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# Selective disassembly for virtual prototyping as applied to de-manufacturing

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**Abstract**

Selective disassembly involves separating a selected set of components from an assembly. Applications for selective disassembly include de-manufacturing (maintenance and recycling), and assembling. This paper presents a new methodology for performing design for selective disassembly analysis on the CAD model of an assembly. The methodology involves the following three steps: (i) identifying the components to be selectively disassembled for de-manufacturing by a software program or designer, (ii) determining an optimal (e.g. minimal cost) disassembly sequence for the selected components that involves a computationally efficient two-level reduction procedure: (a) the determination of a set of sequences with an objective of minimal component removals via a wave propagation approach that topologically order components in an assembly for selective disassembly, and (b) the evaluation of resulting sequences based on an objective function (e.g. minimal cost) to identify an optimal sequence, and (iii) Performing disassembly design decisions based on the evaluated optimal sequence. Preliminary implementation results of the selective disassembly methodology in sequencing and disassembly cost evaluation, and application of the selective disassembly technique for de-manufacturing assessment are presented. © 1999 Elsevier Science Ltd. All rights reserved.

*Keywords:* Selective disassembly; Sequencing; Cost evaluation; Product development; Wave propagation; VR-CAD system; $\mathscr{A}3\mathscr{D}$

## Nomenclature

| | |
|---|---|
| $\mathscr{A}$ | assembly |
| AG | accessibility graph |
| $\mathscr{A}3\mathscr{D}$ | assembly disassembly in three dimensions |
| $\mathrm{AC}_i^j$ | accessibility of component $C_i$ with respect to component $C_j$ |
| $C_\mathrm{b}$ | boundary component |
| $C^\mathrm{s}$ | a selected set of components to be disassembled |
| $n$ | number of components in $\mathscr{A}$ |
| $\mathscr{OF}$ | objective function |
| $\mathscr{OS}$ | optimal sequence |
| RG | removal influence graph |
| $\mathrm{RI}_i^j$ | removal influence of component $C_j$ on component $C_i$ |
| $\mathscr{S}$ | sequence |
| $\{\mathscr{S}\}$ | a set of sequences |
| $\mathscr{SD}$ | selective disassembly |
| $\mathscr{WP}$ | wave propagation |
| $\tau_\mathrm{a}$ | ath wavefront of a $\tau$ wave |
| $\beta_\mathrm{a}$ | ath wavefront of a $\beta$ wave |
| $\Delta_i$ | disassemblability of component $C_i$ |
| $\mathscr{I}$ | rating index |

## 1. Introduction

Disassembling a selected set of components ($C^\mathrm{S}$) in an assembly ($\mathscr{A}$), defined as selective disassembly, $\mathscr{SD}$, is important for product de-manufacturing (maintenance and recycling), and assembling [1]. For example, product maintenance usually requires servicing only a subset of components in $\mathscr{A}$, not the entire assembly, hence providing a need for $\mathscr{SD}$ [2].

The motivation to design for $\mathscr{SD}$ is illustrated with the product development cycle in Fig. 1. Performing $\mathscr{SD}$ analysis on the CAD model of a product well before production – a virtual prototyping procedure – results in the reduction of both disassembly cost and time for product maintenance/recycling.

- *Maintenance* requires the replacement of certain components in $\mathscr{A}$. Designing the components to be

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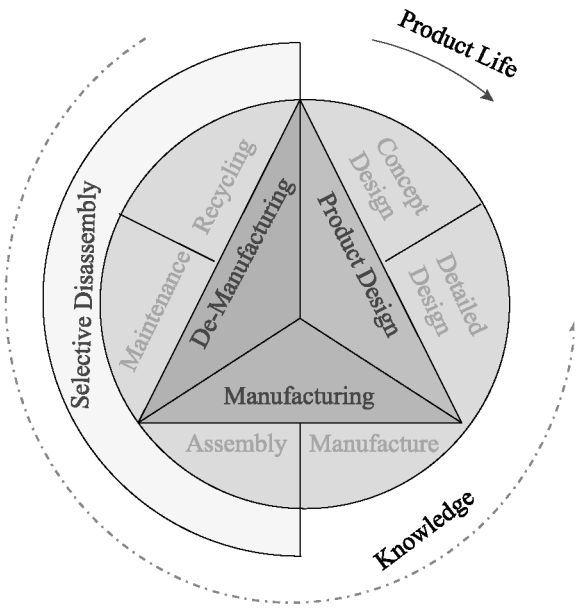


Fig. 1. Motivation: selective disassembly for virtual prototyping.

maintained for $\mathscr{SD}$ facilitates cost-effective product maintenance.

- *Recycling* requires the separation of components of different materials from $\mathscr{A}$. Designing components of different materials in $\mathscr{A}$ for $\mathscr{SD}$ allows profitable recycling, thereby reducing the burden placed on the environment from the ever-increasing number of obsolete products.

Thus, as illustrated in Fig. 1, performing design for $\mathscr{SD}$ analysis on the CAD model of $\mathscr{A}$ is an important area of research in *product development*. However, this virtual prototyping procedure requires an $\mathscr{SD}$ tool that can analyze the CAD model and generate a $\mathscr{SD}$ sequence ($\mathscr{S}$) – order of component removals – to disassemble the selected components. In this research, $\mathscr{S}$ satisfying an Objective Function, $\mathscr{OF}$ (e.g., minimal disassembly cost) is defined as an $\mathscr{OS}$. In turn, an $\mathscr{OS}$ can serve as the basis to compare alternate product designs and to perform design changes to minimize the disassembly cost. Prior to describing a $\mathscr{SD}$ methodology for $\mathscr{OS}$ evaluation and design assessment, the related research is presented.

### 1.1. Related research

Both the potential for assembly modeling in product development and the growing importance of disassembly [3–6] have resulted in a significant amount of research in the areas of: (i) assembly planning [7–11], (ii) disassembly planning [1,12–18], and (iii) disassembly evaluation for de-manufacturing [19–33].

Evaluation of an optimal sequence is an important area of research in disassembly planning. Several representations allow evaluation of complete disassembly sequences, and include: (i) *assembly sequence diagram* [34] which represents the ability or inability to assemble a part to a subassembly, (ii) *AND/OR graph* [35] which establishes conditions and precedence relationships between components, (iii) *non-directional blocking graph* [36] which describes part interactions from the blocking nature of parts and (iv) *geometrical constraints* [37,38] and *metrics* [1,27,39] which quantifies the ease of disassembly of components for disassembly sequencing. However, the complete disassembly approaches involve disassembling all of the components in $\mathscr{A}$.

Researchers have focused primarily on the development of complete disassembly for automated assembly/disassembly planning (e.g. [36–38]); however, there have been no techniques for optimal $\mathscr{SD}$ sequence generation. In contrast to existing research that focuses on disassembly of all the components in $\mathscr{A}$, the current research emphasizes the importance of $\mathscr{SD}$ for de-manufacturing applications.

In our previous researches [2,40,41], we presented Wave Propagation ($\mathscr{WP}$) sequencing algorithms for single component $\mathscr{SD}$ [2], multiple components $\mathscr{SD}$ [40] and a computational complexity reduction procedure [41] for sequence determination with minimal component removals.

This paper presents a methodology to perform design for $\mathscr{SD}$ analysis on a CAD model of $\mathscr{A}$. Preliminary implementation results of the $\mathscr{SD}$ methodology in optimal $\mathscr{SD}$ sequencing based on the $\mathscr{WP}$ approach and $\mathscr{SD}$ cost evaluation as applied to maintenance and recycling applications are presented.

### 1.2. Overview of selective disassembly methodology

The $\mathscr{SD}$ methodology for virtual prototyping (illustrated in Fig. 2) has the following three steps:

*Step* 1. *Product analysis* involves: (i) identification of the components to be disassembled ($C^{\mathrm{S}}$) for maintenance/recycling, and (ii) formulation of an objective function ($\mathscr{OF}$), for optimal sequencing based on the specified user requirements.

*Step* 2. *Sequence evaluation*: determination of an optimal sequence ($\mathscr{OS}$) for $\mathscr{SD}$ of $C^{\mathrm{S}}$, and involves an efficient two-level reductionn procedure:

(i) Determination of a set of disassembly sequences, $\{\mathscr{S}\}$, with locally minimum component removals for $\mathscr{SD}$ using the *wave propagation* ($\mathscr{WP}$) concept – involves topologically ordering the components in an assembly denoting the disassembly order (defined as the topological disassembly arrangement) and to ensure minimal component removals for $\mathscr{SD}$.

(ii) Determination of an $\mathscr{OS}$ satisfying an $\mathscr{OF}$, from the sequences in $\{\mathscr{S}\}$.

