A Rule Based Assembly Sequence Generation Method for Product Design

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Ming-Chyuan Lin,[1,]* Yuan-Yeuan Tai,[1] Ming-Shi Chen,[1] and C. Alec Chang[2]

[1]*Department of Industrial Design, College of Planning and Design National Cheng Kung University, Tainan, Taiwan 701*

[2]*Department of Industrial and Manufacturing Systems Engineering, College of Engineering University of Missouri-Columbia, Columbia, MO 65203, USA*

Abstract: In concurrent engineering, the integration of the designers' knowledge and experience, and computer technology into the design process is very important to improve design quality and production efficiency. A feasible design alternative that follows the design rules for assembly will make product manufacturing and assembly more successful. However, designers seldom consider assembly problems in their product development processes. This drawback often occurs due to conflicts in communication between the design and production departments and will cause severe assembly and manufacturing problems. To assist designers with the assembly issue in the design process this research presents a contact relation matrix (CRM) approach to generate assembly sequences for product design. The procedure developed for the CRM approach is based on the four rules identified from the part contact relations and a matrix representation to match the recommended design alternative with the four rules. A procedure is then employed to identify the assembly priority for the recommended design alternative. The part assembly sequence is generated with a sorting procedure. A hand-held hairdryer and an Italian style coffee maker are used as cases to help explain the feasibility of the CRM approach. The results from this study should help designers to examine the possible part combinations and make the necessary modifications for the recommended design alternative. The CRM approach can also be linked with an existing matrix approach in generating and evaluating design alternatives. By integrating the CRM and matrix approaches, the design quality and efficiency will be greatly improved.

Key Words: product design, assembly sequence, contact relation matrix, matrix representation.

1. Introduction

Product design is a creative process that integrates abstract design components into a complete specification of product characteristics that satisfies customer requirements. Jiao and Chen [1] summarized a comprehensive review of the state-of-art product design research and indicated how product design is influenced by customer requirements. However, many manufacturing and assembly problems can be attributed to poor product design. Owing to competitive market considerations, product design has become the most important factor in securing competitive advantages in product quality, assembly and production efficiency. As manufacturing technology and computer performance have improved, many companies have evolved design strategy from computer-aided design (CAD), computer-integrated manufacturing (CIM) to concurrent engineering (CE) to enhance the efficiency. The design for assembly (DFA) concept is also widely used.

In DFA, Boothroyd and Dewhurst [2] proposed an assembly oriented product analysis method that considers assembly sequences, product functions, parts handling and insertion to generate a product assembly plan. Whitney et al. [3] introduced a strategic approach concept to product design (SAPD) which integrates product design, manufacturing process and assembly to rationalize the product design, and the assembly process. Boothroyd and Dewhurst [4] further developed a DFA/DFM software incorporating assembly and design rules for designers to evaluate the feasibility of a design, based on the assembly sequences. Since then, much research related to assembly sequences has been introduced. Pu [5] presented an algorithm to assist designers to develop an assembly sequence plan based on case-based reasoning (CBR) paradigm. In the meantime, Dini and Santochi [6] used adjacency matrices including interference matrix, contact matrix, and connection matrix in the Cartesian coordinate system to deal with module assembly for reverse assembly planning. Tonshoff [7] also identified three inference rules,

*Author to whom correspondence should be addressed.
E-mail: minglin@mail.ncku.edu.tw

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namely (1) task-related rules, (2) object-related rules, and (3) organizational rules to transfer parts and modules information for sequence planning. Lee and Shin [8] constructed a liaison graph to transfer the parts into nodes and identify the merge rules for parts assembly. Liao et al. [9] developed a computer-aided planning system to use the bill of materials (BOM) for the aircraft frame assembly. Yee and Ventura [10] used the Petri Net model to identify the assembly operation constraints and then converted this into integer programming to minimize the total assembly time or cost. Wu and O'Grady [11] further improved the original Petri Nets by developing a CE-net system that includes additional objects to attach each transition and place note to help evaluate the design process. Siddique and Rosen [12] introduced the design spaces concept, which considers physical connectivity, function, and assembly for a product family. Chen et al. [13] proposed a blackboard-based concurrent product design evaluation system (CONDENSE), which assesses the assembly of a design according to DFA guidelines. Zhang et al. [14] developed a procedure to derive feasible assembly sequences for a number of automobile parts. Yin et al. [15] presented a connector-based relational model (CBRM) to construct a feasible parts assembly sequence. A three-stage procedure to develop graph and transformation rules together with a penalty index to generate parts assembly sequence was then proposed by Chen et al. [16]. Barnes [17] also introduced a two-stage decision support procedure to create parts and their subassembly sequences. Liverani et al. [18] further exploited a PAA (Personal Active Assistant) tool to generate assembly by geometrical features matching to improve object recognition, best assembly sequence optimization and operator instruction generation. Grewal et al. [19] applied an entity-relationship (E-R) diagram to represent the data objects and their interrelationships for the generation of part and assembly plans. Chan et al. [20] then illustrated a framework of a web-based 3D assembly system to assist the customers to make their design decision. In brief, the development of design for assembly techniques mentioned above is very helpful for designers to consider assembly issues in the design process.

However, most product design activities still seldom place attention in the integration of design and manufacturing processes, especially the assembly process. This is because product designers always concentrate on the design balance between form and function instead of considering feasible assembly. Note that a design stage involving feasible assembly sequences will compromise design concepts, configurations, function, and even facilitate manufacturing. Most of the assembly techniques are primarily dealing with mechanical parts and may not be suitable for product design. In general, a design alternative that has the characteristics of simple product structure, few components, and durable construction will make product manufacturing and assembly more successful. Determining a feasible assembly sequence for the product has become more important today. The objective of this research is to develop a contact relation matrix (CRM) method for identifying feasible assembly sequences and assist designers in evaluating generated simplified design alternatives. The CRM method is also suitable for modular assembly product sequences. A hand-held hairdryer and a coffee maker are used to demonstrate the applicability of the CRM method. It is expected that the designer can use the feasible assembly sequence identified from the CRM method to examine the generated design alternatives for possible combinations between components, elimination of unnecessary components, or the manufacturing process and production plan.

2. A Framework for the Development of the CRM Approach

The development of the CRM approach is based on the design recommendation generated from the product design process. Use of the CRM approach assists designers to screen off unfeasible assembly sequences and evaluate feasible assembly sequence for the recommended design alternative. To obtain the feasible assembly sequences, product functional information and geometric relations are reviewed.

Let DP denote the set of design parameters identifying labels or names.

$$\mathrm{DP} = \{\mathrm{DP}_i | i = 1, 2, \ldots, n\}.$$

Meanwhile, let DPV_i denote the set of A_i alternative design parameter values corresponding to design parameter DP_i.

$$\mathrm{DPV}_i = \left\{\mathrm{DPV}_{i,j_i} | j_i = 1, 2, \ldots, A_i, \quad \text{and} \quad i = 1, 2, \ldots, n\right\}.$$

Note that the concatenation of design parameters identifiers DP and design parameter values DPV_i will represent a specific design recommendation.

Let FDA denote an n-dimensional column vector describing a feasible design alternative, with typical element FDA_i specifying a selected design parameter value DPV_{j_i} for design parameter DP_i.

Hence, $\mathrm{FDA}_i = \mathrm{DPV}_{j_i}$, if any value DPV_{j_i} is pairwise feasible, $i = 1, 2, \ldots, n$; $j_i = 1, 2, \ldots, A_i$.

In general, a product design development may generate many design alternatives that are feasible for a specific set of user requirements. The designer will need to evaluate the generated design alternatives and determine the most suitable one as the design recommendation. There are several ways for designers to generate and evaluate feasible design alternatives. However, the research will focus on the determination of assembly sequences for the generated design alternatives.

2.1 Rules for the Generation of Assembly Sequences

There are four rules that can be used to help identify the assembly sequence for each design alternative value.

Rule 1: If the choice of a particular design parameter value $\mathrm{DPV}_{i_a,j_{i_a}}$, $i_a \in n$, $j_{i_a} \in A_i$, for design parameter DP_{i_a} can be independently assembled with a specific design parameter value $\mathrm{DPV}_{i_b,j_{i_b}}$, $i_b \in n$, $i_b \neq i_a$, $j_{ib} \in A_i$, for design parameter DP_{i_b}, the assembly sequence for these two values should be assembled first.

