 Case Study

A product shown in Fig. 4 is used for the case study to verify the proposed method. The product model is built using Solidworks. The disassembly planning and cost analysis are integrated in a 3D virtual environment, EON Studio [20]. Numbers are used as labels for different parts for coding convenience. If a part number is greater than ten, brackets are used to indicate its sequence in a disassembly plan. For example, the part number 12 will be indicated as (12) for the difference from parts 1 and 2. The product is a wrist of a painting robot. The wrist product consists of a base and three joints, each joint contains many parts. Figure 4 shows the product model and its main parts.

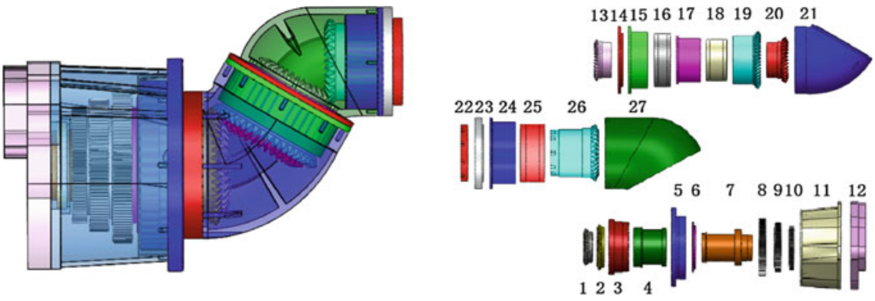
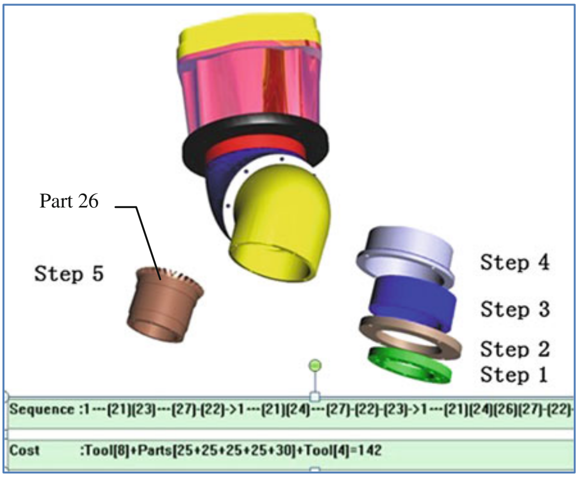


Fig. 4 Product and its components



Sequence :1---(21)(23)---(27)-(22)->1---(21)(24)---(27)-(22)-(23)->1---(21)(24)(26)(27)-(22)-

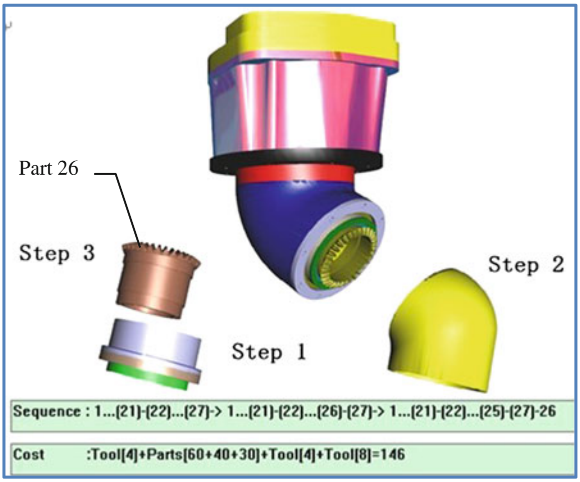
Cost :Tool[8]+Parts[25+25+25+25+30]+Tool[4]=142

Fig. 5 Disassembly simulation of part 26 (operation 1)

Using the proposed method based on product's structure, alternative disassembly sequences are generated for a selected component to be removed for replacement. Normally, there exists more than one of feasible operation sequences for a selected part. For example, if Part 26 is selected to be disassembled. For the disassembly sequence: 1… (27)->1…(21)(23)…(27)-(22)->1…(21)(24)…(27)-(22)-(23)->1…(21)(24)(26)(27)-(22)-(23)-(25)->1(21)(26)(27)-(22)-(23)-(25)-(24)->1 …(21)(27)-(22)-(23)-(25)-(24)-(26), part 26 can be removed after parts (22)(23)(25)(24). But for the sequence 1…(27)->1…(21)-(22)…(27)->1…(21)-(22)…(26)-(27)->1…(21)-(22)…(25)-(27)-(26), Part 26 moves with all the parts of Joint 3 together, then it can be disassembled after the removal of Part 27. Obviously, the time spent for these two operations are different.

Simulation is used to show disassembly operations for the solution verification. A user interface is developed for visualizing the disassembly process and for users to select part to be removed. A part can be interactively chosen for the disassembly. If there is no constraint for the selected part, the part can be disassembled directly. Otherwise, the part constraints will be released one by one until the selected part is reached based on the constraint matrix. The cost of operations is calculated based on the operation time and time for tools change. Figures 5 and 6 show different operations for the disassembly of Part 26. An optional sequence is selected based on the minimum operation cost. The cost calculation is programmed using Java script language embedded in EON Studio. A 'check sequence' selection is designed for users to compare the cost of a current operation with other disassembly sequence cost if there are different operation solutions. The compared results are used for the disassembly sequence evaluation and the optimal selection.