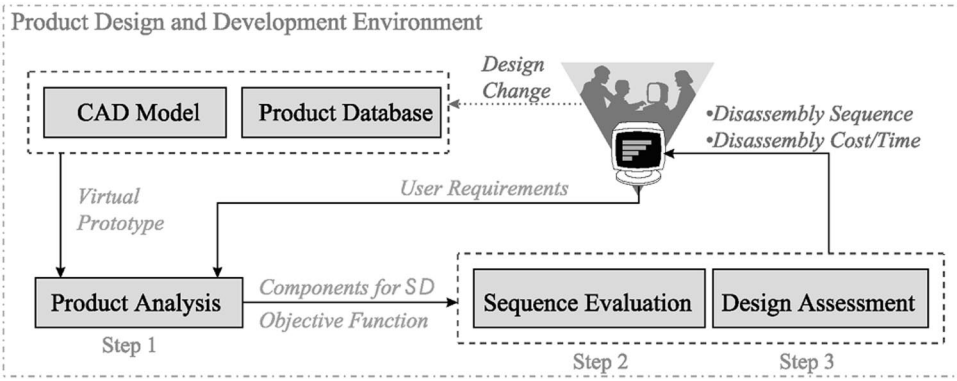


Fig. 2. Methodology: $\mathcal{SD}$ for virtual prototyping.

Determination of an $\mathcal{OS}$ could be carried out without the use of step (i), i.e. by determining all possible disassembly sequences and subsequently applying an $\mathcal{OF}$. However, the total number of disassembly sequences is combinatorial in the number of components in $\mathcal{A}$ [35].

The two-level reduction procedure involves first determining $\{\mathcal{S}\}$ – locally minimum component removal sequences – using the $\mathcal{WP}$ concept, which allows an initial pruning of the solution space, and next determining a sequence from $\{\mathcal{S}\}$ that satisfies the formulated $\mathcal{OF}$. Section 3 describes this two level reduction procedure in detail.

*Step* 3. *Design assessment* involves making disassembly design decisions such as comparison of alternate product designs and selection of a better design for $\mathcal{SD}$ with respect to maintenance/recycling application.

### 1.3. Benefits of the proposed $\mathcal{SD}$ methodology for virtual prototyping

(i) Determination of an $\mathcal{OS}$ (e.g. minimal cost $\mathcal{SD}$) for maintenance and (e.g. maximal profitable $\mathcal{SD}$) for recycling, in disassembling $C^{\mathrm{S}}$.

(ii) Computationally efficient (non-exponential complexity) two-level reduction procedure in optimal $\mathcal{SD}$ sequencing. This also allows determination of $\mathcal{OS}$'s for different $\mathcal{OF}$s, with one step in determination of $\{\mathcal{S}\}$.

(iii) The $\mathcal{SD}$ results can assist the designer in making disassembly design decisions regarding: (a) components to be disassembled for recycling/disposal for profitable recycling, and (b) selection between in-place or replacement maintenance. Moreover, the $\mathcal{OS}$ evaluated can serve as the basis to compare alternate product designs, thereby also permitting to design a better product for $\mathcal{SD}$.

The main section of the paper present the $\mathcal{SD}$ methodology for virtual prototyping and the implementation results in detail.

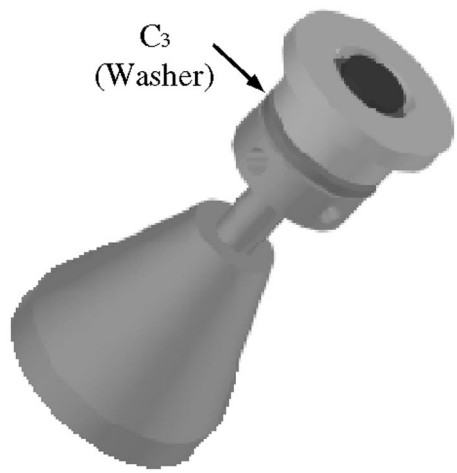


Fig. 3. Identification of components for $\mathcal{SD}$.

## 2. Methodology: Step 1 – product analysis

Components to be designed for maintenance or recycling (and hence $C^{\mathrm{S}}$ for $\mathcal{SD}$) are either identified by the user or by a software analysis of the product material and domain databases. The material database includes: (i) material type, and (ii) recycling value. The domain database includes: (i) component functionality, and (ii) life time.

For example, Fig. 3 shows a test assembly, where component $C_3$ (washer) needs frequent replacement and hence must be analyzed for ease of $\mathcal{SD}$.

Evaluation of an $\mathcal{OS}$ for $\mathcal{SD}$ satisfying the specified user requirements (such as minimum disassembly cost) involves formulation of an $\mathcal{OF}$. An $\mathcal{OF}$ is necessary since $\mathcal{SD}$ of $C^{\mathrm{S}}$ from $\mathcal{A}$ can be done in several sequences, one of which is usually better (faster and less expensive) [1,39].

Having the set of sequences $\{\mathcal{S}\} = \{\mathcal{S}_1, \mathcal{S}_2, \ldots, \mathcal{S}_p\}$ where$\mathcal{S}_j = \{C_{j1}, C_{j2}, \ldots, C_{jm}\}$ for $1 \leqslant j \leqslant p$, where the total number of sequences is $p$. Let $W_{jk}$ = weight of $C_{jk} \in \mathcal{S}_j$ and $W$ = weight of $\mathcal{A}$. Eqs. (1) and (2) show two

example $\mathcal{OF}$'s – modeling the user requirement of minimizing the $\mathcal{SD}$ cost:

$$\mathcal{OF} = Minim\,(cardinality\ \text{of}\ (\mathcal{S}_j)), \tag{1}$$

$$\mathcal{OF} = Minim\,(\Sigma W_{jk}/W), \quad \text{for } C_{jk} \in \mathcal{S}_j. \tag{2}$$

Eq. (1) minimizes the number of component removals, and Eq. (2) minimizes the total weight of components removed. The implementation of a more detailed cost equation, is presented in Section 6.2.

## 3. Methodology: Step 2 – sequence evaluation

Evaluation of an $\mathcal{OS}$ for $\mathcal{SD}$ of $C^S$ following a two-level reduction procedure involves: (i) determination of $\{\mathcal{S}\}$ with locally minimum component removals using the $\mathcal{WP}$ concept, which involves topologically ordering of $C_i \in \mathcal{A}$ – denoting the disassembly order – for $\mathcal{SD}$, and (ii) determination of an $\mathcal{OS}$ satisfying an $\mathcal{OF}$ from $\{\mathcal{S}\}$. This two-level reduction procedure is followed, since enumeration of all possible sequences of $C^S$ and then application of an $\mathcal{OF}$ to obtain an $\mathcal{OS}$ is a combinatorial procedure [35].

Prior to the description of the $\mathcal{WP}$ concept for $\mathcal{SD}$ of $C^S$ in $\mathcal{A}$, the definitions and the assumptions of the current research are presented.

### 3.1. Definitions

- *Accessibility* of $C_i$ with respect to its adjacent component $C_j$ is defined as the set of directions with which $C_i$ can move relative to $C_j$, and is denoted as $\mathrm{AC}_i^j$ [2]. For example, Fig. 4 illustrates the accessibility of some of the components.
- *Accessibility Graph*, AG [2,41] is a directed graph representing $\mathcal{A}$ in which nodes correspond to the components in $\mathcal{A}$ and an arc, $C_i \to C_j$, indicates that $C_i$ is adjacent to $C_j$ and stores an attribute $\mathrm{AC}_i^j$. The type of joint (fasteners) between components is attributed to each component (node) in AG.
- *Disassemblability*, $\Delta_i$, is a binary value that indicates if $C_i \in \mathcal{A}$ is removable. $\Delta_i$ is computed as the intersection of all $\mathrm{AC}_i^j$ [2]. For example in Fig. 4, $\Delta_8 = \mathrm{TRUE}$ for $C_8$ and $\Delta_7 = \mathrm{FALSE}$ for $C_7$.
- *Removal influence*, $\mathrm{RI}_i^j$, is a binary value that indicates if $C_i \in \mathcal{A}$ is removable after the removal of $C_j \in \mathcal{A}$ [2,40]. For example, in Fig. 4, $\mathrm{RI}_7^8 = \mathrm{TRUE}$, since $\Delta_7$ is TRUE with removal of $C_8$ in $\mathcal{A}$. Similarly, $\mathrm{RI}_7^4 = \mathrm{FALSE}$.
- *Removal influence graph* $RG = (\mathcal{C}, \mathcal{E})$ is a directed graph [2,40] where $\mathcal{C}$ corresponds to a set of components in $\mathcal{A}$ and $\mathcal{E}$ corresponds to a set of directed arcs. An arc, $C_i \to C_j$, indicates that $\mathrm{RI}_i^j = \mathrm{TRUE}$.

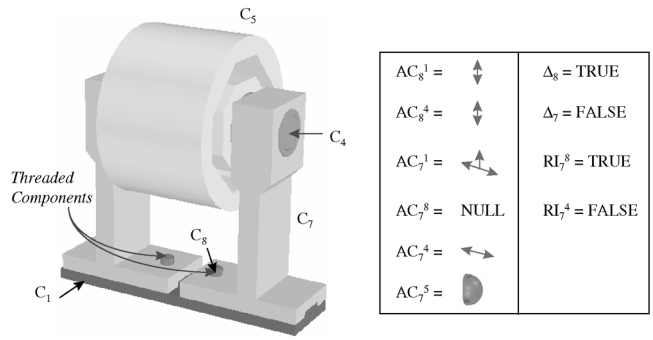


Fig. 4. Wheel support assembly: example assembly/disassembly features.