Rule 2: If the choice of a particular design parameter value $\mathrm{DPV}_{i_a,j_{i_a}}$, $i_a \in n$, $j_{i_a} \in A_i$, for design parameter DP_{i_a} can be assembled with a specific design parameter value $\mathrm{DPV}_{i_b,j_{i_b}}$, $i_b \in n$, $i_a \neq i_b$, $j_{i_b} \in A_i$, for design parameter DP_{i_b} only when the value $\mathrm{DPV}_{i_b,j_{i_b}}$ has been assembled with a particular value $\mathrm{DPV}_{i_c,j_{i_c}}$, $i_c \in n$, $i_c \neq i_b$, $j_{i_c} \in A_i$, for design parameter DP_{i_c}, then the sequence of the assembly for the two values $\mathrm{DPV}_{i_a,j_{i_a}}$ and $\mathrm{DPV}_{i_b,j_{i_b}}$ should wait till the two values $\mathrm{DPV}_{i_b,j_{i_b}}$ and $\mathrm{DPV}_{i_c,j_{i_c}}$ have been assembled.

Rule 3: If the choice of a particular design parameter value $\mathrm{DPV}_{i_a,j_{i_a}}$, $i_a \in n$, $j_{i_a} \in A_i$, for design parameter DP_{i_a} follows Rule 2 and will be assembled with a specific design parameter value $\mathrm{DPV}_{i_b,j_{i_b}}$, $i_b \in n$, $i_a \neq i_b$, $j_{i_b} \in A_i$, for design parameter DP_{i_b}, the sequence of the assembly for the two values $\mathrm{DPV}_{i_a,j_{i_a}}$ and $\mathrm{DPV}_{i_b,j_{i_b}}$ should wait untill the previous assembly of $\mathrm{DPV}_{i_a,j_{i_a}}$ has been finished. Similarly, If the choice of a particular design parameter value $\mathrm{DPV}_{i_a,j_{i_a}}$, $i_a \in n$, $j_{i_a} \in A_i$, for design parameter DP_{i_a} will be assembled with a specific design parameter value $\mathrm{DPV}_{i_b,j_{i_b}}$, $i_b \in n$, $i_a \neq i_b$, $j_{i_b} \in A_i$, for design parameter DP_{i_b} that follows Rule 2, then the sequence of the assembly for the two values $\mathrm{DPV}_{i_a,j_{i_a}}$ and $\mathrm{DPV}_{i_b,j_{i_b}}$ should wait untill the previous assembly of $\mathrm{DPV}_{i_b,j_{i_b}}$ has been finished. Note that if both values $\mathrm{DPV}_{i_a,j_{i_a}}$ and $\mathrm{DPV}_{i_b,j_{i_b}}$ follow Rule 2, then Rule 3 will also be applied.

Rule 4: If the choice of a particular design parameter value $\mathrm{DPV}_{i_a,j_{i_a}}$, $i_a \in n$, $j_{i_a} \in A_i$, for design parameter DP_{i_a} is assembled with more than three design parameter values, say $\mathrm{DPV}_{i_b,j_{i_b}}$, $\mathrm{DPV}_{i_c,j_{i_c}}$ and $\mathrm{DPV}_{i_d,j_{i_d}}$, i_b, i_c and $i_d \in n$, $i_b \neq i_c \neq i_d$, j_{i_b}, j_{i_c} and $j_{i_d} \in A_i$, simultaneously, then the assembly of this value should wait till three values have been assembled. In general, the study of assembly operation is helpful for the identification of this kind of assembly sequence. However, this kind of assembly is not an efficient design and should be improved by redesign or reduced to the minimum. Based on the concept of contact relations, if the choice of a particular design parameter value $\mathrm{DPV}_{i_a,j_{i_a}}$, $i_a \in n$, $j_{i_a} \in A_i$, for design parameter DP_{i_a} will be assembled with a design parameter value $\mathrm{DPV}_{i_b,j_{i_b}}$, $i_b \in n$, $j_{i_b} \in A_i$ and either one of them follows Rule 3, then Rule 4 is also applied.

2.2 Identification of Contact Relations Between Design Parameter Values

Based on the four rules defined above, it is possible to identify the set of design parameter values that have contact relations with other design parameter values.

Let CR denote the set of contact relations between design parameter values, then

$$\mathrm{CR} = \big\{(\mathrm{DPV}_{i_e,j_{i_e}}, \mathrm{DPV}_{i_f,j_{i_f}}, R_k) | i_e \quad \text{and} \quad i_f \in n, i_e \neq i_f, j_{i_e} \\ \text{and} \quad j_{i_f} \in A_i,\ i = 1, 2, \ldots, n, \quad \text{and} \quad k = 1, 2, 3, 4\big\}$$

where $\mathrm{DPV}_{i_e,j_{i_e}}$ represents a choice of design parameter values for design parameter DP_{i_e}, $\mathrm{DPV}_{i_f,j_{i_f}}$ represents a selection of design parameter values for some other design parameter DP_{i_f} so that each pair of values $(\mathrm{DPV}_{i_e,j_{i_e}}, \mathrm{DPV}_{i_f,j_{i_f}})$ has a contact relation, and R_k represents a contact relation between values $\mathrm{DPV}_{i_e,j_{i_e}}$ and $\mathrm{DPV}_{i_f,j_{i_f}}$ that follows Rule k.

2.3 General Steps of the CRM Approach

Once rules for the determination of assembly sequences and contact relations between design parameter values are identified, a matching procedure can be employed to form a contact relation matrix for the generated design alternative. The contact relation matrix will then be forwarded to generate an assembly sequence. The general steps for the development of CRM approach are briefly discussed as follows:

Step 1: Develop a contact relation matrix CRM for the generated design alternative.
A contact relation matrix CRM is created based on the generation of a feasible

design alternative. This matrix documents the contact relationships among design parameter values. If there is a contact relation, the value between the corresponding matrix elements will be assigned as the type of the rules mentioned above. Otherwise, assign the value "0" to the matrix element.

Let CRM be a $n \times n$ matrix to represent the set of contact relations that is identified from each design parameter value for the generated design alternative, with typical element $\mathrm{CRM}_{i,j}$,

$$\mathrm{CRM}_{i,j} = \begin{cases} R_k & \text{if and only if design parameter values} \\ & \quad \mathrm{DPV}_{i_a,j_{i_a}} \text{ and } \mathrm{DPV}_{i_b,j_{i_b}} \text{ in a FDA} \\ & \quad \text{match values } \mathrm{DPV}_{i_e,j_{i_e}} \text{ and } \mathrm{DPV}_{i_f,j_{i_f}} \\ & \quad \text{of array entries } \mathrm{DPV}_{i_e,j_{i_e}},\ \mathrm{DPV}_{i_f,j_{i_f}},\ R_k \\ & \quad \text{in CR to represent a candidate} \\ & \quad \text{assembly between values } \mathrm{DPV}_{i_a,j_{i_a}} \\ & \quad \text{and } \mathrm{DPV}_{i_b,j_{i_b}} \\ 0 & \text{otherwise} \end{cases}$$

Step 2: Generate an assembly priority matrix APM.

An assembly priority matrix APM is then developed based on the CRM. The assembly priority matrix array has the same number of rows and columns as the number of CRM.

Let APM denote the set of positive integer numbers that are determined from CRM to indicate the assembly priority between design parameter values of the feasible design alternative, with typical element $\mathrm{APM}_{i,j}$,

$$\mathrm{APM}_{i,j} = \begin{cases} \text{positive integer number } I & \text{if an array entry } [R_k]\ k = 1, 2, 3, \\ & \quad \text{or 4 in } \mathrm{CRM}_{i,j} \text{ is identified} \\ & \quad \text{and compared, then replace} \\ & \quad \text{the } R_k \text{ with an appropriate} \\ & \quad \text{integer number to represent} \\ & \quad \text{an assembly priority sequence} \\ & \quad \text{between the corresponding} \\ & \quad \text{design parameter values} \\ 0 & \text{otherwise} \end{cases}$$

Note that the lower integer number means the corresponding design parameter values will be assembled before those of higher integer numbers. In this research, the incremental integer numbers will be assigned to represent the assembly priority for the design parameter values of the generated design alternative. The judgment of the integer numbers is based on the four rules R_1, R_2, R_3 and R_4. If two or more arrays in CRM have the same contact relation R_k, then assign consecutive numbers for the corresponding arrays with which the assignment starts from the first row to the last row of the CRM.

Step 3: Generate a part assembly sequence matrix PASM.

To generate a part assembly sequence matrix PASM, a sorting procedure is used with the assembly priority matrix APM. The sorting procedure starts by comparing the integer numbers of two rows of array entries from the first row to the last row, and then from the first column to the last column. The sorting of each row and column is based on an increasing order corresponding to the smallest integer number in the related APM array entry.

