A Research on an Efficient Derivation Method for Feasible Assembly Sequences

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Abstract. This research describes new methods for determining constraints when deriving assembly sequences. The manufacturing industry should develop more efficient production preparation techniques as product life cycles become shorter. Assembly sequences have effects on product evaluation; therefore multiple assembly sequences should be tested. However, the number of assembly sequences increases rapidly as the number of parts of the product increases. In the Prototype-less Production (PLP) system, the precedence constraints for the elements of the assembly are set during the derivation of assembly sequences. However, this determination is inefficient because of successive determination for two or more elements of the assembly. Thus, this research proposes two determination methods for the elements of the assembly so as to derive assembly sequences efficiently. The first method is that of eliminating the elements of the assembly that infringe on the constraints. This method is proposed based on the fact that the parts comprising partly finished products must have been combined. The other method is that of dividing the continuous elements of the assembly into groups. This method is proposed on the basis of the uniqueness of the continuous elements of an assembly. When these methods are applied to products comprising 11 and 22 parts, the derivation time of the assembly sequences is drastically reduced. Using these methods, feasible assembly sequences are efficiently derived in the case of setting the constraints.

Keywords: Digital manufacturing, Assembly sequence, CAD/CAM, Prototype-less production

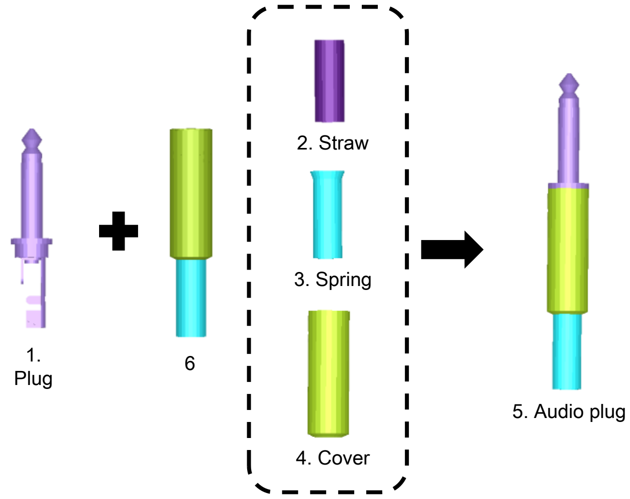

Figure 1: An element of the assembly of the audio plug

(1, 2)	+	(3, 4)	→	(1, 2, 3, 4)
1	+	(2, 3, 4)	→	(1, 2, 3, 4)
2	+	3, 4	→	(2, 3, 4)
3	+	4	→	(3, 4)
1	+	2	→	(1, 2)

Figure 2: All elements of the assembly of the audio plug

Assembly sequence 1					Assembly sequence 2					Assembly sequence 3				
1	+	2	→	(1, 2)	3	+	4	→	(3, 4)	3	+	4	→	(3, 4)
3	+	4	→	(3, 4)	1	+	2	→	(1, 2)	2	+	(3, 4)	→	(2, 3, 4)
(1, 2)	+	(3, 4)	→	(1, 2, 3, 4)	(1, 2)	+	(3, 4)	→	(1, 2, 3, 4)	1	+	(2, 3, 4)	→	(1, 2, 3, 4)

Figure 3: All assembly sequences of the audio plug

1. INTRODUCTION

Product diversification, reduction of production cost, and shortening of the lead time for production preparation are required because of diversification of consumer needs, sharp rise of material cost, and shortened product life cycle. Recently, there has been considerable research on improving the processes of product design, prototyping, and evaluation and construction of product lines. One such proposal is the prototype-less production system (hereinafter referred to as PLP). PLP is a system that can simulate production preparation on a computer without prototyping and comprehensively derive feasible assembly sequences from three dimensional computer aided design (3DCAD). Therefore, we can evaluate and consider various assembly sequences without the need to depend on experience and intuition. Assembly sequences are among the most necessary information for product manufacturing because they include an order for assembling parts. Accordingly, evaluating multiple assembly sequences and adopting the best one are very important. However, a product comprising of n parts may have n factorial assembly sequences, and the number of assembly sequences rapidly increases with an increase in the number of product parts. Consequently, efficient derivation of assembly sequences is necessary for the evaluation and investigation of products having many parts.