### 3.2. Assumptions

1. The relative motions of the components are determined without considering the tools, fixtures or robots required to achieve these motions.
2. Assemblies are assumed to be frictionless and defined by nominal geometry.
3. Components are 1-disassemblable (single linear motion to be removed fro m $\mathcal{A}$) and single dependent (a component is removable after removing one of its adjacent component) [2,40]. Moreover, a fastener is not considered as a component.
4. Disassembly sequences are sequential (one component is removed at a time), monotonic (components are totally removed while disassembling) and non-destructive (no component is destroyed) [1].

### 3.3. Sequence determination

The $\mathcal{WP}$ approach [2,40,41], defines two types of disassembly waves:

1. $\tau$ waves from $C^S$ which propagate outwards.
2. $\beta$ waves from the boundary of $\mathcal{A}$ which propagate inwards.

$\tau$ and $\beta$ waves determine the disassembly ordering with respect to $C^S$ and the boundary of $\mathcal{A}$, respectively. Based on the intersection event between $\tau$ and $\beta$ waves, a sequence with locally minimum component removals to disassemble $C^S$ is determined.

The importance of the intersection between waves lies in the determination of the component at which the waves intersect (therefore the shape of the wave in the geometry space is irrelevant; the wave merely provides the topological ordering of the components in the assembly with respect to either $C^S$ or $\beta$).

Let $\tau_a = a^{\text{th}}$ wavefront of a $\tau$ wave, $\beta_a = a^{\text{th}}$ wavefront of a $\beta$ wave, $\{C_b\}$ = set of removable components and $X \overset{p}{\to} Y$ denotes the shortest path from $X$ to $Y$. An illustration for $\tau$ and $\beta$ waves for $C^S = \{C_x\}$ is shown in Fig. 5.

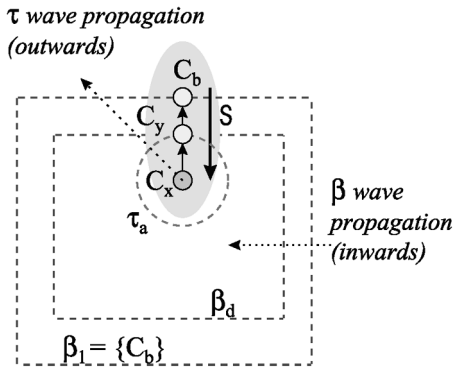


Fig. 5. $\mathscr{WP}$ concept for single component $\mathscr{SD}$.

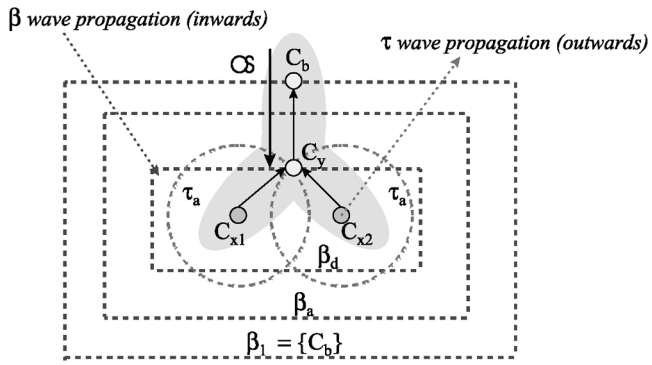


Fig. 7. $\mathscr{WP}$ concept for multiple $\mathscr{SD}$.

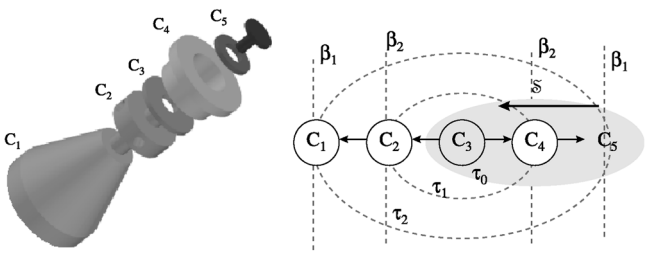


Fig. 6. (a) Screw jack assembly: $C^S = \{C_3\}$ and (b) RG: sequence determination.

An intersection event occurs at $C_y \in \mathscr{A}$, where $\tau_a$ wavefront intersects the $\beta_d$ wavefront ($d <= a$). This intersection event determines a sequence $\{C_b \overset{p}{\rightarrow} C_y, C_y \overset{p}{\rightarrow} C_x\}$ with locally minimum component removals for $C^S = \{C_x\}$ [2]. The disassembly ordering of a component is determined based on disassemblability and removal influence values of components. By representing the nodes corresponding to the components in $\tau$ and $\beta$ waves, and arcs corresponding to the $\mathscr{WP}$ as an RG, a sequence $\mathscr{S}$ is derivable for $\mathscr{SD}$.

The following is an example illustrating determination of $\mathscr{S}$ for single component $\mathscr{SD}$. Fig. 6a shows the CAD model of a Screw Jack assembly and Fig. 6b shows the RG and determination of $\mathscr{S}$. For $C^S = \{C_3\}$: $C_3$ is disassemblable by removing $C_4$ in $\tau_1$ ($RI_3^4 = TRUE$) and $C_4$ is disassemblable after removing $C_5$ in $\tau_2$ ($RI_4^5 = TRUE$). An intersection event occurs at $C_5 \in \beta_1$ (set of removable components). Therefore, $\mathscr{S} = \{C_5, C_4, C_3\}$.

An illustration for $\tau$ and $\beta$ waves for multiple component disassembly e.g., $C^S = \{C_{x1}, C_{x2}\}$ is shown in Fig. 7. An intersection event occurs at $C_y \in \mathscr{A}$, where $\tau$ wavefronts of $C_{x1}$ and $C_{x2}$ intersect the $\beta$ wavefront ($d <= 2a$). This intersection event determines a sequence $\{C_b \overset{p}{\rightarrow} C_y, C_y \overset{p}{\rightarrow} C_{x1}, C_y \overset{p}{\rightarrow} C_{x2}\}$ with locally minimum component removals for $C^S = \{C_{x1}, C_{x2}\}$ [41].

The following is an example illustrating the determination of $\mathscr{S}$ for a multiple component $\mathscr{SD}$. Fig. 8a shows the CAD model of a wheel support assembly and Fig. 8b–8d show the RGs and sequence determination for $C^S = C_3, C_6$.

1. From the $\tau$ wave of $C_3 : C_3$ is disassemblable by removing $C_2$ or $C_4$ in $\tau_1$ ($RI_3^2 = TRUE, RI_3^4 = TRUE$). $C_2$ and $C_4$ are disassemblable by removing $C_9$ and $C_6$ in $\tau_2$, respectively.
2. From the $\tau$ wave of $C_6 : C_6$ is disassemblable by removing $C_4$ or $C_7$ in $\tau_1$ ($RI_6^4 = TRUE, RI_6^7 = TRUE$). $C_7$ and $C_4$ are disassemblable by removing $C_8$ and $C_3$ in $\tau_2$, respectively.
3. From the $\beta$ wave: $C_8$ and $C_9$ (in $\beta_1$) are disassemblable components. Components $C_2$ and $C_7$ (in $\beta_2$) are disassemblable by removing $C_9$ and $C_8$ in $\beta_1$, respectively ($RI_2^9 = TRUE, RI_7^8 = TRUE$). Similarly, $C_3$, $C_6 \in \beta_3$ and $C_4 \in \beta_4$.

The $\tau$ waves of $C_3$ and $C_6$ intersect the $\beta_1$ wavefront at $C_9$ and $C_8$, respectively. This event determines $\mathscr{S}_1 = \{C_9, C_2, C_3, C_8, C_7, C_6\}$ as shown in Fig. 8b. At $C_4$, the $\tau$ waves of $C_3$ and $C_6$ intersect the $\beta_4$ wavefront, which determines $\mathscr{S}_2 = \{C_8, C_7, C_6, C_4, C_3\}$ and $\mathscr{S}_3 = \{C_9, C_2, C_3, C_4, C_6\}$ as shown in Fig. 8c and Fig. 8d, respectively.

An $\mathscr{OS}$ is obtained by identifying an $\mathscr{S}$ from $\{\mathscr{S}\}$ that satisfies the formulated $\mathscr{OF}$. For the Wheel Support assembly example, $\{\mathscr{S}\} = \{\mathscr{S}_1 = \{C_9, C_2, C_3, C_8, C_7, C_6\}, \mathscr{S}_2 = \{C_8, C_7, C_6, C_4, C_3\}, \mathscr{S}_3 = \{C_9, C_2, C_3, C_4, C_6\}\}$. For an $\mathscr{OF}$ in Eq. (2), $OS = \{C_8, C_7, C_6, C_4, C_3\}$ and $\{C_9, C_2, C_3, C_4, C_6\}$.