Let TPASM denote a transitional part assembly sequence matrix that the entries in the r-th row of the APM having a smaller integer number than those of in the s-th row of the APM will be placed in the upper row. Similarly, let PASM denote a part assembly sequence matrix that the entries in the u-th TPASM column having a smaller integer number than those in the v-th TPASM column will be placed in the left column.

The research follows the above three steps to generate the relevant matrices and assembly sequence. A detailed process will be presented in the next section. Figure 1 shows the overall development procedures for the CRM approach.

3. The Development of Procedures for the CRM Approach

In order to assist designers to deal with assembly problems in the design stages, the research developed a CRM approach which incorporates the design process that can integrate design and assembly processes into a whole product design system. Since there are many available design methodologies in generating feasible design alternatives that can meet specific sets of user requirements, the CRM approach will concentrate on the assembly sequences for the generated design alternatives. Therefore, the CRM approach starts by defining design parameter values for the generated design alternatives. The design parameters and values characterize the product components that are essential to the design of final product. Once the design parameters and generated design alternative values have been identified,

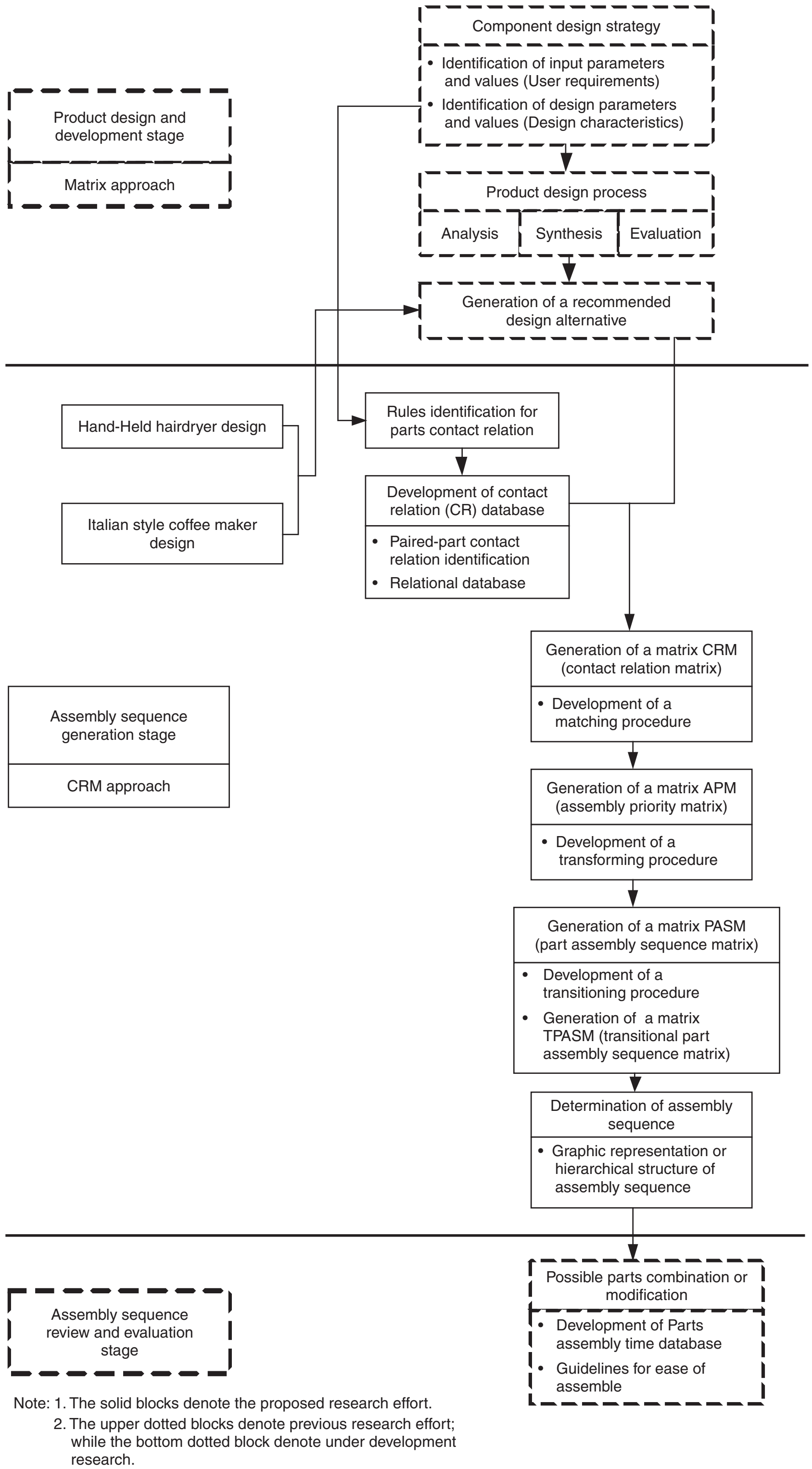


Figure 1. Development framework for the CRM approach.

the CRM approach can then proceed with the above three development steps.

3.1 Procedures for the Development of a Contact Relation Matrix (CRM)

A matching procedure that considers design parameter values of the generated feasible design alternative FDA can be employed to identify sets of contact relations among design parameter values in CR. The matching procedure uses a back and forth route to iteratively check for contact relations. The following three steps will be used to form a contact relation matrix CRM.

Step 1: For each array entry DPV_{i_g,j_i} in FDA, create an array $[\mathrm{DPV}_{i_g,j_{i_g}}, \mathrm{DPV}_{i_h,j_{i_h}}]$ in FDAPV, where FDAPV denotes the collection of array entries for paired design parameter values from FDA, and

$$\mathrm{FDAPV} = \{(\mathrm{DPV}_{i_g,j_{i_g}}, \mathrm{DPV}_{i_h,j_{i_h}})|i_g \in n, \quad i_h = 1, 2, \ldots, n, \text{ and } j_{i_g}, j_{i_h} \in A_i\}.$$

Step 2: Once the arrays $[\mathrm{DPV}_{i_g,j_{i_g}}, \mathrm{DPV}_{i_h,j_{i_h}}]$ in FDAPV are formed, check each array entry of the paired design parameter values $\mathrm{DPV}_{i_g,j_{i_g}}$ and $\mathrm{DPV}_{i_h,j_{i_h}}$ in FDAPV to see if both of them match a $\mathrm{DPV}_{i_e,j_{i_e}}$ and $\mathrm{DPV}_{i_f,j_{i_f}}$ array entry in CR. If so, then place the associated value R_k in CRM in the position corresponding to the row value $\mathrm{DPV}_{i_g,j_{i_g}}$ in FDA. Otherwise, place a 0 value in CRM. Therefore, an array entry is formed for the row i_g of CRM.

Step 3: The matching procedure moves back and forth through Step 1 and Step 2 until all of the entries in CRM are filled with values R_k and 0.

3.2 Procedures for the Generation of an Assembly Priority Matrix (APM)

To identify the assembly priority for the generated design alternative FDA that is based on the contact relation matrix CRM, a four-step search procedure is developed with the array entry from the first row entries of CRM serving as a starting point. The search procedure developed here also uses a back and forth route to iteratively identify the assembly priority for each design alternative value.

Step 1: In Step 1, each array entry "R_1" in CRM is checked to determine the sequence of an assembly for the corresponding design parameter values $\mathrm{DPV}_{i_g,j_{i_g}}$ and $\mathrm{DPV}_{i_h,j_{i_h}}$ in FDA. In the first pass through Step 1, check the array entries from the first row of CRM. If at least one array entry "R_1" appears in that CRM row, then place an array entry "1" for the first identified array entry "R_1", an array entry "2" for the second identified array entry "R_1", and so forth, in the corresponding APM entries. The positive integer numbers in the APM array entries are incremental and represent the assembly sequences for the corresponding FDA values in CRM. Since the APM matrix is symmetrical to the diagonal, place the same integer numbers to the transposed array entries. As to the corresponding array entries "0" in CRM, place array entries "0" in the related APM row entries.

Step 2: In Step 2, each array entry "R_2" is checked from the first CRM row. A similar search procedure that is developed in Step 1 will also be applied in Step 2. Note that design parameter values with an array entry "R_2" should be assembled right after all design parameter values with array entries "R_1" have been assembled.

Step 3: In Step 3, the search procedure continues to identify the array entries "R_3" from the first CRM row. In general, there will be two array entries "R_3" appearing in the same CRM row for the related design parameter values. Therefore, arbitrarily select an array entry or choose the first appearing array entry "R_3" of CRM, and then place an incremental positive integer number for the corresponding APM array entry. For the other "R_3" CRM array entries, place a "0" for the corresponding APM array entry. Again, a similar search procedure that is developed in Step 1 will also be applied in Step 3.