Therefore, the purpose of this research is to suggest new methods for determining constraints when deriving assembly sequences. The first method is that of eliminating any element of an assembly that infringes on the constraints. The second method is that of dividing the continuous elements of an assembly into groups. A system that incorporates the two methods is developed and verified.

2. DERIVATION OF ASSEMBLY SEQUENCES FROM THE ELEMENTS OF THE ASSEMBLY

2.1 Elements of the assembly and assembly sequences

Elements of the assembly refer to assembly parts, as well as partly finished products, assemblies of partly finished products, and the finished product itself.

For example, Figure 1 shows that the finished product comprises PN1, PN2, PN3, and PN4 (PN: part number), which are assembled by combining PN1 and the partly finished product comprising PN2, PN3, and PN4.

If a derived partly finished product (or finished product) assembled from two parts and/or derived partly finished products exists, then it is a feasible element of the assembly. Therefore, we can derive a comprehensive list of the elements of the assembly by considering combinations of parts or partly finished products. Figure 2 shows that five elements of the assembly are derived in the case of an audio plug.

An assembly sequence describes the sequential order used

PN1 , PN2 </<< PN3 , PN4

PN: Part number

Symbol “<<”: Consecutive relation
Symbol “<” : Preference relation

Figure 4: The form of the Pr-check

to assemble a product. In the case of a product comprising n parts, an assembly sequence has n−1 elements of the assembly. An assembly sequence is derived by listing n−1 elements of the assembly and rearranging them. For the audio plug in Figure 1, three assembly sequences are derived in Figure 3.

2.2 A method of deriving assembly sequences from the elements of the assembly

In the case where a product comprises n parts, its assembly sequence will have n-1 steps. However, for one partly finished product, there may be multiple elements of the assembly depending on the combinations of parts or partly finished products. In order to comprehensively derive assembly sequences from many elements of the assembly, the flow of the derivation of assembly sequences from the elements of the assembly comprises two steps given as follows.

The first step is listing the elements of feasible assembly sequences, and the second step is rearranging the elements of this list.

At the first step, n−1 elements of an assembly in a feasible assembly sequence are listed. A feasible assembly sequence means that it yields a finished product. Listing the elements of the assembly from a number of elements eliminates the need to consider infeasible assembly sequences. At the second step, assembly sequences are derived by rearranging the elements of the list obtained at the first step. Multiple assembly sequences may be derived from a list of the elements of the assembly, depending on putting a partly finished product. In addition, we can set “Pr-check” as a precedence constraint that specifies the preference and consecutive relation of the elements of an assembly. In this research, feasible assembly sequences are defined such that they can complete a product and satisfy a Pr-check.

2.3 Pr-check

The Pr-check is a constraint that specifies the order of the elements for preference and the consecutive relation of the elements of the assembly. However, the Pr-check does not specify the preference and consecutive relation but specifies a part contained in a partly finished pro

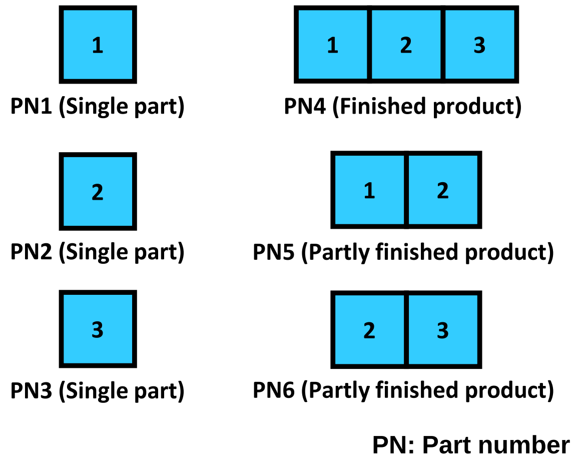

Figure 5: The parts, partly finished product and finished product of the product model comprising three parts

duct.

