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Paul STIEF, Jean-Yves DANTAN, Alain ETIENNE, Ali SIADAT - Fixturing-driven determination of multi-product assembly plans in the context of product variety and reconfiguration - Flexible Services and Manufacturing Journal p.25p. - 2024

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# Fixturing-driven determination of multi-product assembly plans in the context of product variety and reconfiguration

**Paul Stief**[1] · **Jean-Yves Dantan**[1] · **Alain Etienne**[1] · **Ali Siadat**[1]

**Abstract**
The design and use of assembly systems for more than one dedicated product becomes more important to manufacturing industries as product variety increases and lot sizes decrease. Since their introduction in the late 90's, reconfigurable production systems have become a lever to enable those multi-product assembly systems. The question remains how can the needed reconfiguration degree be defined and how can be determined where in the assembly line reconfiguration makes sense. A new method for fixturing driven determination of multi-product assembly plans is presented in this paper to answer this question. It relies on LCS/SCS analysis of the assembly plan signature of a product variety. A case study is furnished to illustrate the application of the new approach.

**Keywords** Assembly plan · Longest common subsequence · Shortest common super-sequence · Multi-product assembly line

## 1 Introduction

Decreasing lot-sizes and increasing product variety put classical production systems dedicated to a single product under pressure (Kusiak 2019). In combination with shortened product lifecycles and production cycles, these systems have an increasing risk to fail the return on investment objectives or even the break-even point. To face these challenges, the concepts of agile, reconfigurable or flexible production systems have emerged (Bortolini, Galizia and Mora 2018). Those may cope with the production of a product mix on the same production line (Bejlegaard, ElMaraghy et

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al. 2018). To decide which products are adapted for a common production line and where reconfigurable or flexible modules have to be placed in this production line, the process plans of each of the products have to be compared. Especially in product assembly, the design of a multi-product assembly system is a challenging task as different products may need different fixtures and may have different operation sequences. In this context, this paper proposes a new assembly-oriented approach for the comparison of process plans for the determination of a common multi-product assembly plan. A fixture-driven compatibility analysis is proposed in addition.

In the following, Sect. 2 gives an overview about the related literature focusing on reconfigurable process plans and the use of longest common subsequences (LCS) and shortest common super-sequences (SCS) in assembly sequencing, as these two topics are the backbone of the new approach. Section 3 introduces then the approach and explains the reason for the fixturing orientation of the application. A complete industrial case study is presented in Sect. 4 and discussed in Sect. 5. Finally, conclusion and perspectives are provided in Sect. 6.

## 2 Related literature

Two main issues of related literature have been identified and are detailed in the following. The first part concerns the generation of process plans in general and the emerging concept of reconfigurable process plans. The second part concerns the upcoming application of operation sequence comparisons for the identification of reconfiguration needs in process plans.

### 2.1 Reconfigurable process plans

Conventional process planning methods like for example variant process planning based on group technology (Kusiak 1987; Kusiak and Heragu 1987), mainly focus on the process plans generation for one individual product/part. The philosophy aims at grouping parts which require similar operations with machines performing these operations. Group Technology approaches can be applied for the layout design of cellular manufacturing systems (Heragu 1994). The conventional process planning methods reach their limits when being applied on product variety and product families as they are outset for a dedicated product variant. Therefore, the generated dedicated process plans become fast obsolete for new product/part variants and are not able to generate a common process plan for a product family as illustrated in Fig. 1.