Let $N_S$ = number of sequences in $\{\mathscr{S}\}$ and $n$ = number of components in $\mathscr{A}$. Applying the minimal component removals as an objective to derive $\{\mathscr{S}\}$, using the $\mathscr{WP}$ concept, significantly reduces the search space from exponential, $N_S = O(2^n)$, set of sequences to polynomial, $N_S = O(n)$, set of sequences [41]. In general, $N_S$ will be a feasible number. However, for assemblies with larger values of $n$, if $N_S$ exceeds a feasible number, then the sequences in $\{\mathscr{S}\}$ are ordered based on the number of component removals and the first constant number of sequences are selected as a feasible set $\{\mathscr{S}\}$. Alternatively, $N_S$ can be further minimized using other objectives such as space, weight of components removed, etc.

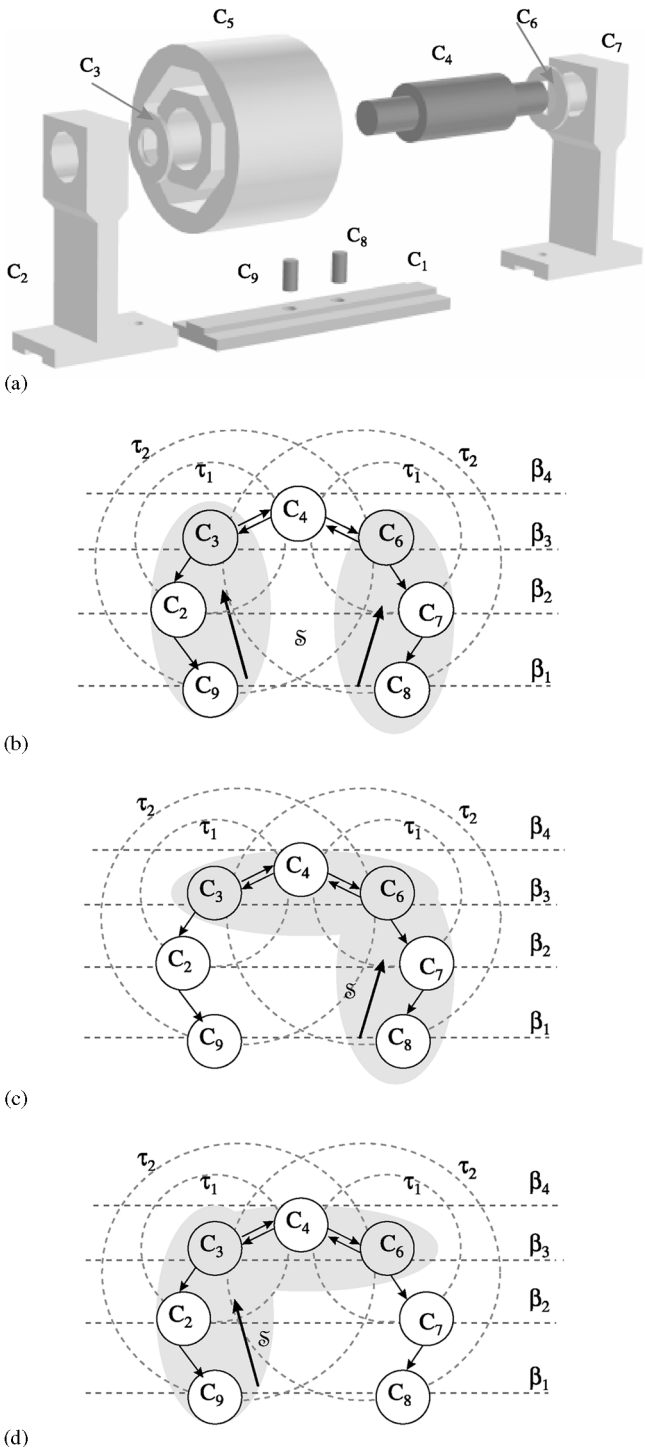


Fig. 8. (a) Wheel support assembly: $C^S = \{C_3, C_6\}$, (b) RG: sequence determination, (c) RG: sequence determination and (d) RG: sequence determination.

## 4. Methodology: Step 3–design assessment

Product design assessment involves performing disassembly design decisions, based on the $\mathscr{SD}$ results, such as comparing alternate product designs in order to determine a better design for $\mathscr{SD}$.

Comparison of alternate product designs considers a disassembly rating index, $\mathscr{I}$, such as the number of disassembly motions in an $\mathscr{OS}$. For example, Fig. 9 shows two alternate designs of a screw jack assembly with $C^S = \{C_3\}$. Design B differs from Design A only in $C_3$ (washer with a cut in Design B), such that $C_3$ can be directly disassembled. An $\mathscr{OS}$ for *Design A* has $\mathscr{I} = 3$ (i.e., disassembly of $C_3$ require prior disassembly of two other components). For *Design B*, $C_3$ can be disassembled directly without requiring prior disassembly of any other components and hence $\mathscr{I} = 1$. Therefore, *Design B* is better than *Design A* for $\mathscr{SD}$.

The above analysis suggests that with minor modifications in design, components to be maintained or recycled may be easily disassembled resulting in an efficient product maintenance and recycling.

## 5. Selective disassembly: implementation

This section describes a $\mathscr{SD}$ software tool, $\mathscr{A}3\mathscr{D}$ (assembly and disassembly design in three dimensions), being implemented based on the $\mathscr{SD}$ methodology. The $\mathscr{A}3\mathscr{D}$ software determine sequences and evaluates cost to disassemble a subset of components from an assembly.

### 5.1. Implementation architecture and software systems

The $\mathscr{A}3\mathscr{D}$ $\mathscr{SD}$ software tool (illustrated in Fig. 10) has two parts: (i) $\mathscr{SD}$ sequencing and (ii) $\mathscr{SD}$ Evaluation. $\mathscr{SD}$ sequencing takes in as inputs $\mathscr{A}$ and $C^S$ (components to be disassembled for maintenance/recycling) and outputs $\{\mathscr{S}\}$ – local optimum $\mathscr{SD}$ sequences. $\mathscr{SD}$ evaluation module takes in as input the $\mathscr{SD}$ sequences and output an optimal $\mathscr{SD}$ cost in disassembling the components for de-manufacturing.

Fig. 11 describes the $\mathscr{SD}$ sequencing software tool to generate $\mathscr{SD}$ sequences. The $\mathscr{A}3\mathscr{D}$ software has been developed using the C++ as a programming language, OpenGL™ graphics library for rendering and WorldToolKit™ as a development library. WorldToolKit™ is a library of C++ callable functions that allow interfacing with a wide range of virtual–reality input/output devices. The $\mathscr{SD}$ software is supported in Unix™ and Windows-NT™ operating system. $\mathscr{A}3\mathscr{D}$ $\mathscr{SD}$ sequencing takes in as input an AG of $\mathscr{A}$ generated from conventional CAD systems (ProEngineer™ or UniGraphics™). In an $\mathscr{A}3\mathscr{D}$ system: (i) user inputs $C^S$ via a menu-interface, (ii) disassemblability and removal influence are determined from AG, and (iii) $\{\mathscr{S}\}$ : $\mathscr{SD}$ sequences are determined using the $\mathscr{WP}$ abstraction. The generated $\mathscr{SD}$ sequences are then simulated in $\mathscr{A}3\mathscr{D}$ system.

The user interface for $\mathscr{SD}$ sequencing is also provided via a virtual–reality (VR) system called COVIRDS (Conceptual VIRtual Design System) [42–44]. COVIRDS coupled with 3D Hand tracking, voice command, and

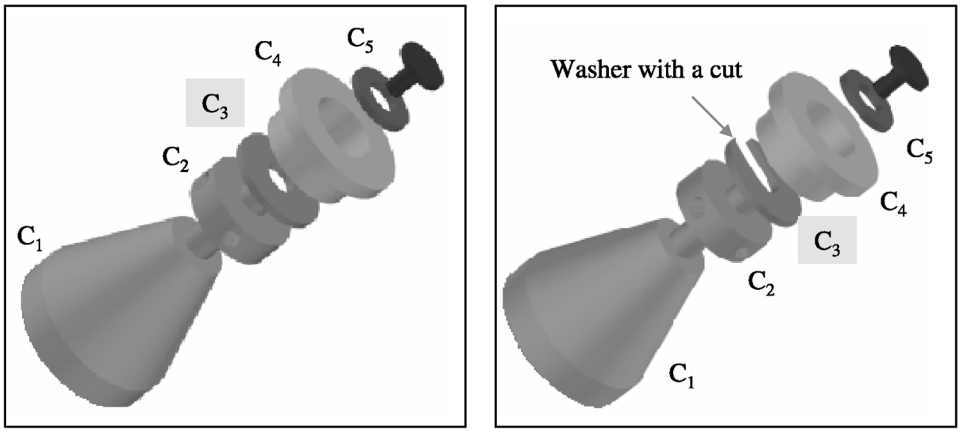


Fig. 9. Alternate designs of screw jack assembly: (a) design A, (b) design B.