Figure 4 shows the specifications of the Pr-check. Symbol “<” indicates a preference relation and symbol “<<” indicates a consecutive relation. PN1, PN2, PN3, and PN4 indicate the number of single parts. This Pr-check shows that a partly finished product involving PN3 (or only PN3) and one involving PN4 (or only PN4) are assembled after (or once) the assembly of partly finished products involving PN1 (or only PN1) and PN2 (or only PN2).

3. A METHOD FOR ELIMINATING THE ELEMENTS OF THE ASSEMBLY INFRINGING THE PR-CHECK

3.1 Concept of an elimination method for the elements of the assembly infringing the Pr-check

The conventional determination of Pr-check makes use of an assembly sequence level determination method that needs two or more elements of the assembly. The element level determination method proposed here needs only one element of the assembly.

Let us explain the elements of the assembly infringing the Pr-check and those not infringing it using a product model comprising three parts in Figure 5 as an example. The numbers in squares are part numbers of single parts and those beside the squares are part numbers of partly finished or finished products.

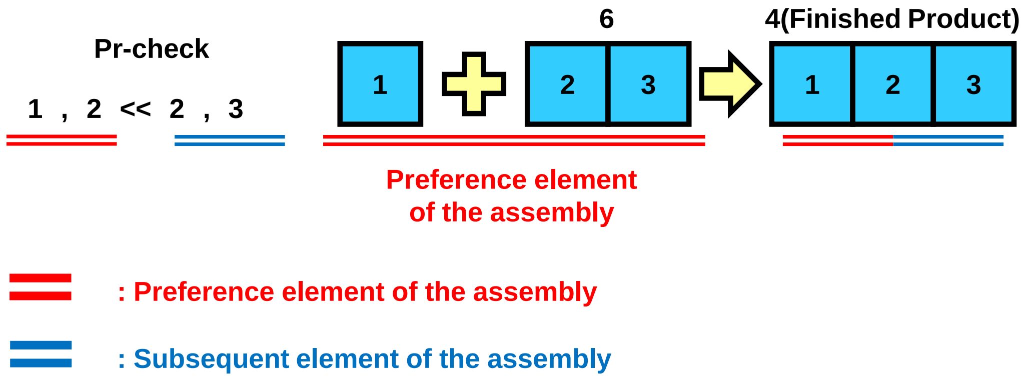

Figure 6: The elements of the assembly infringing the Pr-check at the element level

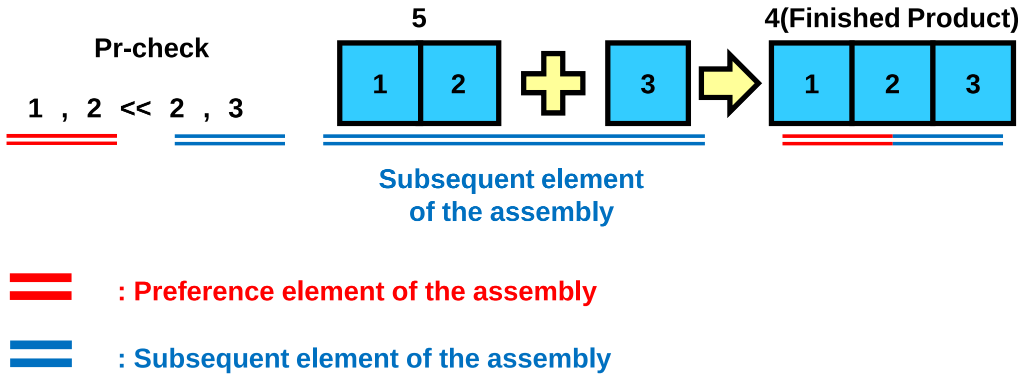

Figure 7: The elements of the assembly not infringing the Pr-check at the element level