For the product disassembly in this case study, two types of screwdrivers are used for different types of screws as shown in Fig. 7. It is assumed that the screwdriver operation will need one unit time. For the disassembly of Joint 3, there are four screws to be disassembled. The flange has eight screws and the cover have four screws to be removed. As shown in Fig. 8, in order to disassemble Part 19,



Sequence : 1...(21)-(22)...(27)-> 1...(21)-(22)...(26)-(27)-> 1...(21)-(22)...(25)-(27)-26

Cost :Tool[4]+Parts[60+40+30]+Tool[4]+Tool[8]=146

Fig. 6 Disassembly simulation of part 26 (operation 2)

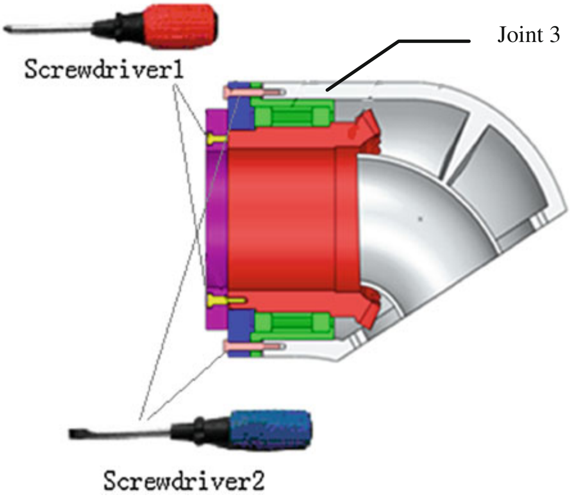
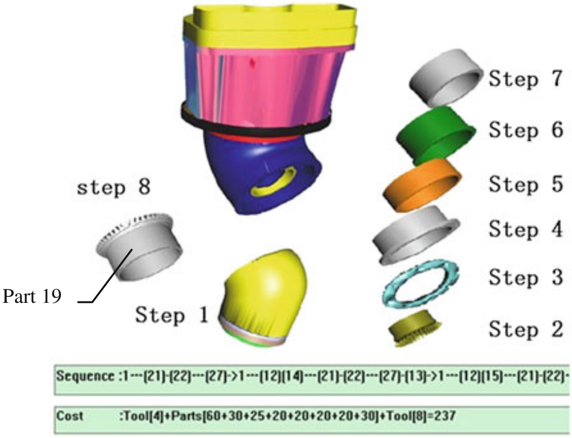


Fig. 7 Tools used in the disassembly



Sequence :1···(21)-(22)···(27)->1···(12)(14)···(21)-(22)···(27)-(13)->1···(12)(15)···(21)-(22)-

Cost :Tool[4]+Parts[60+30+25+20+20+20+20+30]+Tool[8]=237

Fig. 8 The analysis with the tool change cost

Table 1 Disassembly cost for part 19 with tool changes (unit dollar)

Sequence	Time cost	Tool cost	Total cost
(22)…(27)-(13)-(14)-(16)-(15)-(18)-(17)-(19)	225	13	238
(22)…(27)-(13)-(14)-(18)-(17)-(16)-(15)-(19)	225	13	238
(22)…(27)-(13)-(14)-(18)-(16)-(17)-(15)-(19)	225	13	238
(22)…(27)-(13)-(14)-(18)-(16)-(15)-(17)-(19)	225	13	238
1…(12)-(21)-(20)-(19)	180	5	185

total eight operation steps are required. The time used is then converted into cost based on the cost per unit time. The tool cost is 4 unit dollars for the first step while tool costs in rest several steps are 8 unit dollars. Table 1 shows disassembly sequences costs with the tool change cost included. It can be observed that different sequences may have the same cost based on the existing measures used which will need the human interaction to select the final operation sequence. Additional measures, such as operation environments and part handling information, can be introduced to limit the same cost generated in the optional search.

This case study shows use of the cost-based method to evaluate disassembly sequences. The cost calculation considers the operation complexity and tool changes. As the uncertainty of parts to be repaired or replaced in a product lifecycle, the product structure should be carefully planned in the design stage to make parts easy disassembly with less constraint and interaction in the geometric connection. For selective disassembly planning, the disassembly sequence will affect the operation cost. The fasteners used in a product should be easily operated using the same tool for less operation time.

6 Conclusions

Effective sequence planning of product disassembly is essential to reduce the cost of product disassembly. This paper introduces the analysis of product selective disassembly and the related cost. The proposed method measures the product disassemblability with a quantitative method. A simplified AND/OR graph and improved constraint matrix are introduced for product selective disassembly planning. The cost-based disassembly evaluation and a 3D visualization system are integrated for the solution verification. The case study shows the effectiveness of the proposal method to provide a quantities measure for the product disassembly, which improves the existing methods of design for disassembly.

Further work will develop methods for the automatic generation of the product representation from the product CAD model. Human factors will be included in the operation analysis of disassembly. Other factors, such as the product shape, size, and weight, and operation environments, will also be considered in the time estimation. Time spent for different product structures and tool using details will also be collected for the analysis to support the accurate time calculation. The method will also be evaluated using more examples.

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