Step 4: In Step 4, the search procedure continues to identify the array entries "R_4" from the first CRM row. If there exists an array entry "R_4" in row i_a and the corresponding column j_b of CRM, then check the array entries of row i_a and row j_b in CRM to see other design parameter values that have both array entries of "R_3" and "R_4" in row i_a and row j_b. Place an incremental positive integer number in the corresponding array entry of APM_{i_a,j_b}. As to the other array entries "R_4" in row i_a or row j_b of CRM, place a "0" in the corresponding array entries of APM.

The search procedure moves back and forth through Step 1, Step 2, Step 3, and Step 4 until all of the array entries in APM are filled with the sequential numbers and "0". The identified integer numbers in APM represent the assembly between design parameter values of a feasible design alternative FDA and their respective assembly sequence. However, to obtain a clear view of assembly associating with sequences for design parameter values of a FDA and even direct towards connecting with a computer-integrated manufacturing system, a sorting procedure for the generated APM will be employed.

3.3 Procedures for the Generation of a Part Assembly Sequence Matrix (PASM)

Based on the APM generated above, the research further develops a sorting procedure to generate a part assembly sequence matrix PASM. The PASM reorders the design parameter values for the generated FDA. In general, the corresponding design parameter values with a smaller integer number will be assembled earlier than those with larger integer numbers. Therefore, the sorting procedure will reorder the design parameter value sequence and the corresponding array entries from APM to generate a PASM. Note that a transitional part assembly sequence matrix TPASM will be developed as a bridge to link the two matrices APM and PASM. In PASM, the array entry with the smallest integer number will be arranged on top of the left side; while the array entry with the largest integer number will be arranged to bottom of the right side. The following two steps will be used to form PASM.

Step 1: In Step 1, a sorting procedure is employed to generate a transitional part assembly sequence matrix TPASM based on APM. Since the matrix APM is symmetrical to the diagonal, each positive integer number in the array entries is in pairs. Therefore, in the first pass through Step 1, the sorting procedure identifies the two values of "1" from the first row entries of APM. If the first value of "1" appears in the first row entries of APM, then place the row values in the first row entries of TPASM. If none of array entries in the first row of APM are with a value "1", then move to the second APM row and continue to identify row entries till two values of "1" have been found. All the row entries in APM having the second value of "1" will be placed in the second TPASM row. In subsequent passes through Step 1, identify array entries with the paired-value of "2", "3", ... and "$n-1$", and place the row values in the third, forth, ... and n-th row entries of TPASM, respectively. It is possible that two or more positive integer numbers are in the same APM row. When identifying the paired values in each pass, check to see if the corresponding row has been placed. If the corresponding row has been placed in the TPASM because of other smaller positive integer numbers in that row, then go to the next APM row and continue to identify the other paired value. If all array entries in TPASM have been assigned a value, then go to Step 2.

Step 2: In Step 2, the rearrangement of each column of TPASM will actually generate the part assembly sequence matrix PASM. In Step 2, the sorting procedure continues to identify the paired-value of "1", "2", ... and "$n-1$" from the first column to the last column of TPASM, and then place the identified column entries in the first, second, ... and n-th column of PASM. A similar procedure used in Step 1 will also be applied in Step 2 till PASM is formed.

Once the PASM is generated, the assembly sequence for the generated design alternative has been completed. The computer programs used in this process were written in Microsoft Visual Basic 6.0. Note that the relational database system has been used throughout the procedure development.

4. Implementation of the CRM Approach

To help explain how the procedures of the CRM approach are developed, two types of product design cases are used as examples. They are (1) a hand-held hairdryer design and (2) a coffee maker design. The hand-held hairdryer is considered as a simple product type; while the coffee maker is considered as a complex product type. The chosen cases are familiar products in almost everyone's daily life, and each year many new styles of these two products come into the competitive market. In general, the CRM approach is also applicable in some product design areas as varied as electronic and electrical appliances, office equipment, and sports equipment.

4.1 A Hand-held Hairdryer Design Case

The appearance characteristics of a typical hand-held hairdryer include hot air outlet, outlet protection net, handle, cold air outlet, power switch, handle joint, heat-tube, motor cover, and plug. Assume that a recommended design alternative is generated for a specific set of user requirements. The design parameters and values

(a)

Design parameter	Recommended deisgn parameter value
1. Hot air outlet	No. 1–2
2. Outlet protect net	No. 2–5
3. Handle	No. 3–9
4. Cold air inlet	No. 4–6
5. Power switch	No. 5–2
6. Handle joint	No. 6–3
7. Heat tube	No. 7–8
8. Motor cover	No. 8–34
9. Plug	No. 9–2

(b)

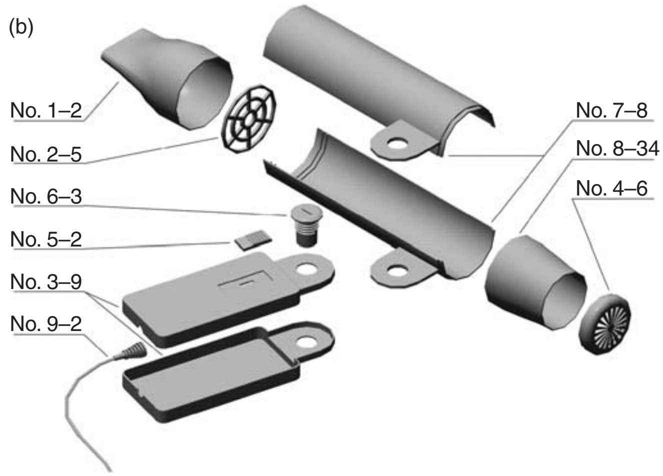


Figure 2. Characteristics of a hand-held hairdryer design case. (a) Coding representation; (b) Graphic representation.

for this recommended design alternative are shown in Figure 2.

In accordance with the defined four rules, the identification of the set of contact relations CR among design parameter values for the hand-held hairdryer design case is partially illustrated in Figure 3. To form a CRM for the recommended design alternative, a matching procedure is then employed to identify contact relations among CR that directly relate to the recommended design parameter values. Figure 3 also illustrates how a contact relation matrix CRM is generated for the recommended hand-held hairdryer design alternative. In Figure 3, each design parameter value of the recommended hand-held hairdryer design alternative checks the CR database from the first row array to the last row array to identify which rules are available for some specific design parameter values. For example, the value "No.3–9" of design parameter "Handle" in the recommended hand-held hairdryer design alternative matches the values "No.5–2", "No.6–3", "No.7–8", and "No.9–2" of design parameters "Power switch", "Handle joint", "Heat tube", and "Plug" with their corresponding contact relations "R_1", "R_4", "R_3", and "R_2", respectively. Assign "R_1", "R_4", "R_3", and "R_2" in the corresponding entries of CRM. The value "No.3–9" that does not have any contact relations with other values including self-value will then assign "0" to the corresponding CRM entries. The matching process continues paired-checking from the first row value to the last row value of recommended design alternative till all values have been examined and the entries in CRM have been assigned. In Figure 3, note that there are four entries of "R_4" in CRM indicating three values "No.3–9", "No.6–3", and "No.7–8" will be assembled together at almost the same time. Since the two values "No.3–9" and "No.7–8" follow Rule 3, the assembly of each pair of values ("No.6–3" and "No.3–9") and ("No.6-3" and "No.7-8") will both follow Rule 4.

After forming the CRM matrix, a transforming procedure is employed to generate an APM assembly priority matrix. During the generation of an APM, three intermediate stages are considered as illustrated in Figure 4 for the hand-held hairdryer design example. In stage 1, entries in CRM with "R_1" are transformed and assigned with a starting number "1" and then an incremental integer number from a pass through the first row to the last CRM row. Because the CRM is a diagonally symmetric matrix, there will be two identical numbers for each assigned number. Similarly, stage 2 and stage 3 deal with entries in CRM with "R_2" and "R_3". In stage 4, entries in CRM with "R_4" will be transformed and led to form an assembly priority matrix APM. As mentioned above, there are four entries of "R_4" in CRM which means that three values "No.3–9", "No.6–3", and "No.7–8" will be assembled together at almost the same time. However, only the first appearing row entry as well as the reflective row entry of "R_4" in CRM will be assigned a number to the corresponding row entries of APM for simplification. Therefore, assign a number of assembly sequence to the corresponding row entries of APM for the first appearing pair ("No. 3–9" and "No. 6–3") of row entries "R_4" in CRM and assign "0" to the corresponding APM row entries for the other pair ("No. 6–3" and "No. 7–8") of row entries "R_4" in CRM. It is because at least one of the values for the corresponding row entry of "R_4" in CRM follows Rule 3 and will be assembled with a value in the previous assembly stage. In Figure 4, the assembly of values "No.6–3" and "No.7–8" follows Rule 3 and will be assembled in advance.