To overcome these shortcomings, inspired by the paradigm of reconfiguration (Koren et al. 1999), the concept of reconfigurable process plans (RPP) has been introduced in (ElMaraghy 2007). It is outset to support the process plan changeability for evolving products and production systems. One method for RPP has been developed by Azab and ElMaraghy (2007), identifying new and missing features in a product variety by comparing the new product/part with original ones, and then to adapt the new changes by configuring the existing process plans. This avoids to newly generate another one. A Mathematical modelling method for RPP is presented by Azab et al. (2009). For new products, the belonging process variants are generated by (re-)

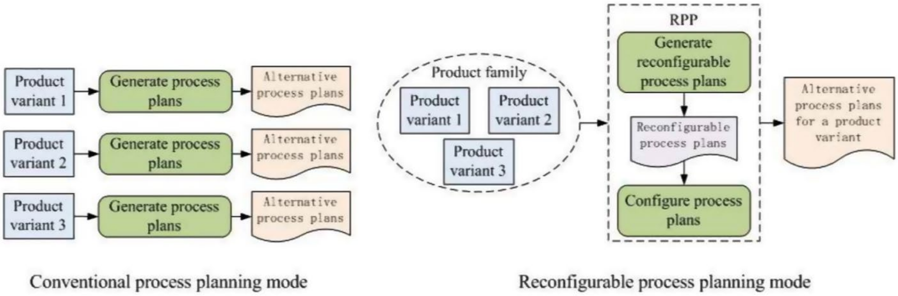


**Fig. 1** Conventional process planning (left) vs. RPP (right), adapted from (Xia 2017)

configuring the existing process components. Available manufacturing resources are considered during this reconfiguration.

The shortcoming of RPP is the orientation to the manufacturing of parts and products. No assumption can be done about the use of the RPP approaches on assembly issues. As stated by Hu et al. (2011), research is needed concerning the design and planning of new types of “personalised” manufacturing system.

## 2.2 Longest common subsequence and shortest common super-sequence

The identification of common items in assembly sequences is a quite instinctive way to compare the assembly process plans of several products. A mathematical method which being similar to this reasoning is the search for the longest common subsequence (LCS) or, related, the shortest common super-sequence (SCS). It is a method which has been for a while now the issue of research in mathematics and computer sciences. Going to the origins, theoretical discussions of LCS concerning its complexity boundaries and some general LCS problems have been presented by Ullman et al. (1976) and Maier (1978). With upcoming computer sciences, Bergroth et al. (2000) propose a review of algorithmic solutions solving LCS problems.

Despite of their use in mathematics and computer sciences, the application of LCS/SCS analyses to assembly sequence comparison is a relatively new field of research. Only few applications could be found in literature, applied mainly to part family formation based on operation sequence similarity (Koren et al. 2018). These applications are presented in Table 1.

Effectively, through the applications presented in literature, the use of the LCS/SCS principle on sequence comparison problems may be an efficient way to identify common and distinct sequence partitions. As mentioned in the introduction section, this is a key issue in the determination of multi-product assembly plans for the design of mutually used assembly lines.

However, one shortcoming of the evaluated approaches is their orientation towards manufacturing and not assembly. The challenges of manufacturing are different as those concerning assembly as manufacturing machines have in general a high intrinsic operation flexibility and can cope with different geometries more easily whereas assembly modules are often dedicated and rigid. Another shortcoming is that component variety is not taken into account because the comparison criteria which are

**Table 1** Assembly operation comparison methods

| Reference | Model | Application |
|---|---|---|
| (Askin and Ming 1998) | LCS + modified hierarchical clustering | LCS (longest common subsequence) based similarity coefficient for part family |
| (Gupta et al. 2012) | POIM | Similarity is calculated out of the Part Operation Incidence Matrix. A PCA analysis is used for classification and k-means algorithm for clustering. |
| (Goyal et al. 2013a; Goyal, Jain and Jain Goyal et al. 2013b) | BMIM | Similarity coefficient evaluating by-pass moves, idle machines and handling moves with LCS |
| (Wang et al. 2016) | LCS/SCS | Similarity coefficient and clustering based on LCS/SCS, idle machines and by-pass moves. |
| (Shivads and Telsang 2018) | BMIM + clustering | BMIM based product family formation method |
| (Ali et al. 2018) | BMIMS | Similarity coefficient evaluating by-pass moves, idle machines and handling moves with LCS in setups |
| (Jiang, Wang et al. 2019) | SJMF / LCMF | Similarity model to estimate reconfiguration efforts |
| (Huang and Yan 2019a) | LCS/SCS | Similarity with LCS, weighted with process time and demand considering the impact of process time and capacity demand. Clustering is done by setting a similarity value as threshold. |
| (Huang and Yan 2019b) | LPCS | Combining Jaccard's similarity with LCS analysis for the design of delayed RMS (searching optimum place for reconfigurable stations). |
| (Wi, Wang and Ji 2021) | LCS/PCA | Combining LCS with Jaccard's similarity for analysis of operation sequence similarities |