- **Elements of the assembly infringing the Pr-check at the element level**

Figure 6 shows that PN4 (finished product) is assembled from PN1 (single part) and PN6 (partly finished product). In addition, a Pr-check is set. This means that a partly finished product including PN2 and a partly finished product involving PN3 must be combined immediately after a partly finished product including PN1 and a partly finished product including PN2. PN4 has all the parts specified by the Pr-check (PN1, PN2, and PN3). Judging from the component information of PN4, the elements of the assembly corresponding to the precedence and subsequent elements are evaluated before PN4 is assembled. Focusing on PN1 and PN6, these elements of the assembly correspond to the precedence elements because PN1 is a single part and PN6 includes PN2 (single part). Although the element of the assembly corresponding to the subsequent element is evaluated when PN4 is assembled, this element of assembly is carried out. Therefore, this element of the assembly is determined to infringe the Pr-check at the element level.

- **Elements of the assembly not infringing the Pr-check at the element level**

Figure 7 shows that PN4 is assembled with PN3 (single part) and PN5 (partly finished product). PN4 has all the parts specified by the Pr-check (PN1, PN2, and PN3). Judging from the component information of PN4, the elements of the assembly corresponding to the precedence and subsequent elements are evaluated before PN4 is assembled. Focusing on PN3 and PN5, these elements of the assembly correspond to the subsequent elements because PN3 is a single part and PN5 has PN2. The element of the assembly corresponding to the subsequent element is evaluated after the element of the assembly corresponding to the preference element. Therefore, it is determined that this element of the assembly does not infringe the Pr-check at the element level. Nevertheless, it may still infringe the Pr-check at the assembly sequence level.

Therefore, it can be noted that the elements of the assembly infringing the Pr-check are those that satisfy the following conditions.

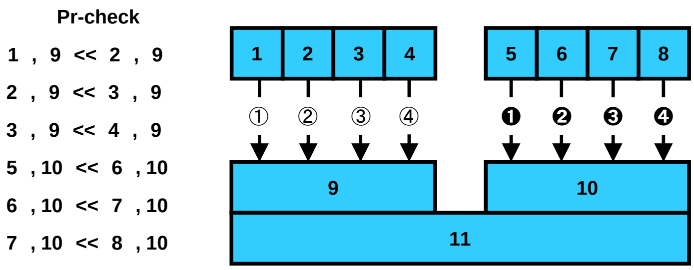

Figure 8: The product comprising 11 parts and Pr-checks

- Those with single parts specified in the PR-check
- Those corresponding to the preference elements specified in the Pr-check

3.2 Procedure for eliminating the elements of the assembly infringing the Pr-check

The procedure for the elimination of the elements of the assembly that infringe the Pr-check is described below. Elimination is introduced to the input step of the elements before derivation of the assembly sequences.

Step 1: Determine whether an element of the assembly is an assembly of partly finished products with all single parts specified in the Pr-check.
Step 2: Determine whether the elements satisfying the condition at step 1 correspond to the preference elements.
Step 3: Repeat steps 1 and 2 for every element of the assembly.

By undertaking these steps, we can eliminate the elements of the assembly infringing the Pr-check at the element level and derive assembly sequences from a smaller number of the elements of the assembly.

4. A DIVISION METHOD OF THE CONTINUO US ELEMENTS OF THE ASSEMBLY

4.1 Concept of division of the continuous elements of the assembly

The conventional determination of the Pr-check is done during the process of rearranging the elements of the assembly. In this research, the elements of the assembly are rearranged after being divided into groups, and the elements must be rearranged within each group. Thus, we should regard an element of the assembly not corresponding to the Pr-check as a group. Therefore, in this research, we define groups of the continuous elements of the assembly as groups of one or more continuous elements satisfying the Pr-check.