Figure 5 illustrates how a sorting process is employed to form a part assembly sequence matrix PASM for the hand-held hairdryer design case. The sorting process starts to identify the lowest integer number from the first row entries to the last APM

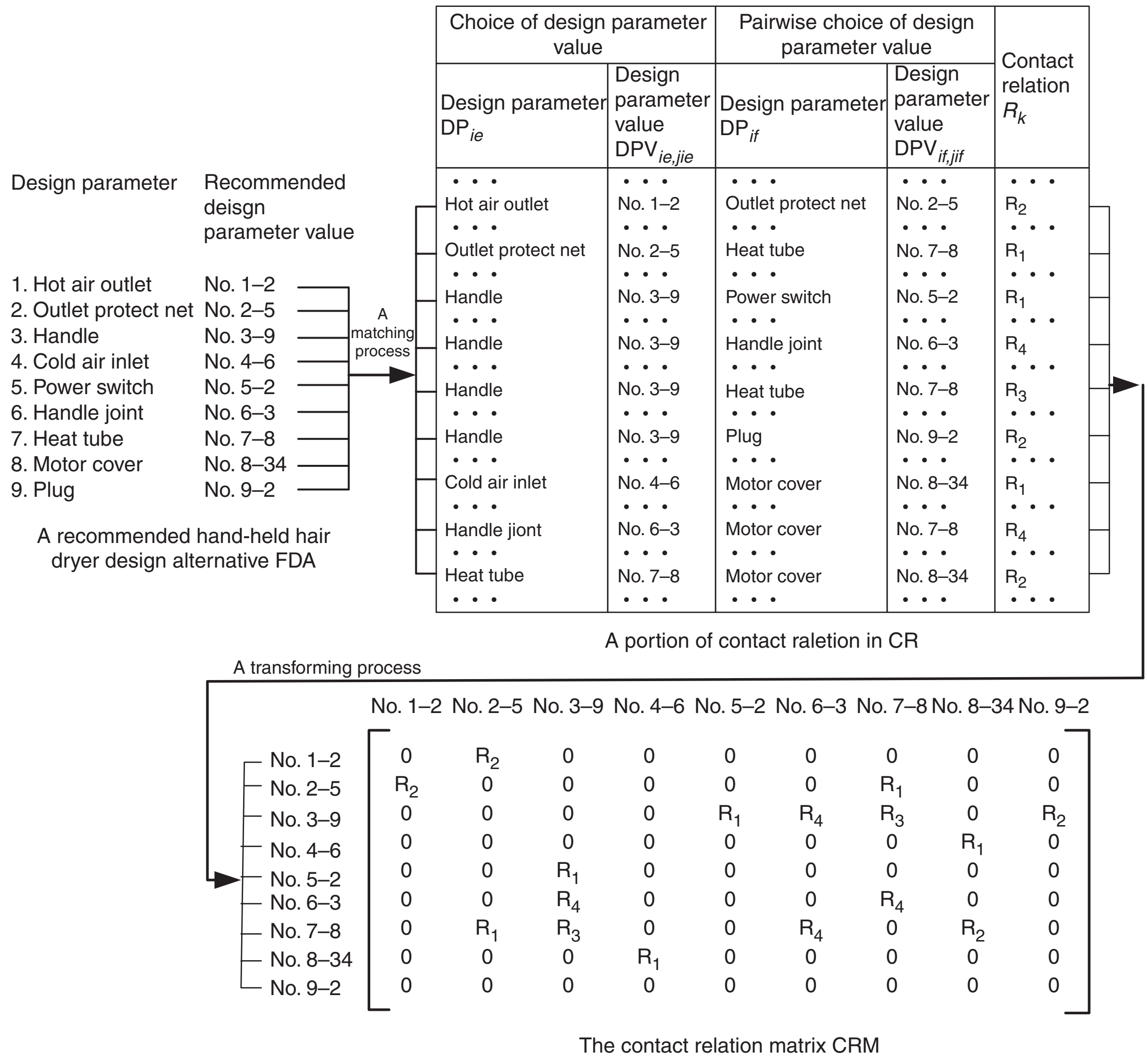


Figure 3. Generation of a CRM for the hand-held hairdryer design alternative.

row entries. If the row entries has a "1" in APM, then place the APM row entries into the unassigned TPASM row entries. The matrix APM in Figure 5 shows that the second row array [4 0 0 0 0 0 1 0 0] and the seventh row array [0 1 7 0 0 0 0 6 0] have a "1" in a specific entry, then place [4 0 0 0 0 0 1 0 0] and [0 1 7 0 0 0 0 6] to the first and second TPASM row, respectively. After the row entries with "1" in APM having been identified and assigned to the upper TPASM row, the sorting process continues to identify the incremental integer number from the first row entries to the last APM row entries. In this situation, the APM matrix shows that the third row array [0 0 0 0 2 8 7 0 5] and the fifth row array [0 0 2 0 0 0 0 0 0] have a "2" in a specific entry, then place [0 0 0 0 2 8 7 0 5] and [0 0 2 0 0 0 0 0 0] to the third and fourth TPASM row, respectively. When all numbers in APM have been identified and the row entries in TPASM have been assigned, the sorting of APM row arrays is completed. Similarly, a sorting process will then continue to form a PASM by identifying the lowest integer number from the first column array to the last TPASM column array. When all numbers in TPASM have been identified and the column entries in PASM have been assigned, the sorting process for APM is finished and the PASM is formed. The generation of the matrix PASM provides the information about the assembly sequence for the recommended design alternative. Figure 6 presents how the assembly process is made based on the generated PASM shown in Figure 5.

4.2 An Italian Style Coffee Maker Design Case

The appearance characteristics of an Italian style coffee maker include about 29 detailed parts.

	No. 1–2	No. 2–5	No. 3–9	No. 4–6	No. 5–2	No. 6–3	No. 7–8	No. 8–34	No. 9–2
No. 1–2	0	R_2	0	0	0	0	0	0	0
No. 2–5	R_2	0	0	0	0	0	R_1	0	0
No. 3–9	0	0	0	0	R_1	R_4	R_3	0	R_2
No. 4–6	0	0	0	0	0	0	0	R_1	0
No. 5–2	0	0	R_1	0	0	0	0	0	0
No. 6–3	0	0	R_4	0	0	0	R_4	0	0
No. 7–8	0	R_1	R_3	0	0	R_4	0	R_2	0
No. 8–34	0	0	0	R_1	0	0	R_2	0	0
No. 9–2	0	0	R_2	0	0	0	0	0	0

The contact relation matrix CRM

A transforming process for R_1

	No. 1–2	No. 2–5	No. 3–9	No. 4–6	No. 5–2	No. 6–3	No. 7–8	No. 8–34	No. 9–2
No. 1–2	0	R_2	0	0	0	0	0	0	0
No. 2–5	R_2	0	0	0	0	0	1	0	0
No. 3–9	0	0	0	0	2	R_4	R_3	0	R_2
No. 4–6	0	0	0	0	0	0	0	3	0
No. 5–2	0	0	0	0	0	0	0	0	0
No. 6–3	0	0	R_4	0	0	0	R_4	0	0
No. 7–8	0	1	R_3	0	0	R_4	0	R_2	0
No. 8–34	0	0	0	3	0	0	R_2	0	0
No. 9–2	0	0	R_2	0	0	0	0	0	0

The generation of assembly priority matrix APM (1)

A transforming process for R_2

	No. 1–2	No. 2–5	No. 3–9	No. 4–6	No. 5–2	No. 6–3	No. 7–8	No. 8–34	No. 9–2
No. 1–2	0	4	0	0	0	0	0	0	0
No. 2–5	4	0	0	0	0	0	1	0	0
No. 3–9	0	0	0	0	2	R_4	R_3	0	5
No. 4–6	0	0	0	0	0	0	0	3	0
No. 5–2	0	0	2	0	0	0	0	0	0
No. 6–3	0	0	R_4	0	0	0	R_4	0	0
No. 7–8	0	1	R_3	0	0	R_4	0	6	0
No. 8–34	0	0	0	3	0	0	6	0	0
No. 9–2	0	0	5	0	0	0	0	0	0

The generation of assembly priority matrix APM (2)

A transforming process for R_3

	No. 1–2	No. 2–5	No. 3–9	No. 4–6	No. 5–2	No. 6–3	No. 7–8	No. 8–34	No. 9–2
No. 1–2	0	4	0	0	0	0	0	0	0
No. 2–5	4	0	0	0	0	0	1	0	0
No. 3–9	0	0	0	0	2	R_4	7	0	5
No. 4–6	0	0	0	0	0	0	0	3	0
No. 5–2	0	0	2	0	0	0	0	0	0
No. 6–3	0	0	R_4	0	0	0	R_4	0	0
No. 7–8	0	1	7	0	0	R_4	0	6	0
No. 8–34	0	0	0	3	0	0	6	0	0
No. 9–2	0	0	5	0	0	0	0	0	0

The generation of assembly priority matrix APM (3)

A transforming process for R_4

	No. 1–2	No. 2–5	No. 3–9	No. 4–6	No. 5–2	No. 6–3	No. 7–8	No. 8–34	No. 9–2
No. 1–2	0	4	0	0	0	0	0	0	0
No. 2–5	4	0	0	0	0	0	1	0	0
No. 3–9	0	0	0	0	2	8	7	0	5
No. 4–6	0	0	0	0	0	0	0	3	0
No. 5–2	0	0	2	0	0	0	0	0	0
No. 6–3	0	0	8	0	0	0	0	0	0
No. 7–8	0	1	7	0	0	0	0	6	0
No. 8–34	0	0	0	3	0	0	6	0	0
No. 9–2	0	0	5	0	0	0	0	0	0

The assembly priority matrix APM

Figure 4. Generation of an APM matrix for the hand-held hairdryer design case.