proposed are the type of one-to-one comparisons of parts or stations. Concerning the one-to-one comparison of stations, it is not detailed, how the capabilities of stations can be included.

To conclude, the application of LCS/SCS methods to a whole multi-product assembly system has not been proved yet. This paper contributes to close this research gap by proposing a new assembly-oriented approach for multi-product assembly plan generation with LCS/SCS methods.

### 2.3 Applying LCS and SCS logic to assembly comparison

The method of LCS-SCS analysis has being examined in mathematics and computer sciences for a certain time now. Though, its applications to industrial problems is quite recent, as highlighted in the literature review. In this section, the generic concept of LCS and SCS is reminded in a first step. Then the new approach is detailed. with the example of the two initial character sequences here called seq1 = {FAAHFR} and seq2 = {ADHDFNR}. Their LCS and SCS are illustrated in Table 2. The shortest common super-sequence contains always the longest common subsequence, as shown by the bold letters.

Transposing the sequences on an assembly plan comparison problem, each letter stands for an assembly plan unit (in general an assembly operation). Same letters mean same operations. The LCS gives thus an information, which operations can be used mutually and the LCS gives an information about the operation sequence which

**Table 2** LCS versus SCS

| **Longest common subsequence** | | **Shortest common super-sequence** | |
|---|---|---|---|
| FAA HDFNR | *(seq1)* | FA AH F R | *(seq1)* |
| A H F R | *(LCS)* | FADAHDFNR | *(SCS)* |
| ADHDFNR | *(seq2)* | AD HDFNR | *(seq2)* |

is valid for all of the different examined sequences. This comparison cannot only be binary but also for more than two assembly operation sequences.

## 3 A new methodology to determine a multi-product assembly plan with LCS/SCS analysis

The previous section has reminded the concept of reconfigurable process planning (RPP) and the generic method of LCS and SCS and presented three possible indicators based on it. The question is now, how to use efficiently this method of LCS/SCS identification in the context of assembly. And, in the context of fixturing-driven determination of multi-product assembly plans, how can information of component fixturing and assembly operations with their sequences and orientations modelled to be adequate to the LCS-SCS reasoning. The aim is, that after the comparison different and common partitions are identified in the assembly plans and the differences are quantified. These differences can be interpreted as an indicator for reconfigurability needs. The overall methodology is illustrated in Fig. 2. Compared to the conventional process planning approaches and RPP, it can be used in both cases (illustrated in Fig. 1): either to compare a set of process plans which have been generated in the conventional way, i.e. dedicated for each of the products. Or to be integrated into a global approach for reconfigurable process planning, by directly supporting the generation of a common process plan highlighting the needs for reconfiguration.

All elements used by the methodology are detailed in the following subsections: starting with compatible fixturing (3.1), describing then the generation of assembly plan signatures and information vectors, detailing their use for the definition of a comparison granularity level (3.2), and emphasising the determination of character sequences for LCS/SCS analysis (3.3). The interpretation of the LCS/SCS analysis-based indicators is illustrated in the case study section.