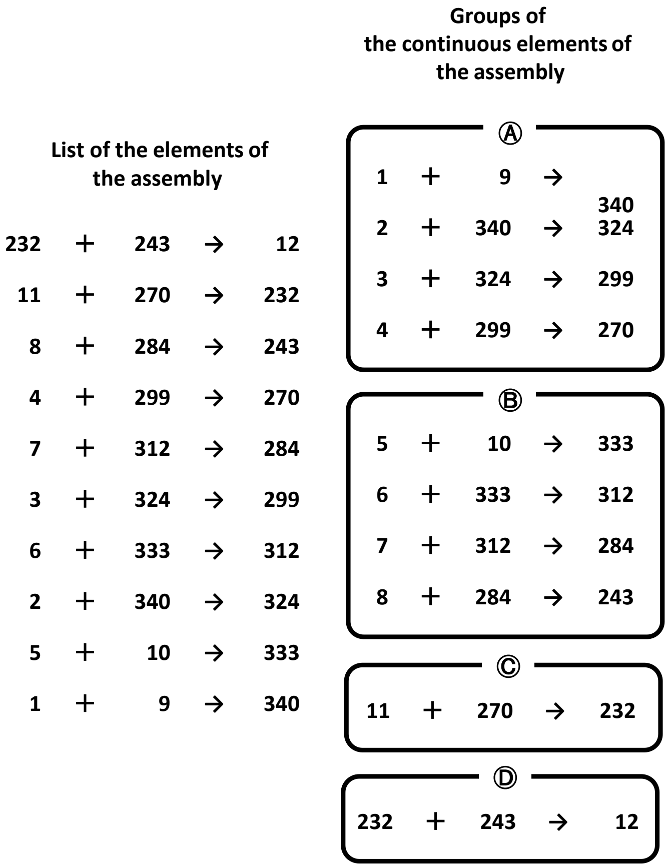

Figure 9: The divided groups of the elements of the assembly

We explain groups of the continuous elements of the assembly with a product comprising 11 parts and Pr-checks in Figure 8. The circled numbers 1, 2, 3, and 4 are the elements of the assembly that have been specified as continuous by Pr-checks. They are evaluated in numerical order. The negative circled numbers 1, 2, 3, and 4 are also the elements of the assembly that have been specified continuous by the Pr-checks and are evaluated in numerical order.

The elements of the assembly are divided into four groups, A, B, C, and D in Figure 9, by setting the Pr-checks. The list of elements of the assembly at the left includes feasible assembly sequences for the product in Figure 8. The set of elements enclosed with a rounded rectangle at the right includes A, B, C, and D, which are groups of elements of the assembly divided by the Pr-checks. Group A is the group of elements of the assembly corresponding to the circled numbers and group B is that corresponding to the negative circled numbers. Groups C and D are also groups of elements of the assembly because they do not correspond to the Pr-checks. In the case when the Pr-check is set to specify a continuous relation, the elements of the assembly are divided into groups and rearranged within each group at the second step.