	No. 1–2	No. 2–5	No. 3–9	No. 4–6	No. 5–2	No. 6–3	No. 7–8	No. 8–34	No. 9–2
No. 1–2	0	4	0	0	0	0	0	0	0
No. 2–5	4	0	0	0	0	0	1	0	0
No. 3–9	0	0	0	0	2	8	7	0	5
No. 4–6	0	0	0	0	0	0	0	3	0
No. 5–2	0	0	2	0	0	0	0	0	0
No. 6–3	0	0	8	0	0	0	0	0	0
No. 7–8	0	1	7	0	0	0	0	6	0
No. 8–34	0	0	0	3	0	0	6	0	0
No. 9–2	0	0	5	0	0	0	0	0	0

The assembly priority matrix APM

A transitioning process for row arrays

	No. 1–2	No. 2–5	No. 3–9	No. 4–6	No. 5–2	No. 6–3	No. 7–8	No. 8–34	No. 9–2
No. 2–5	4	0	0	0	0	0	1	0	0
No. 7–8	0	1	7	0	0	0	0	6	0
No. 3–9	0	0	0	0	2	8	7	0	5
No. 5–2	0	0	2	0	0	0	0	0	0
No. 4–6	0	0	0	0	0	0	0	3	0
No. 8–34	0	0	0	3	0	0	6	0	0
No. 1–2	0	4	0	0	0	0	0	0	0
No. 9–2	0	0	5	0	0	0	0	0	0
No. 6–3	0	0	8	0	0	0	0	0	0

The transitional part assembly sequence matrix TPASM

A transitioning process for column arrays

	No. 2–5	No. 7–8	No. 3–9	No. 5–2	No. 4–6	No. 8–34	No. 1–2	No. 9–2	No. 6–3
No. 2–5	0	1	0	0	0	0	4	0	0
No. 7–8	1	0	7	0	0	6	0	0	0
No. 3–9	0	7	0	2	0	0	0	5	8
No. 5–2	0	0	2	0	0	0	0	0	0
No. 4–6	0	0	0	0	0	3	0	0	0
No. 8–34	0	6	0	0	3	0	0	0	0
No. 1–2	4	0	0	0	0	4	0	0	0
No. 9–2	0	0	5	0	0	0	0	0	0
No. 6–3	0	0	8	0	0	0	0	0	0

The part assembly sequence matrix PASM

Figure 5. Generation of a PASM matrix for the hand-held hairdryer design case.

Same as the previous case, assume a recommended design alternative is generated for a specific set of user requirements. The design parameters and values for this recommended coffee maker design are shown in Figure 7. Based on the identification of the set of contact relations CR among design parameter values for the coffee maker design case and a matching procedure among CR and the recommended coffee maker design alternative, a CRM is generated as shown in Figure 8. Figure 9 illustrates a matrix APM for the coffee maker design case generated by a transitional procedure that follows the generated matrix CRM. After the matrix APM has been generated, a sorting procedure is employed to form a matrix PASM as shown in Figure 10. The generated matrix PASM provides the recommended coffeemaker design with the assembly sequence. A hierarchical representation depicting this assembly sequence is illustrated in Figure 11. The assembly sequence presented in Figure 11 also implies that the recommended coffee maker design can be assembled by two modules: (1) P01, P02, P03,P04, P05, P06, P07, P08, P15, P16, P20, P21, P22, P23, P24, and P25 and (2) P09, P10, P11, P12, P13,

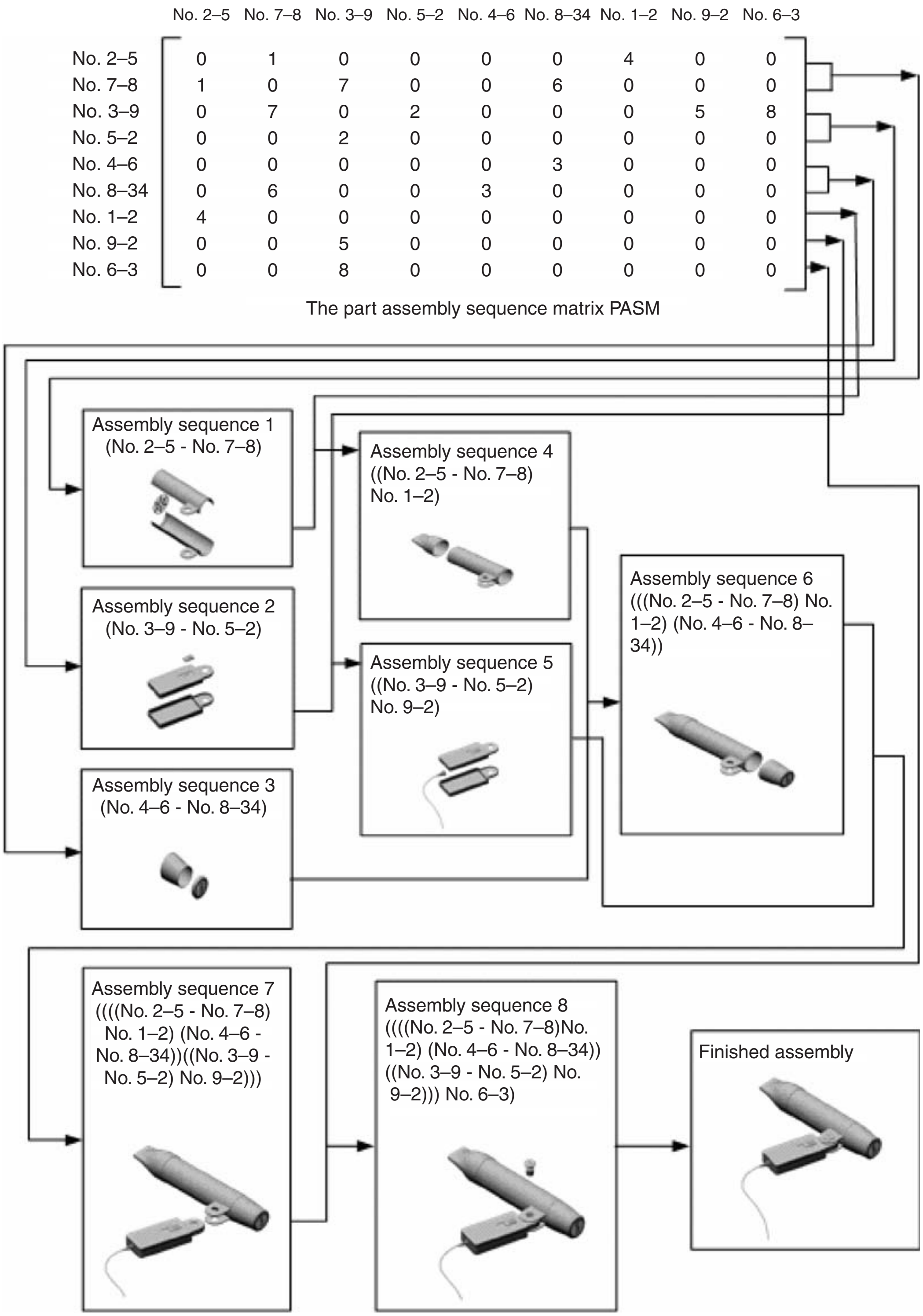
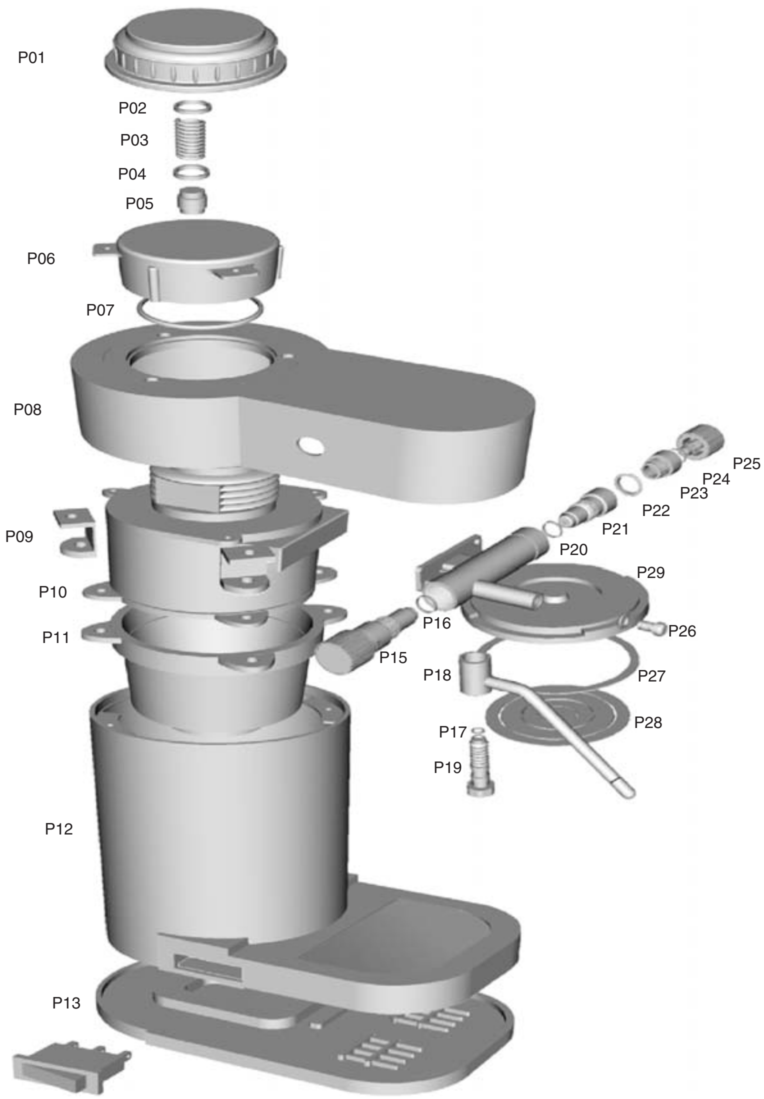