### 3.1 Product and fixturing compatibility issues

The here presented work is focusing on the fixture driven determination of common process plans. This idea is based on the strong hypothesis that common fixturing is a key enabler for common assembly. The work hypothesis has been developed following a product variety analysis. The finding has been that very often the used assembly operations types (screwing, press fitting, etc.) are identical with similar process parameters, but the variations in the product design are an obstacle to a common

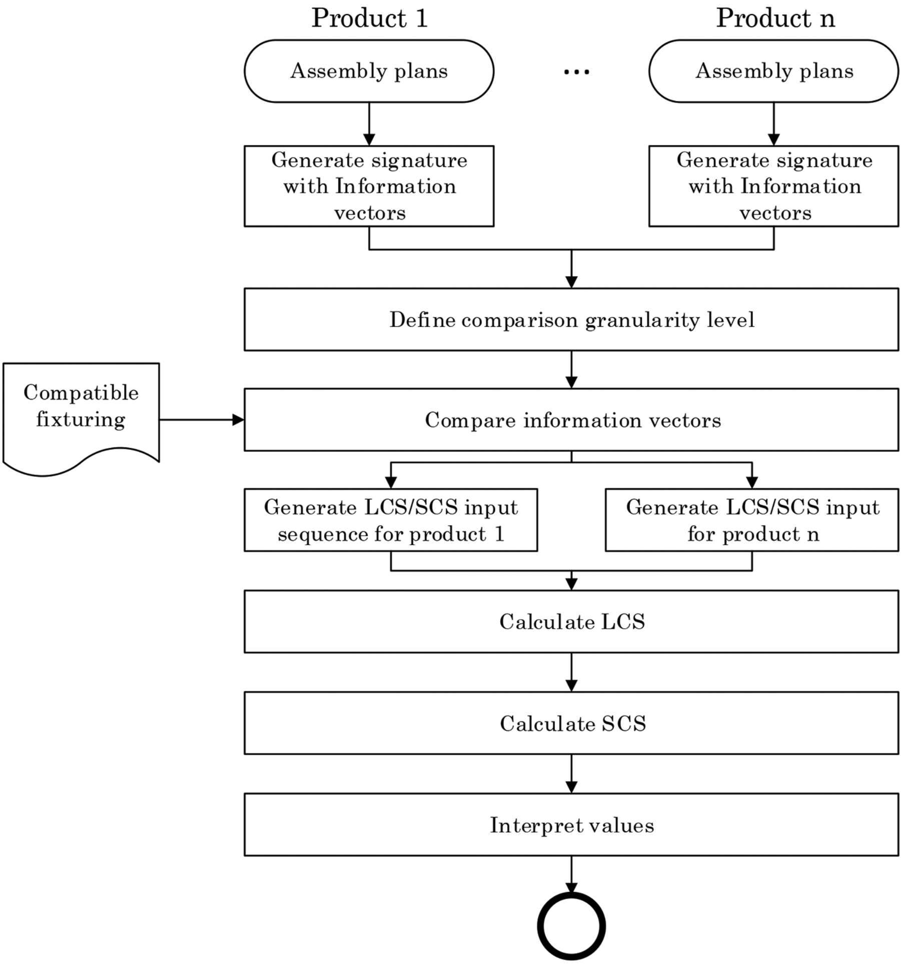


**Fig. 2** Methodology to compare assembly plans with LCS/SCS analysis

assembly. Here, variations in product design means that same functional subassemblies are designed in a different way, which are characterised by a variety of shapes, geometries and sometimes even materials. As described by Stief et al. (2023), identifying common fixturing allows that the assembly operations of different products can be conducted on the same assembly station. In this case, the focus on fixturing allows to regard products with partial similarity. Fixturing is regarded as the physical equipment allowing to position and locate the base part on which the other components are assembled and common fixturing can be achieved when a same fixturing equipment is able to cope with different part references. The here presented new methodology can be seen as complementary to the cited article as it provides assembly plans for shared assembly systems.

In order to determine the compatibilities in the process plans of different products, it is necessary, in a preliminary step, to identify compatible fixtures for the product variety which is aimed to be assembled on the same assembly line. To do so, the components which are needed for positioning have to be assessed individually by engineering experts. To ensure the fixturing compatibility for a multi-product assembly, it must be checked that the corresponding components in all the products have a shape and geometry compatible for a common fixturing. For this, the similarities have to be examined in a first step by an expert and a list of components allowing the use of the same fixtures has to be dressed. Up to now, this analysis has been realised manually during the industrial case studies. It is recommended to set up gradually a file where this information is saved.