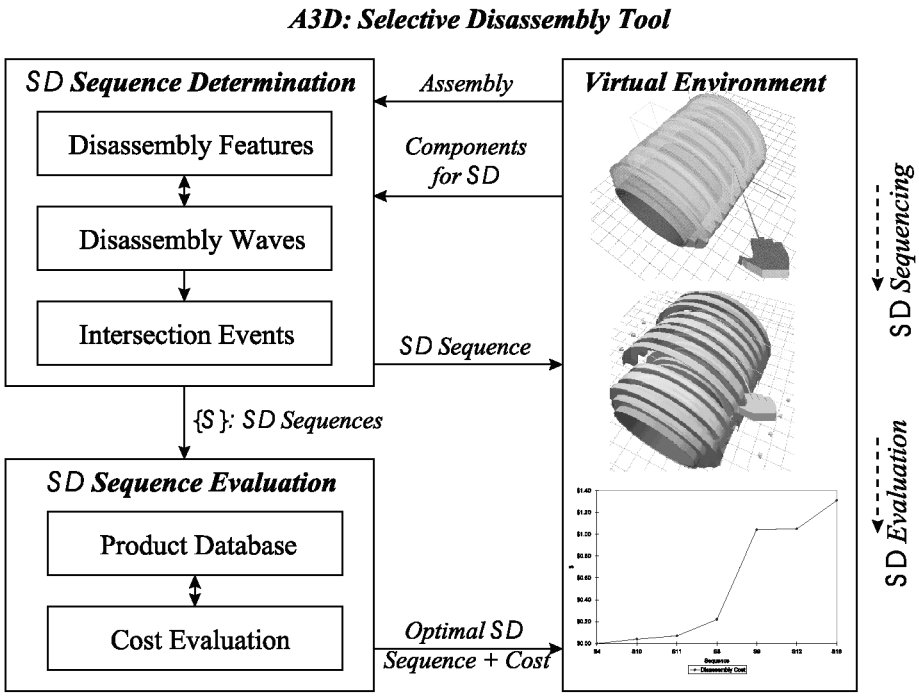


Fig. 10. $\mathscr{A}3\mathscr{D}$ selective disassembly tool: architecture.

stereoscopic visual display provide a high fidelity visualization and an easy-to-use interface for geometry creation and manipulation [44]. This system allows the designer to select the components to be disassembled, ($C^S$) using a virtual hand selection or through a voice command. For example, Fig. 11 shows an Augmentor assembly in the VR-CAD system and the $\mathscr{SD}$ sequence generated for $C^S$, selected using a virtual pointer.

Fig. 12 describes the $\mathscr{A}3\mathscr{D}$ $\mathscr{SD}$ cost evaluation software tool. The software program utilizes the generated $\{\mathscr{S}\}$: $\mathscr{SD}$ sequences in conjunction with: (i) component weight, (ii) labor cost, and (iii) standard time to remove fasteners, to evaluate a minimal cost $\mathscr{SD}$ sequence and outputs a graph describing the cost in disassembling components for de-manufacturing.

## 6. Results and discussions

This section presents the $\mathscr{SD}$ software results and discusses the contributions, limitations and future work of the proposed $\mathscr{SD}$ methodology.

### 6.1. Multiple selective disassembly SD sequence generation

The $\mathscr{SD}$ Sequencing tool generates $\{\mathscr{S}\}$ and simulates them in the CAD environment for the designer

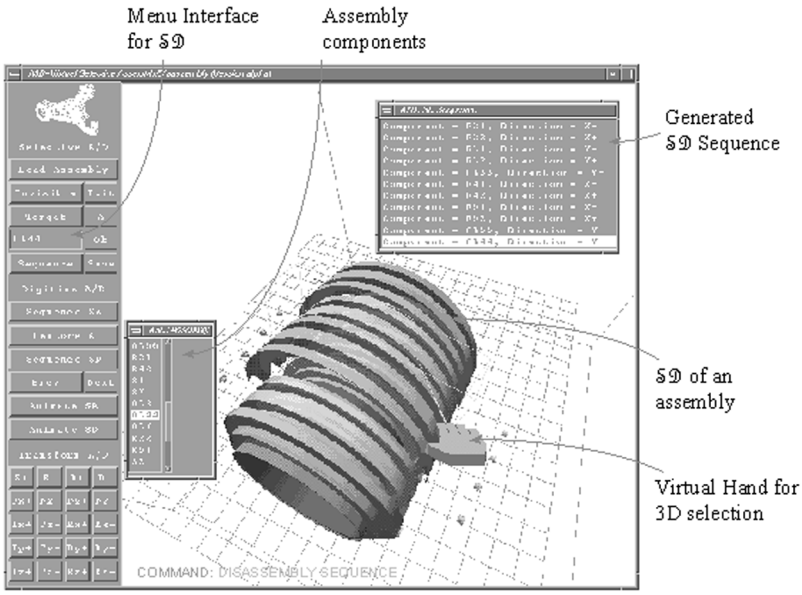


Fig. 11. *A3D*: selective disassembly sequencing tool.

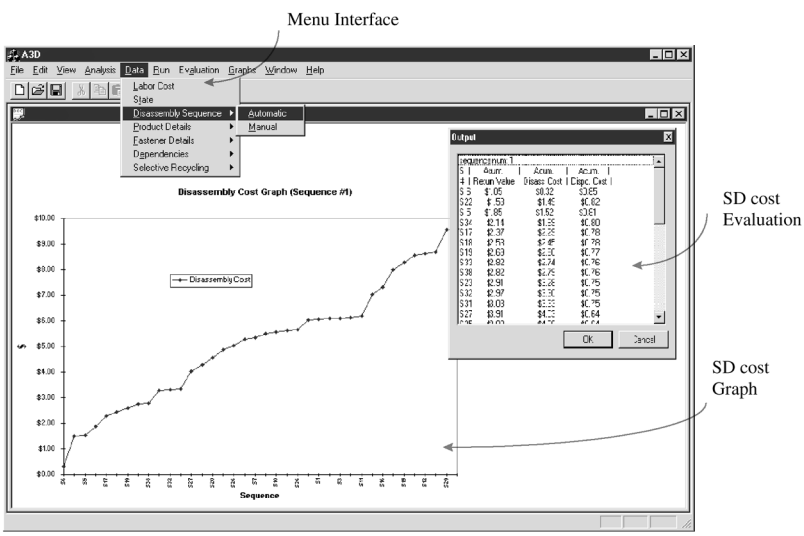


Fig. 12. *A3D* selective disassembly evaluation tool.

to visualize the sequences. For example, the wheel support assembly with $C^{S} = \{C3, C6\}$, $\{\mathscr{S}\} = \{S_1 = \{C9, C2, C3, C8, C7, C6\}, \mathscr{S}_2 = \{C8, C7, C6, C4, C3\}, \mathscr{S}_3 = \{C9, C2, C3, C4, C6\}\}$. Among these three sequences, $\mathscr{S}_1$ and $\mathscr{S}_3$ are shown in Fig. 13. Identification of an $\mathscr{OS}$ from $\{\mathscr{S}\}$ satisfying an user defined objective is presented below.

### 6.2. Selective disassembly time and cost evaluation

For a generated $\mathscr{SD}$ sequence, the evaluation tool determines the $\mathscr{SD}$ cost in terms of the disassembly time, as shown in Eqs. (3)–(5).

$$\mathrm{DT_F} = \sum_i \left( \sum_j (N_{j,i} \times T_j + A_{ji} \times O_{ji}) \right) \text{ for } C_i \in \mathscr{S}, \quad (3)$$

$$\mathrm{DT_C} = \sum_i \left( A_i \times O_i \times (K_t \times d_i) \times \left\lceil \frac{W_i \times Fi}{K_w} \right\rceil \right) \text{ for } Ci \in \mathscr{S}, \quad (4)$$

Disassembly Cost

$$= K_O \times K_S \times \mathrm{LR} \times (\mathrm{DT_F} + \mathrm{DT_C}) \quad (5)$$

where

$\mathrm{DT_F}$ = time to remove fasteners fastening components in $\mathscr{S}$,