Figure 6. Graphic representation of assembly process based on the generated PASM.

P14, P17, P18, P19, P26, P27, P28, and P29. The research suggests that use five modules of assembly for this coffee maker design. They are (1) P01, P02, P03, P04, P05, P06, P07, and P08, (2) P09, P10, P11, P12, P13, and P14, (3) P15 and P16, (4) P20, P21, P22, P23, P24, and P25 and (5) P17, P18, P19, P26, P27, P28, and P29. It is noted that the choice of either the total assembly or the modular assembly will not affect the evaluation of the recommended design alternative.



P01	Upper cover
P02	Cover seal
P03	Uooer insert
P04	Cover rubber seal
P05	Isolation plug
P06	Upper body
P07	O seal
P08	Head cover
P09	Rid connector
P10	Chamfer cover
P11	Main container
P12	Outer cover
P13	Outer civer stand
P14	Switch
P15	Left air control nut
P16	Nut seal
P17	Steam seal
P18	Steam tube
P19	Screw
P20	Nut seal
P21	Right air control screw
P22	Washer
P23	Control nut
P24	Nut seal
P25	Adjust screw
P26	Pressure control nut
P27	Filter seal
P28	Filter
P29	Filter connector

Figure 7. Characteristics of an Italian style coffee maker design case.

5. Conclusions

Highly automated production, enhanced manufacturing technology and product design are important factors in improving product quality and value. Among these factors, product design is the most critical one. Even though most manufacturers may not explicitly stress enhancing product design, many manufacturing and assembly problems can be attributed to poor product design. As competition in every world market has increased, the willingness of manufacturers to tolerate such problems has significantly decreased. Therefore, the product design task should communicate with manufacturing and production systems under the assistance of computer technologies to make sure that the designs can be properly fit into the manufacturing systems. Unfortunately, most designers do not have the chance to think about the assembly problems before the designs are finalized and released to the manufacturing and production departments. This neglect might cause unexpected problems in product quality and production efficiency.

One efficient way in dealing with the enhancement of product development and quality is the use of design for assembly strategy. In fact, the concept of design for assembly is not newly introduced. The problem occurs that very little research has devoted to the integration of design and assembly into an interconnected system. This will make it more difficult for designers to consider the assembly issue as part of design activity. To assist designers in considering assembly requirements at the design stage, this research presented a CRM approach for generating an assembly sequence for the

	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28	P29
P01	0	R_3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P02	R_3	0	R_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P03	0	R_1	0	R_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P04	0	0	R_2	0	R_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P05	0	0	0	R_1	0	R_3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P06	0	0	0	0	R_3	0	R_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P07	0	0	0	0	0	R_1	0	R_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P08	0	0	0	0	0	0	R_2	0	R_4	R_4	0	0	0	0	0	R_2	0	0	0	R_2	0	0	0	0	0	0	0	0	0
P09	0	0	0	0	0	0	0	R_4	0	R_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P10	0	0	0	0	0	0	0	R_4	R_2	0	R_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	R_1
P11	0	0	0	0	0	0	0	0	0	R_1	0	R_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P12	0	0	0	0	0	0	0	0	0	0	R_1	0	R_1	R_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P13	0	0	0	0	0	0	0	0	0	0	0	R_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P14	0	0	0	0	0	0	0	0	0	0	0	R_2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	R_1	0	0	0	0	0	0	0	0	0	0	0	0	0
P16	0	0	0	0	0	0	0	R_2	0	0	0	0	0	0	R_1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	R_2	R_1	0	0	0	0	0	0	0	0	0	0
P18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	R_2	0	0	0	0	0	0	0	0	0	0	0	R_1
P19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	R_1	0	0	0	0	0	0	0	0	0	0	0	0
P20	0	0	0	0	0	0	0	R_2	0	0	0	0	0	0	0	0	0	0	0	0	R_1	0	0	0	0	0	0	0	0
P21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	R_1	0	R_2	0	0	0	0	0	0	0
P22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	R_2	0	R_1	0	0	0	0	0	0
P23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	R_1	0	R_2	0	0	0	0	0
P24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	R_2	0	R_1	0	0	0	0
P25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	R_1	0	0	0	0	0
P26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	R_1
P27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	R_1	R_2
P28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	R_1	0	0
P29	0	0	0	0	0	0	0	0	0	R_1	0	0	0	0	0	0	0	R_1	0	0	0	0	0	0	0	R_1	R_2	0	0

Figure 8. Generation of a CRM matrix for the Italian style coffee maker design case.

	P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28	P29
P01	0	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P02	26	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P03	0	1	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P04	0	0	16	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P05	0	0	0	2	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P06	0	0	0	0	27	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P07	0	0	0	0	0	3	0	17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P08	0	0	0	0	0	0	17	0	28	0	0	0	0	0	0	18	0	0	0	19	0	0	0	0	0	0	0	0	0
P09	0	0	0	0	0	0	0	28	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P10	0	0	0	0	0	0	0	0	20	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5
P11	0	0	0	0	0	0	0	0	0	4	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P12	0	0	0	0	0	0	0	0	0	0	6	0	7	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P13	0	0	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P14	0	0	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0
P16	0	0	0	0	0	0	0	18	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	9	0	0	0	0	0	0	0	0	0	0
P18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	10
P19	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0
P20	0	0	0	0	0	0	0	19	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0
P21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	23	0	0	0	0	0	0	0
P22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	12	0	0	0	0	0	0
P23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	24	0	0	0	0	0
P24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	13	0	0	0	0
P25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0
P26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14
P27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	25
P28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0
P29	0	0	0	0	0	0	0	0	0	5	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	14	25	0	0

Figure 9. Generation of an APM matrix for the Italian style coffee maker design case.