### 3.2 Modelling assembly plan information for SCS/LCS use

The principles of LCS/SCS analysis in general and their theoretical applicability to assembly sequence comparison have been mentioned in the previous sections. As mentioned, the LCS/SCS methods are based on the comparison of character strings. Though, assembly plans are not expressed in this way. In consequence, the information contained in the assembly plans has to be transformed that in a way that it supports the generation of these character strings.

For this purpose, it is proposed to extract relevant assembly information of each step in the assembly plan (i.e. in general for each assembly operation) and to store it into an information vector. The sequence of this information vectors, following the sequence in the assembly plan, constitutes the signature of the assembly plan. In this paper, as it is motivated by the use of fixturing information as key enabler for common process plans, and therefore shared assembly systems, it is proposed to extract the information of fixturing compatibility, assembly operation (type) and the operation orientation in the standard product coordinate system out of the assembly plan. According to the industrial applications, the it may be useful to extract more information out of the assembly plan. The methodology is thought to be adaptive. It means that the information vector can theoretically contain any information which is supposed to be pertinent. The flow charts in Figs. 2 and 3 are valid for any case (for example one may chose only the orientation of the assembly direction, or one may add machine references if the assembly can exclusively be conducted on a single machine). Important is that the same set of information is added to the information vectors of all products in order to assure the consistency of the analysis. Therefore, the information vector may contain more or other information than here described,

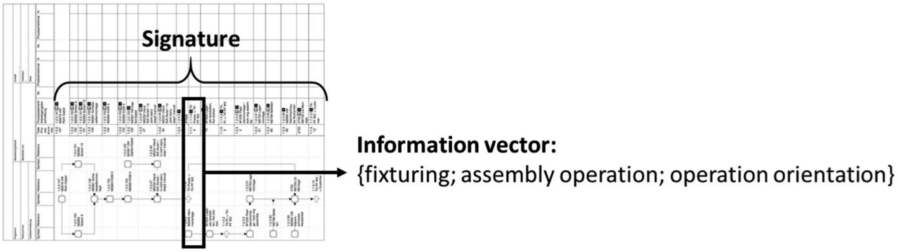


**Fig. 3** Assembly process plan with signature and information vector

however this will not impact the presented methodology. But, logically, at least one information is needed (if there is no information in the information vector, i.e. it is empty, there would be nothing to compare). Figure 4 illustrates the idea of assembly signature and information vector.

To compare different assembly plans, their signatures have to be compared. It means, more in detail, the comparison of the information vectors which are containing in our example the triple information of {fixturing; assembly operation; operation orientation}. The information contained in this vector is situated on three different granularity levels, having an impact on different levels of the assembly system:

- Fixturing (including component positioning): impacts the assembly system structure (same or different modules in the assembly system).
- Assembly operation type: impacts the assembly unit level (decision if the module should be reconfigurable or single operation).
- Operation orientation: impacts the assembly operation level (flexible or rigid assembly operations needed).

Fixturing has been placed on the most general granularity level because it concerns in general a whole workstation, and changing fixtures is in general more time consuming and costly than changing a work tool as fixtures themselves are expensive and a fixture change requires often the shutdown of a production line, whereas tool and operation orientation changes can be realised automatically today.