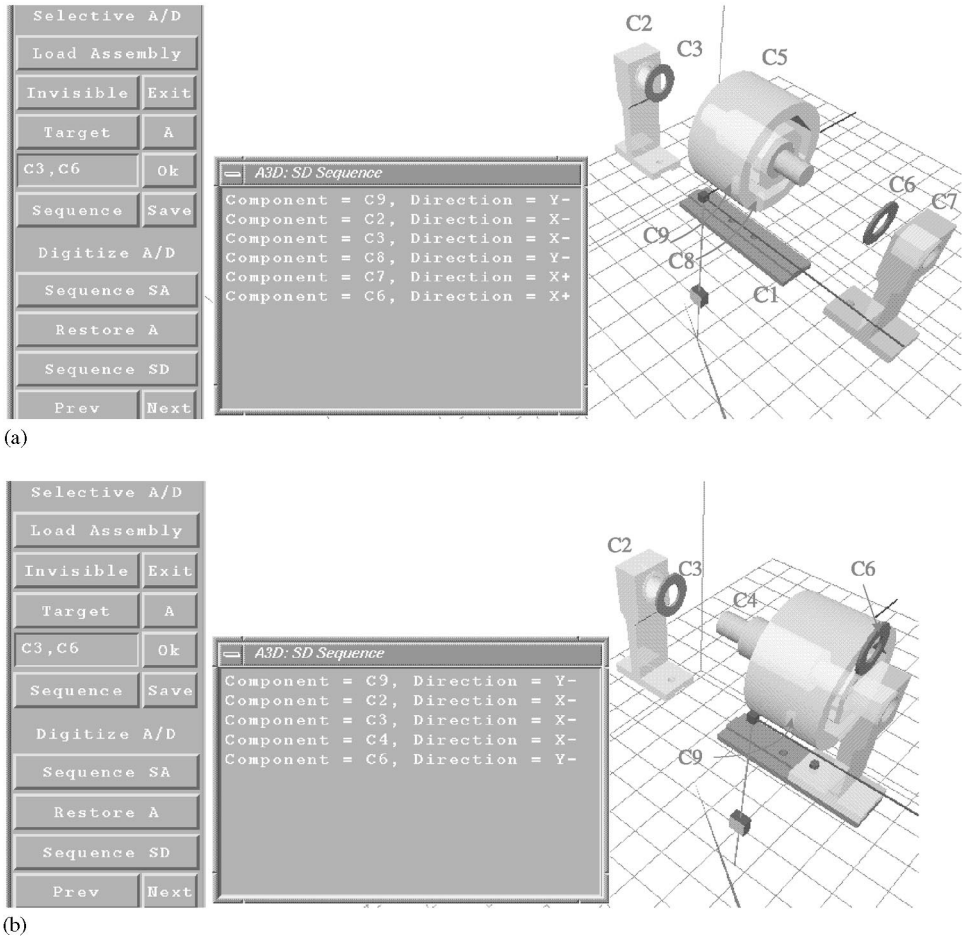


Fig. 13. Wheel support assembly: (a) $C^{S} = \{C3, C6\}$, $\mathscr{S}_1 = \{C9, C2, C3, C8, C7, C6\}$ and (b) $C^{S} = \{C3, C6\}$, $\mathscr{S}_3 = \{C9, C2, C3, C4, C6\}$.

$DT_C$ = time to remove components in $\mathscr{S}$ (once fasteners are removed),
$K_O$ = constant factor to account for space, tooling, etc.,
$K_S$ = constant factor that accounts for component safety,
LR = labor rate ( = cost/time),
$N_{j,i}$ = number of fasteners of type $j$ fastening $i$th component,
$T_j$ = standard time to disassemble a fastener of type $j$,
$A_{ji}$ = accessibility factor of a fastener of type $j$ fastening $i$th component,
$O_{ji}$ = orientation factor of a fastener of type $j$ fastening $i$th component,
$A_i$ = accessibility factor of the $i$th component,
$O_i$ = orientation factor of the $i$th component,
$K_w$ = limiting standard weight that can be lifted by a lifting source,
$d_i$ = distance the $i$th component is moved to disassemble from an assembly,
$K_t$ = standard time to move a component of weight less than $K_w$ by a distance $d_i$,
$W_i$ = weight of the $i$th component, and
$F_i$ = Force factor of the $i$th component.

The $K_O$ factor accounts for space, tooling, etc. The $K_S$ factor accounts for the time delay due to special safety precautions to be observed for assemblies containing fragile or hazardous materials. Both $K_O$ and $K_S$ factors are expressed as a constant factor of the total disassembly time. The accessibility factors $A_{ji}$ and $A_i$, account for the ease in which a fastener/component is removed from $\mathscr{A}$. The orientation factors $O_{ji}$ and $O_i$, account for the operator re-orientation to disassemble a fastener/component from $\mathscr{A}$. The force factor, $F_i$, accounts for the extra force above the component weight, required to remove the required component from $\mathscr{A}$. The accessibility, orientation and force factors are expressed as a constant factor of the time required to disassemble the corresponding fastener/component.

In the current research, $K_O$, $K_S$ and LR are specified by the user. $N_{j,i}$, $A_{ji}$, $A_i$, $F_i$, $d_i$ and $W_i$ for $C_i$'s are identified from the CAD model or assembly representation. $T_j$ is obtained from the standard fastener database. $O_{ji}$ and $O_i$ are obtained from $\mathscr{S}$ and directions. $K_w$ and $K_t$ are constants derived based on the limits set by OSHA [45]. Let $K^*$ refer to the orientation, accessibility, force

and safety factors. For simplicity, in this paper, $K^*$ is set to 1. Assuming manual disassembly, $K_w = 25$ lb and $K_t = 2.5$ s/ft (derived based on the limiting values set by OSHA [45] ).

Applying Eq. (5) to the Wheel Support assembly example, with $K_O = 1.5$ and LR = 20 \$/h, the total disassembly cost for $\mathscr{S}_1$ is \$.36 which includes removal of 6 components (15 s) and 2 threads, components C8 and C9, (28 s). However, the total disassembly cost for $\mathscr{S}_3$ is \$.22 which includes removal of 5 components (12.5 s) and 1 thread, component C9, (14 s). Similarly, for $\mathscr{S}_2$ the cost is \$.22. Therefore, $\mathscr{S}_2$ and $\mathscr{S}_3$ are optimal (minimal cost) sequences. Moreover, $\mathscr{S}_2$ and $\mathscr{S}_3$ are also absolute minimum cost sequences.

In practical situations, the user requirements may vary with respect to $\mathscr{A}$s position and weight. For the wheel support example, if $\mathscr{A}$ is clamped (i.e., C1 is fixed) to the ground, then the user objective may be minimum clamping devices. Therefore, $\mathscr{S}_1$ is an optimal (minimal clamping) sequence, since the number of clamping elements required is none. Whereas for $\mathscr{S}_2$ and $\mathscr{S}_3$ the number of clamping required is one. However if $\mathscr{A}$ is moved to a workbench and the disassembly operation is performed, then the objective may be minimum cost since no clamping force is required with $\mathscr{A}$ being in horizontal position. Therefore $\mathscr{S}_2$ and $\mathscr{S}_3$ are optimal (minimal cost) sequences.

### 6.3. Selective disassembly applied to maintenance application

Product maintenance requires removal of certain components in $\mathscr{A}$ for in-place or for replacement maintenance. Therefore, performing $\mathscr{SD}$ analysis on $\mathscr{A}$ allows determination of the $\mathscr{SD}$ sequence and minimal cost in disassembling components for product maintenance.

**Example 1.** SD results for in-place and replacement maintenance of aircraft engine sub-assembly.

The components that need to be disassembled for maintenance depends on whether the requirement is an in-place or replacement maintenance. For example, Fig. 14a shows the $\mathscr{SD}$ of one of the outer shell of the engine for in-place maintenance of the engine sub-assembly. Similarly, for replacement maintenance, Fig. 14b shows the $\mathscr{SD}$ of the whole engine sub-assembly unit from the aircraft assembly.

Accordingly, based on whether it is in-place or replacement maintenance, the $\mathscr{SD}$ sequence and the corresponding cost will be different. Therefore, if both options are considered for analysis then the selection of one over the other can be made based on $\mathscr{SD}$ evaluation results.

**Example 2.** Sequence and cost evaluation results in $\mathscr{SD}$ of instrument panel from the dashboard assembly of an automobile for maintenance application.

Fig. 15a shown the dashboard assembly of an automobile in the $\mathscr{A}3\mathscr{D}$ CAD environment and the selection of $C_{16}$ (instrument panel) for disassembly. The generated minimal cost $\mathscr{SD}$ sequence = $\{C_4, C_{10}, C_{11}, C_8, C_9, C_{12}, C_{16}\}$ is shown in Fig. 15b.

Fig. 15c shows the cumulative cost plot generated by the $\mathscr{SD}$ evaluation tool for $C^S = \{C_{16}\}$. For this example, Eq. (5) is used with $K_O = 1.5$, LR = 20 \$/h. The disassembly cost = \$1.48; which includes removal of 10 screws (140 s), 2 pins (8 s), 1 nut (4 s), 2 clips (8 s) and 7 components (17.5s) in $\mathscr{S}$.

In this example, $\mathscr{S}$ is practically feasible and also most economical if components are assumed to be rigid. However, the solution determined in not the absolute optimum. In practical situations, $C_{12}$ does not have to be removed, since $C_{12}$ is of a flexible material it can be bent and $C_{16}$ may be removed directly after removing $C_9$. Therefore, the absolute optimum sequence is $\{C_4, C_{10}, C_{11}, C_8, C_9, C_{16}\}$ with disassembly cost = \$1.43; which excludes removal of a clip (4 s) and $C_{12}$ (2.5 s).