	P02	P03	P04	P05	P06	P07	P10	P11	P29	P12	P13	P15	P16	P17	P19	P18	P20	P21	P22	P23	P24	P25	P26	P27	P28	P08	P09	P14	P01
P02	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	26
P03	1	0	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P04	0	16	0	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P05	0	0	2	0	27	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P06	0	0	0	27	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P07	0	0	0	0	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	17	0	0	0
P10	0	0	0	0	0	0	0	4	5	0	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	20	0	0
P11	0	0	0	0	0	0	0	0	0	4	0	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P29	0	0	0	0	0	0	5	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	14	25	0	0	0	0	0
P12	0	0	0	0	0	0	0	6	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	21	0
P13	0	0	0	0	0	0	0	0	0	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P15	0	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P16	0	0	0	0	0	0	0	0	0	0	0	8	0	0	0	0	0	0	0	0	0	0	0	0	0	18	0	0	0
P17	0	0	0	0	0	0	0	0	0	0	0	0	0	0	9	22	0	0	0	0	0	0	0	0	0	0	0	0	0
P19	0	0	0	0	0	0	0	0	0	0	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P18	0	0	0	0	0	0	0	0	10	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0
P21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	23	0	0	0	0	0	0	0	0	0	0
P22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23	0	12	0	0	0	0	0	0	0	0	0
P23	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	12	0	24	0	0	0	0	0	0	0	0
P24	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	24	0	13	0	0	0	0	0	0	0
P25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	0	0	0	0	0	0	0	0
P26	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P27	0	0	0	0	0	0	0	0	25	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0
P28	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	15	0	0	0	0	0
P08	0	0	0	0	0	17	0	0	0	0	0	0	18	0	0	0	19	0	0	0	0	0	0	0	0	0	28	0	0
P09	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	28	0	0	0
P14	0	0	0	0	0	0	0	0	0	21	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
P01	26	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 10. Generation of a PASM matrix for the Italian style coffee maker design case.

recommended design alternative. The designer can consider further improvement of parts appearance or integration of several parts into an individual part based on the generated assembly sequence. In the development of CRM approach, four rules based on the parts contact are identified. A three-stage procedure for the CRM approach is developed followed with the identification of four rules of parts contact relations. They are (1) to develop a contact relation matrix (CRM), (2) to generate an assembly priority matrix (APM) and (3) to generate a part assembly sequence matrix (PASM). To demonstrate how the CRM approach is employed to generate the assembly sequence for product design, a hand-held hairdryer design and an Italian style coffee maker design were used to represent simple and complicated products. The results show the feasibility of the CRM approach linking with the product design process. As mentioned before, the research also suggests that a complicated product be divided into several modules for ease of assembly. However, either individual or modular assembly will not affect the quality of the CRM approach.

Further research is devoted to determining the most suitable assembly operation for each generated assembly sequence based on the CRM approach. In the hand-held hairdryer design case shown in Figure 6, the possible types of assembly operation for each generated assembly sequence are identified as (1) snap fastening, (2) transition fit, (3) insertion, (4) transition fit, (5) insertion, (6) snap fastening, (7) centered orientation, and (8) feeding and pressing, respectively; while the operation time (in seconds) for the corresponding assembly operations are the determined as (1) 3.50, (2) 3.45, (3) 5.95, (4) 3.00, (5) 3.45, (6) 3.70, (7) 3.30, and (8) 14.60, respectively. The total operation time for the hand-held hairdryer design shown in Figure 6 is 38.95 seconds. Designers can then use the total operation time from the assembly of the designed product to compare the efficiency between the modified design and the original. The CRM approach will be also connected with a matrix approach based on a congruent matrix multiplication operator, component design strategy and relational database system to the generation and evaluation of feasible design alternatives for a specific set of customer requirements [21]. It is believed that this research effort incorporating the matrix approach will assist designers in linking customer requirements with products and corresponding assembly sequences during design development and enhance the efficiency of concurrent engineering.

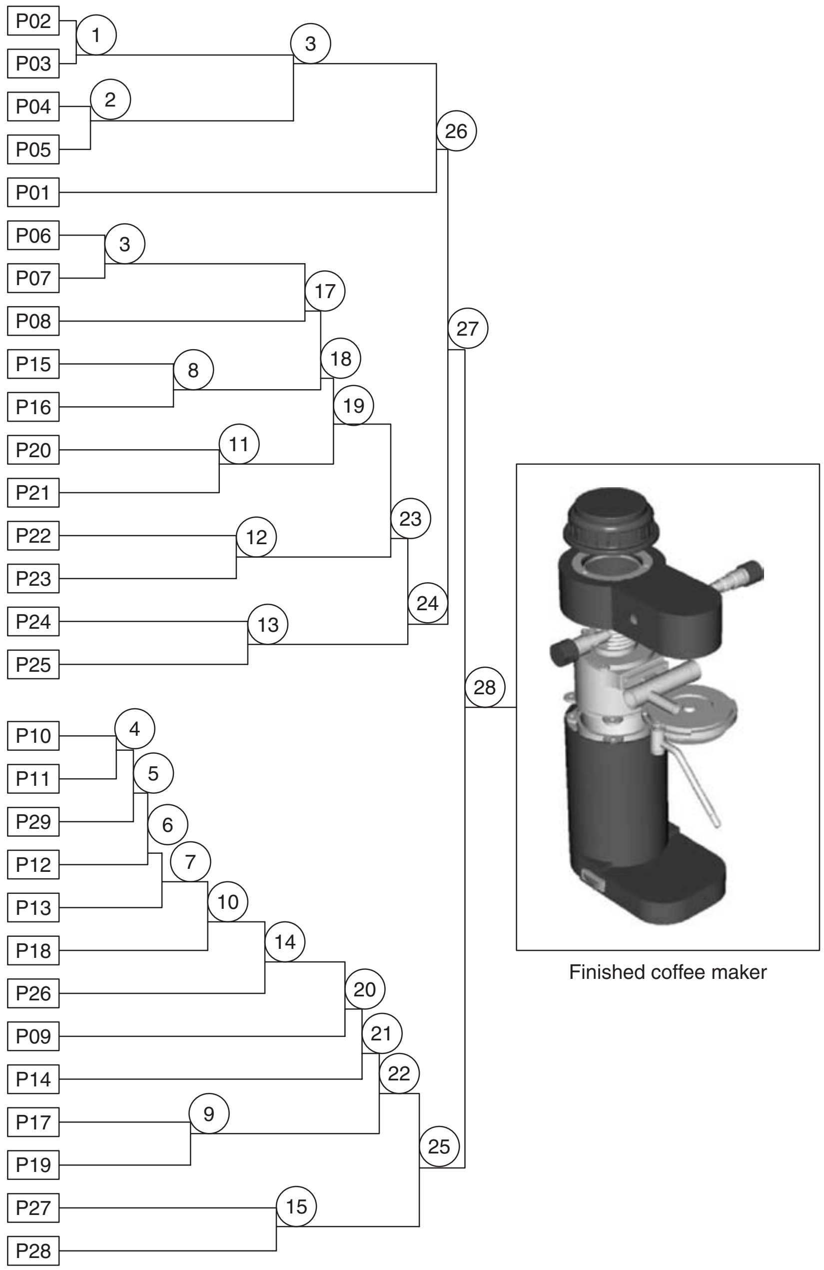


Figure 11. Hierarchical representation of assembly sequence for coffee maker design case.
Note: 1. The code in each rectangular denotes a part number.
2. The number in each circle denotes an assembly sequence.

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Ming-Chyuan Lin

Ming-Chyuan Lin is currently a Professor in the Department of Industrial Design at National Cheng Kung University, Taiwan. He received his BSE in Industrial Design from National Cheng Kung University and MS and PhD in Industrial Engineering from the University of Missouri-Columbia, USA, respectively. His research interests are human factors engineering and computer-integrated design and manufacturing systems.

Yuan-Yeuan Tai

Yuan-Yeuan Tai is currently a PhD candidate in the Department of Industrial Design at National Cheng Kung University, Taiwan. He is also a senior Manager in the Aerospace Industrial Development Corporation in Taiwan. He received his BS and MS in Aeronautical and Mechanical Engineering from Tamkang University, Taiwan, respectively. His research interests are computer-aided design, manufacturing systems, product data management, and design system development.

Ming-Shi Chen

Ming-Shi Chen is currently a PhD candidate in the Department of Industrial Design at National Cheng Kung University, Taiwan. He is also a senior lecturer in the Department of Commercial Technology Management at Transworld Institute of Technology, Taiwan. He received his BS and MS in Industrial Design from National Cheng Kung University, Taiwan, respectively. His research interests are computer-aided design, technical issues for e-commerce, multimedia design for web page, product design and ergonomics.

C. Alec Chang

C. Alec Chang is an Associate Professor of the Department of Industrial and Manufacturing Systems Engineering, University of Missouri-Columbia. He has published more than 80 papers related to quality enhancement using experimental design, engineering data analysis, feature-based design retrieval systems and general database design, and ERP systems.