A granularity level for the comparison can be chosen by selecting the entire information vector or only a part of it. For the information vectors which have been defined here, there are three possibilities to choose the granularity level, reaching from macro-comparison to micro-comparison:

(1) Criterion “fixturing” only: The assembly plan signatures are compared only in regard of compatible fixturing. The result is a macroscopic view of the sequence similarity. Neither the number of operations nor their type or direction considered. An analysis on this granularity level is be suitable for the comparison of assembly plans for assembly systems where all operations are either realised manually or where the system is already fully reconfigurable. Because the operation types and their orientations are not considered and their variety can be absorbed by these types of assembly systems.
(2) Criteria “fixturing” and “assembly operation”: Both information, fixturing and its associated assembly operations are concerned by this comparison. It results in

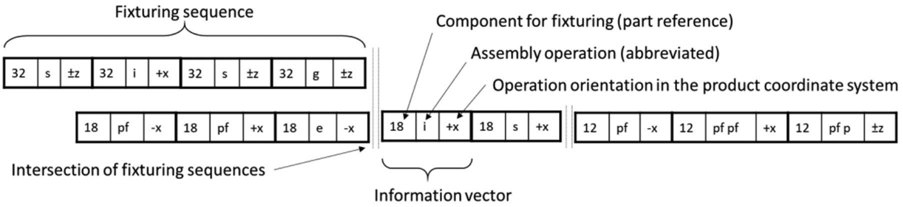


**Fig. 4** Extract of an assembly plan signature (example)

a more detailed analysis of similarity than the first comparison of fixturing only. On this granularity level, assembly plans are compared in regard of fixturing sequences, their compatibility and operation sequences. This allows a vision on the system architecture level identifying which parts of the assembly plan have mutual fixturing and operations and therefore may use also mutual assembly modules.

(3) Criteria “fixturing”, “assembly operation”, and “operation orientation”: Using all available information is the most detailed analysis. It is oriented towards a comparison for go/no-go decisions concerning one dedicated assembly system for multiple products if the assembly plan similarity is high enough.

The user of the methodology, in general the production engineer, has to choose the right granularity level as function of the scope of its analysis. The following section illustrates how those criteria can be used for the determination of character sequences used as input for the LCS/SCS analysis.

### 3.3 Character sequence determination and LCS/SCS analysis

As requirement for the character sequence determination, the information vectors have been defined: Each preliminary assembly plan is transformed into an information vector sequence, the assembly plan signature. Figure 5 shows an example for an assembly plan signature composed of different information vectors. The information vectors are gathered in regard of their content, in function of the predominant element which will be in the focus of the investigation. In the here presented case of fixturing-driven analysis it is the “component for fixturing” information. This fixturing-driven arrangement is the key for the assembly plan comparison of different products as it is needed throughout all of the granularity levels. This representation finally enables comparison of two or more preliminary assembly plans.

The comparison phase is dedicated to generate the input sequences for LCS and SCS calculations. The input sequences are determined by comparing the information vectors in regard of the chosen criteria (scenario (1), (2) or (3) as detailed in the previous subsection). Concerning the components for fixturing and the fixturing sequences, the predefined information of compatible fixturing for all examined products must be used. All the information vectors throughout the assembly plan signatures are analysed. In a first step, characters are assigned to the information vectors of the first assembly plan signature. In a second step, the information vectors of this first assembly plan signature are compared to the information vectors of a second one. If two information vectors are identic in regard of the chosen criteria, the same character is assigned to them. If not, different characters are assigned. The flow chart for this process is illustrated in Fig. 3. It can be carried out for two or more products under condition that the information vectors contain the same elements.

The output is a character sequence for the assembly plan signature of each of the compared products. The character sequences may be similar to the ones used in the precedent section to illustrate the LCS and SCS analysis method. As the assembly plans in the present article are based on fixturing sequences, the analysis of LCS and SCS is based on it as well. In the flow chart, the analysis by fixturing is mentioned.