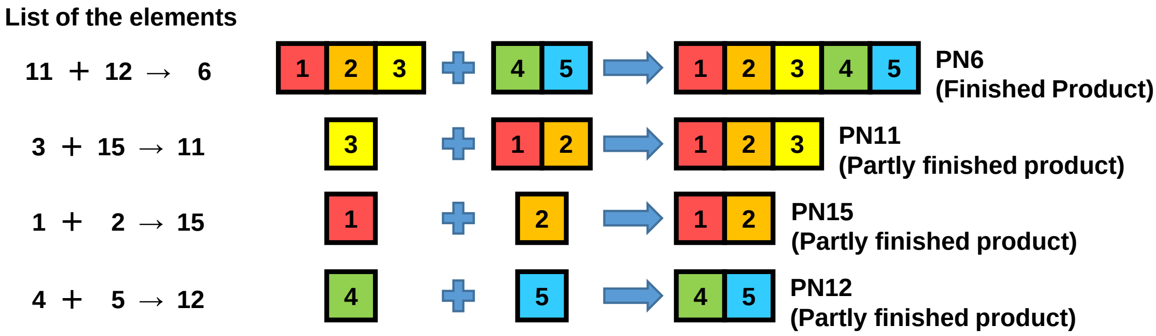

Figure 10: The elements of the product model comprising five parts

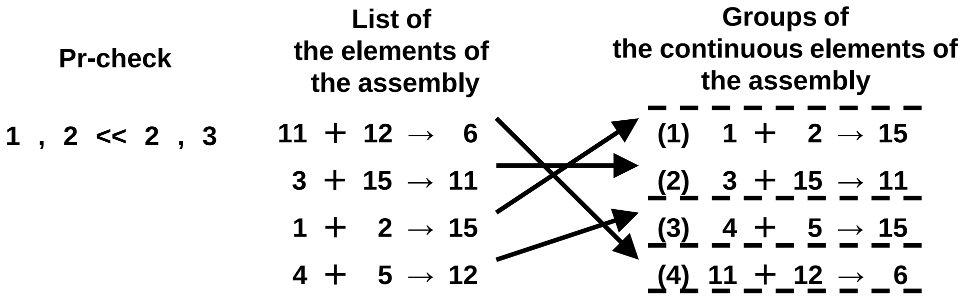

Figure 11: The procedure for dividing the continuous elements of the assembly

4.2 Procedure of division of the continuous elements of the assembly

Division of the elements of the assembly is conducted during the process of selecting an assembly sequence from the list of feasible assembly sequences. The reason for this is that the continuous elements of the assembly in a group must be established as an assembly sequence.

We explain the procedure for dividing the continuous elements of the assembly in Figure 11 using a product model comprising five parts as an example in Figure 10. In Figure 10, the elements of the assembly at the left are a list of feasible assembly sequences, and the squares at the right indicate information about constituent parts or partly finished products in the elements.

Before dividing the elements of the assembly, no element is added to any group and no groups have elements corresponding to the precedence elements specified in the Pr-check.

Step 1: In the order of the list, determine whether each element of the list can be added to the first group. The first and second elements are not added because PN11, PN12, and PN15 have not been assembled yet. The third element is added to the first group because PN1 and PN2 are single parts. Moreover, the third element corresponds to the precedence element specified in the Pr-check. Therefore, the element added next must correspond to the subsequent element specified in the Pr-check.

Step 2: In the order of the list, determine whether each element of the list can be added to the first group. The first element is not added because PN11 and PN12 have not yet been assembled and the first element does not correspond to the subsequent element. However, the second element is added to the first group because PN15 has been assembled and the second element corresponds to the subsequent element. Moreover, the second element does not correspond to the precedence element specified in another Pr-check (not setting in this example), and the second element does not have a continuous relationship with another element. Therefore, the first group has been completed and we proceed to construct the second group.

Step 3: In the order of the list, determine whether an element of the list can be added to the second group. The first, second, and third elements are not added because PN12 has yet to be assembled and the second and third elements have already been added. However, the fourth element is added to the second group because PN4 and PN5 are single parts. Moreover, the third element does not correspond to the precedence element specified in another Pr-check (not setting in this example) and does not have a continuous relation with another element. Therefore, the second group has been completed and we proceed to construct the third group.

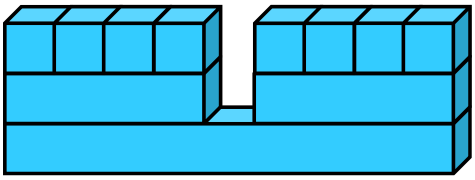

Figure 12: the product model comprising 11

Table 1: The information of the product model comprising 11 parts in the case of specifying the Pr-check

Method	None	Elimination	Division	Elimination and division
Derivation time (hour'minute"second)	0'0"26.544	0'0"0.014	0'0"2.555	0'0"0.013

Table 2: The derivation time of assembly sequences of the product model comprising 11 parts

Part	Element of assembly	Partly finished part	Pr-check	Assembly sequence	Eliminated element of assembly
11	2328	341	6	24	1044

Step 4: In the order of the list, determine whether an element of the list can be added to the third group. The first element is added to the third group because PN11 and PN12 have already been assembled. At this point, all elements of the list are added to the groups. Therefore, division of the continuous elements of the assembly has been completed.