At present, the $\mathscr{A}3\mathscr{D}$ software determines an $\mathscr{OS}$ automatically based on the geometric accessibility of components. However, human interactions are required, sometimes for complex systems, to assist an $\mathscr{OS}$ determination. For example, if the requirement is to remove the entire air-conditioner (AC) unit from a car assembly (dashboard sub-assembly is attached to the car), then the $\mathscr{A}3\mathscr{D}$ system (with non-destructive, sequential, 1-disassembly assumptions) cannot determine a sequence. This is due to the fact that the AC-unit and the fasteners are not accessible and are blocked by the entire dashboard sub-assembly and the metallic frame of the car. However, in practice, the disassembly of the AC-unit is performed by removing the entire dashboard assembly from the car as a single component followed by removing the AC-unit from the dashboard sub-assembly. The information about removing the entire dashboard unit first as a target component followed by disassembling the AC-unit as the target component may be provided as input from the user or from a knowledge-base which can assist the $\mathscr{A}3\mathscr{D}$ system in determining an efficient solution. Performing knowledge-assisted $\mathscr{SD}$ is a topic of future research.

### 6.4. Selective disassembly applied to recycling application

Performing $\mathscr{SD}$ analysis for recycling, allows determination of maximal profitable $\mathscr{SD}$ sequence for separating components of different materials. Maximizing the recycling profit results in greater impetuses for the companies to recycle a product. In addition the $\mathscr{SD}$ software

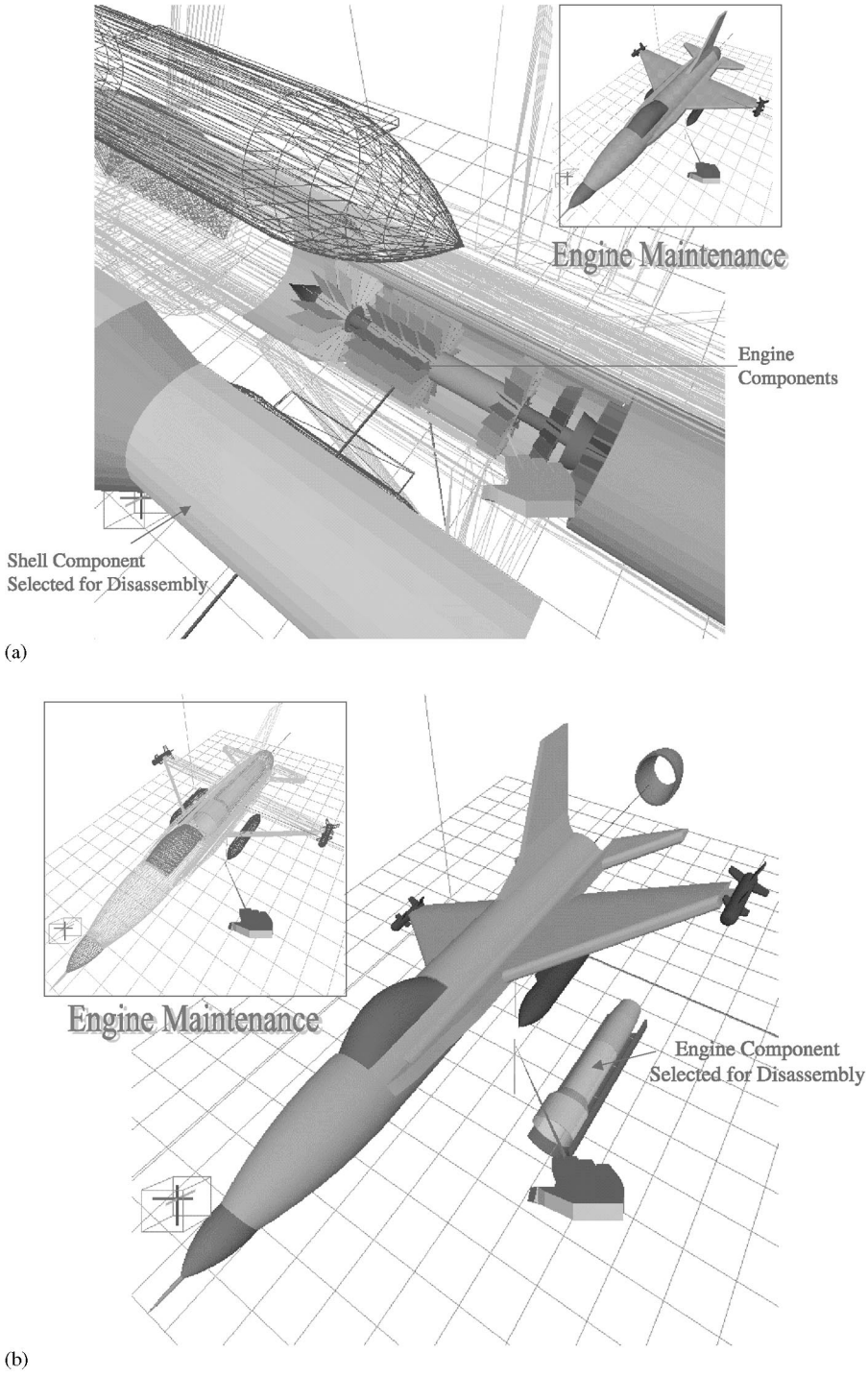


Fig. 14. (a) Aircraft sub-assembly: $\mathscr{SD}$ for in-place maintenance and (b) aircraft sub-assembly: $\mathscr{SD}$ for replacement maintenance.

will allow companies to determine what the disassembly cost is to the company, if and when the product is disassembled for recycling.

**Example.** $\mathscr{SD}$ of components of Nylon and PVC materials for recycling from the dashboard assembly, and disposal of the rest of the components.

Fig. 16a shows the generated maximal profit sequence $= \{C_5, C_6, C_{18}, C_{19}, C_4, C_{10}, C_{11}, C_8, C_9, C_{12}\}$ for $\mathscr{SD}$ of Nylon ($C_5, C_6, C_9, C_{18}, C_{19}$) and PVC ($C_{12}$) material components. Fig. 16b shows the cumulative cost plot. For this example, Eq. (5) is used with $K_O =$ 1.5 and LR = 20 \$/h. The total disassembly cost = \$1.84; which includes removal of 10 screws (140 s), 4 clips

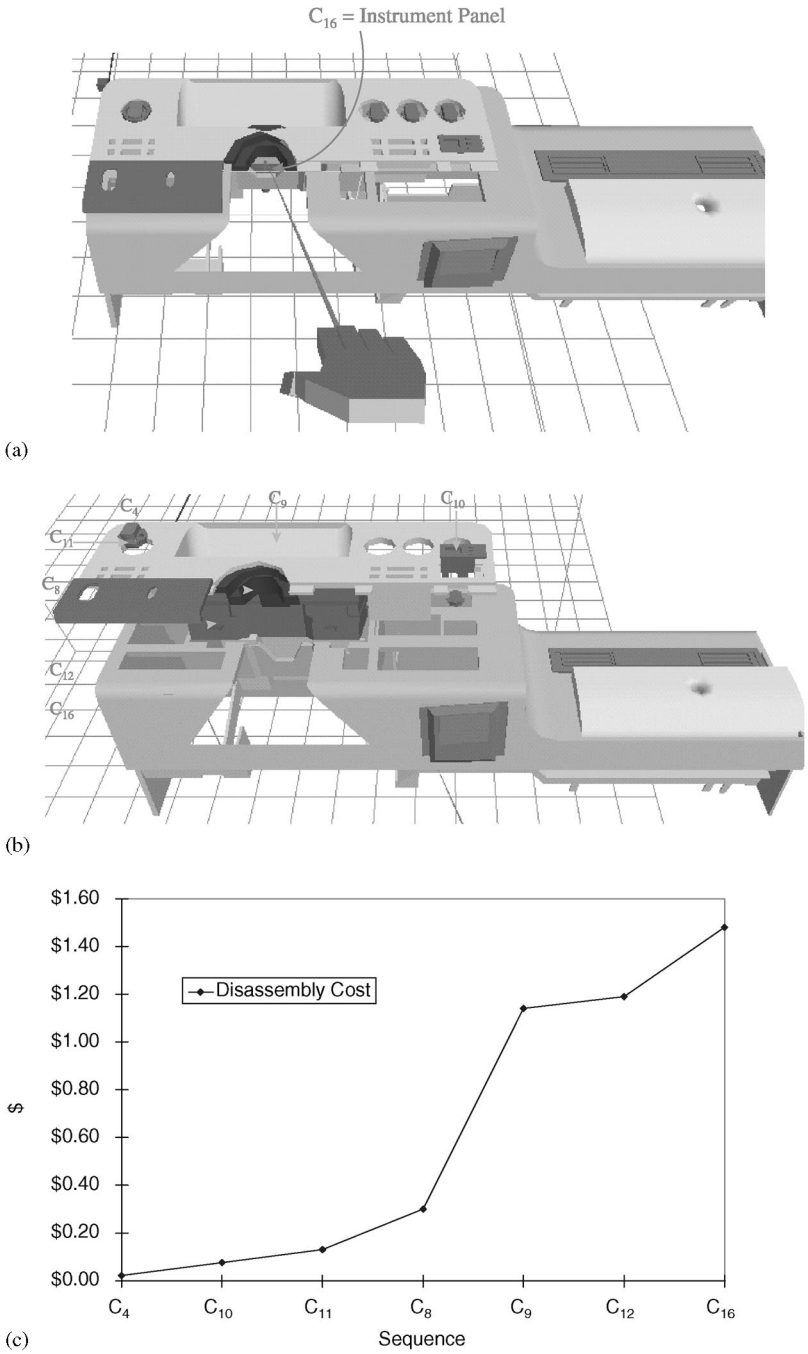


Fig. 15. (a) Dashboard assembly of an automobile: $C^{S} = \{C_{16}\}$, (b) dashboard assembly: minimal cost $\mathscr{S} = \{C_4, C_{10}, C_{11}, C_8, C_9, C_{12}, C_{16}\}$ and (c) dashboard assembly: disassembly cost graph for maintenance.