We can divide the elements of the list (of feasible assembly sequences for a product comprising 5 parts) into three groups using the above procedure.

5. VERIFICATION OF THE NEW METHODS

In this chapter, we explain how the above methods for eliminating the elements of the assembly infringing the Pr-check and for dividing the continuous elements of the assembly are verified.

We developed a system that included the methods, and we verified the methods by adopting them for the product model comprising 11 parts in Figure 12 and an actual product comprising 22 parts.

5.1 Verification with actual data

- **Product model comprising 11 parts**

We applied the methods to the product model comprising 11 parts in Figure 12. In the preceding research, 341 partly finished products and 2,328 elements of the assembly were derived. In the case of setting six Pr-checks specifying a continuous relation, 24 assembly sequences were derived as shown in Table 1.

By deriving assembly sequences from the product model using the new methods, the result in Table 2 was obtained. Out of the 2,328 elements of the assembly, 1,044 elements infringed the Pr-check at the element level. The derivation time without the methods was 26.544 seconds; that with elimination was 0.014 seconds; that with division was 2.555 seconds; and that with elimination and division was 0.013 seconds. The results show that elimination of the elements of the assembly reduced the derivation time of the assembly sequences, regardless of the division of the continuous elements. Division of the continuous elements of the assembly also reduced the derivation time of assembly sequences from 26.544 seconds to 2.555 seconds without eliminating the elements infringing the Pr-check.

- **Actual Product comprising 22 parts**

We applied the methods to the actual product comprising 22 parts. In the preceding research, 149 partly finished products and 297 elements of the assembly were derived. In the case of setting eight Pr-checks specifying the continuous relation, 4,416,438 assembly sequences were derived, as shown in Table 3.

By deriving assembly sequences from the product model

Table 3: The information of the actual product comprising 22 parts in the case of specifying the Pr-check

Part	Element of assembly	Partly finished part	Pr-check	Assembly sequence	Eliminated element of assembly
22	297	149	8	4,416,438	0

Table 4: The derivation time of assembly sequences of the actual product comprising 22 parts

Method	None	Elimination	Division	Elimination and division
Derivation time (hour'minute"second)	3'5"14.36	2'59"14.579	0'0"51.63	0'0"51.334

using the new methods, the result in Table 4 was obtained. No elements of the assembly infringed the Pr-check at the element level. However, the derivation time without the methods was 185 minutes and 14.362 seconds; that with elimination was 179 minutes and 14.579 seconds; that with division was 51.636 seconds; and that with elimination and division was 51.334 seconds. A derivation time gap did not occur for the elimination of elements because no element of the assembly infringed the Pr-check at the element level. However, division of the continuous elements of the assembly drastically reduced the derivation time from ~180 minutes to ~50 seconds, regardless of elimination.

5.2 Result of the verification

The above result demonstrates that the proposed methods for elimination of the elements of the assembly infringing the Pr-check at the element level and division of the continuous elements of the assembly are effective for efficient derivation of feasible assembly sequences.

6. CONCLUSIONS

In PLP, the derived information rapidly increases an d assembly sequences take a long time to derive as the number of parts of a product increase. To solve this pro blem, we proposed two methods for determining constrai nts (Pr-check) for efficient derivation of assembly sequen ces. One method is the elimination of elements of the a ssembly infringing the Pr-check, which focuses on the pr operties of the Pr-check itself. The other is the division of the continuous elements of the assembly, which focus es on the uniqueness of the continuous elements. We als o developed a system that included the methods and ver ified them. The result of the verification found the meth ods to be effective for efficient derivation of feasible ass embly sequences.

A division method for the continuous elements of the as sembly was proposed in this research. However, the ele ments of the assembly with a preference relation are not divided by this method. Moreover, the Pr-check can spe cify single parts, but it cannot specify partly finished pr oducts. Therefore, an efficient determination method for t he Pr-check that specifies a preference relation, a specifi cation method for partly finished products, or constraints to replace the Pr-check will be the topic of future resear ch.

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