(16 s), 9 pins (36 s), 1 nut (4 s), and 10 components (25 s) in $\mathscr{S}$.

The recycling return values and the disposal cost values are incorporated as follows. Nylon and PVC have a high net (accounting for the processing cost) material recycling value of \$.516/lb and \$.20/lb, respectively. The cumulative return value plot (Fig. 16b) shows the recycling value obtained by disassembling and recycling of Nylon and PVC components. For example, a return value of \$2.78 at $C_{12}$ indicates the net value in recycling $C_5$ to $C_{12}$, except $C_4$, $C_{10}$, $C_{11}$ and $C_8$ (which are neither PVC nor Nylon). The cumulative disassembly and disposal cost plot shows the cost of disassembling the components and disposing of the rest of the assembly. For example, the American State of Wisconsin is used as a location for disposal, where the standard disposal cost for non-hazardous material is \$.015/lb [46]. A cumulative cost of \$2.65 at $C_{12}$ indicates the total disassembly

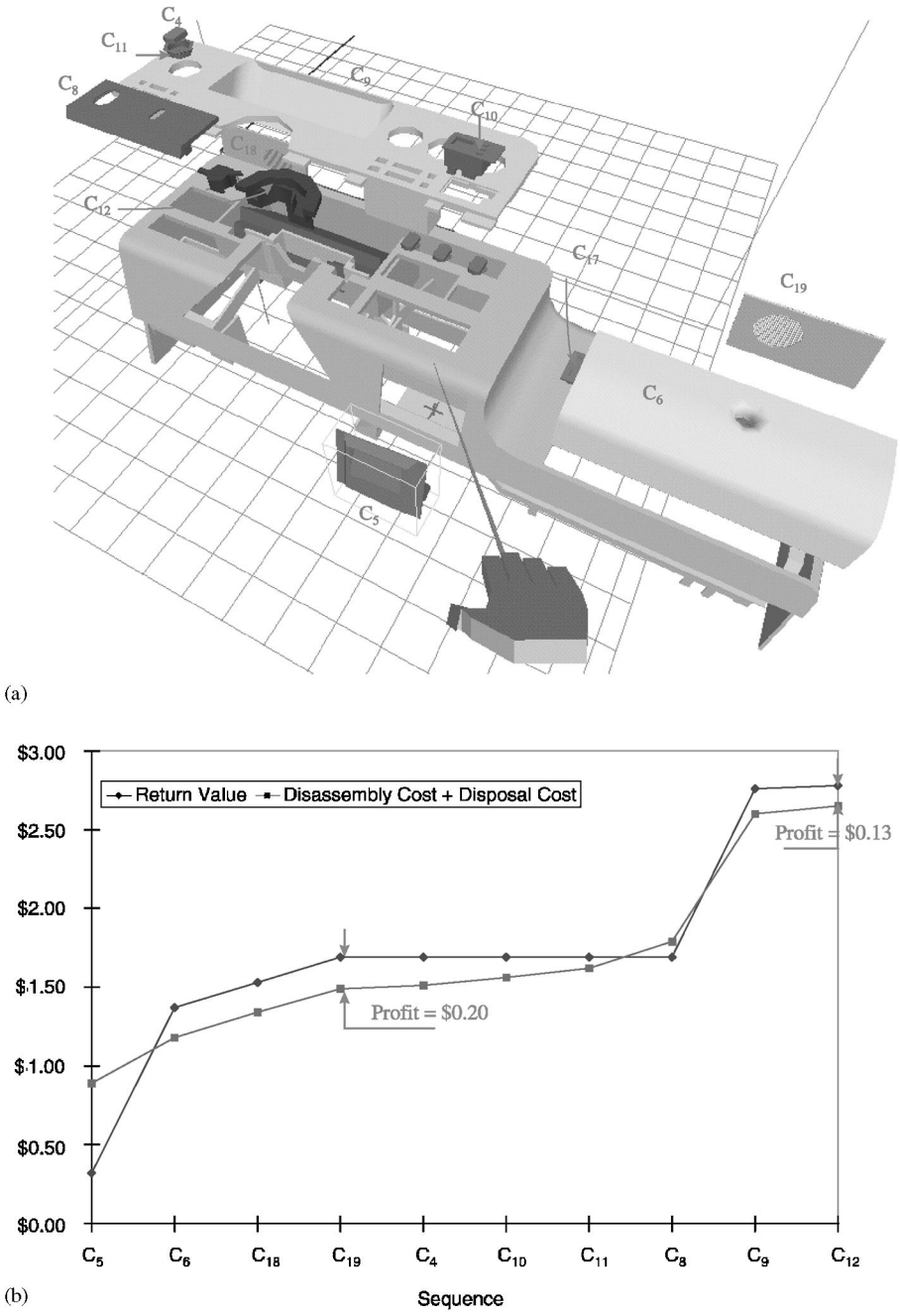


Fig. 16. Dashboard assembly: (a) for $C^S = \{C_5, C_6, C_9, C_{12}, C_{18}, C_{19}\}$ maximal profitable $\mathscr{S} = \{C_5, C_6, C_{18}, C_{19}, C_4, C_{10}, C_{11}, C_8, C_9, C_{12}\}$ and (b) value-sequence graph for recycling.

cost of disassembling components from $C_5$ to $C_{12}$ and disposal of all the components in the assembly except for the PVC and Nylon material components.

The profit in disassembling and recycling/disposing the components is available from the value-sequence plot (Fig. 16b). For example, $\mathscr{SD}$ of Nylon and PVC material components and the disposal of the rest of the assembly results in a total profit of \$.13 (=\$2.21/h) with a net recycling value of \$2.78 and a total disassembly/disposal cost of \$2.65. The solution generated is the most economical and feasible for a given $C^S$.

A $C^S$ for a profitable recycling can also be obtained from the value-sequence graph. For example, in Fig. 16b, at $C_{19}$ the total profit is \$.20 (=\$9.23/h) with the net recycling value = \$1.69 and the total disassembly/disposal cost = \$1.49. To achieve this locally optimum profit, components $C_5$ to $C_{19}$ are disassembled, the Nylon material components $\{C_5, C_6, C_{18}, C_{19}\}$ are recycled, and the rest of the assembly is disposed.

### 6.5. Contributions

The research contributions of this paper are:

1. A new design for selective disassembly methodology for evaluating an optimal disassembly sequence in virtual prototyping of product design.
2. Applying the selective disassembly procedure for demanufacturing (maintenance and recycling) applications.
3. A systematic procedure to assist the designer in making disassembly design decisions.
4. Implementation of selective disassembly sequencing and cost evaluation procedure and presentation of preliminary selective disassembly results.

### 6.6. Limitations and future work

One limitation of the current approach (due to Assumption 1) is that components are assumed to be free-floating and there are no fixture elements. However, the AG may be extended to allow either modeling the fixture elements as constraints on disassembly directions for components or modeling the fixture elements as components with relevant constraints. Moreover, another approach followed is to design the fixture elements based on the sequence generated.

A second limitation is that the assemblies are rigid, frictionless and defined by nominal geometry (Assumption 2), and only sequential, monotonic and non-destructive disassembly is considered in $\mathscr{SD}$ sequencing (Assumption 4). However, relaxation of these assumptions may require a new procedure for accessibility of a component.

A third limitation (due to Assumption 3) is that components are 1-disassemblable and 1-dependent. Multiple dependency for multiple component $\mathscr{SD}$ is limited due to the time-based intersection event definition [40]. However, a multiple dependency $\mathscr{WP}$ procedure for single $\mathscr{SD}$ presented in [2] is aggregated and used for multiple component SD for which only multiple dependent solution is possible.

A fourth limitation is that the $\mathscr{SD}$ sequencing procedure determines only locally optimum sequence, however, with polynomial complexity. This is due to the fact that the global optimum $\mathscr{SD}$ sequencing problem is exponential [41] and may not be feasible for larger assemblies.

## 7. Conclusion

This paper first presents a design for *selective disassembly* methodology to analyze the CAD model of an assembly during the *product development* cycle. Components to be disassembled are identified by analyzing the product material and application domain databases. User requirements for optimal sequence evaluation are formulated mathematically as an objective function. A *selective disassembly* technique, called *wave propagation*, evaluates sequences of locally minimum component removals and an optimal sequence is then determined based on the formulated objective function.

The paper next presents preliminary implementation results of a selective disassembly software tool for sequencing and cost evaluation. Based both on disassembly sequences and cost graphs, a designer may assess the design for disassembly and its applicability to demanufacturing applications. Moreover, performing the disassembly analysis at the product design stage can allow the designer to compare alternate designs and perform design changes for product development.

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