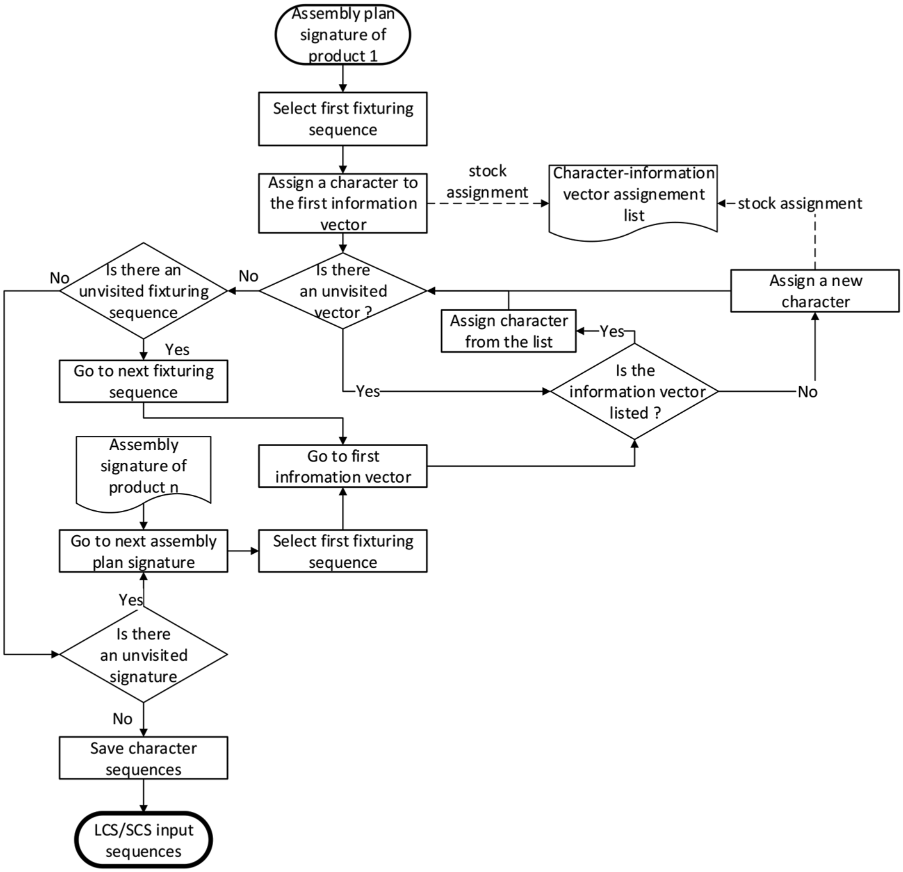


**Fig. 5** Flow chart for the determination of LCS/SCS analysis input sequences

This means that similar to the assembly plan signatures, the input character sequences used for the LCS and SCS calculations are also divided into fixturing sequences. It determines which assembly plan partitions are compatible for different products, and therefore which parts of the assembly plan signature can be submitted to the LCS/SCS analysis. With the information on compatible components for fixturing, similar modules in the assembly system can then be identified. The character sequences of these partition having compatible fixturing are analysed with LCS and SCS. If there is no compatible fixturing, the according parts of the assembly plan signatures are not available for LCS/SCS comparison. An illustration is given in the industrial case study in the following section.

Beside the analysis of the LCS or SCS strings themselves, three indicators are proposed hereafter to synthesise the characteristics of the comparison outcomes at one glance:

(1) The LCS length compared to the length of the shortest initial sequence(s);
(2) The length of the longest initial sequence(s) compared to the SCS length;

(3) The number all different characters used compared to the number of characters used in the LCS (similarity calculation according to Jaccard (1902).

For the first indicator (1), it is analysed if the sequence lengths are equal or not (binary analysis). If the LCS length is equal to the length of the shortest common initial sequence, this means that one of the initial sequences is at the same time the longest common sub-sequence. On the assembly system level, this implies that one of the products can be realised entirely with the LCS. And, in extension, supplementary assembly operations are needed to assemble other products on the same assembly line.

The second indicator (2) is a binary analysis as well: if it is equal to one, it means that the longest common super-sequence is entirely represented in one of the initial sequences. On the assembly system level, this means that the assembly plan of one product is adapted to realise all products. However, some assembly operations are not mutual which implies that some of the assembly units are not fully charged (idle machines).

In addition to their use in a binary analysis (equal to 100% or not), the values of both indicators (1) and (2) give also an idea of the fitness of two compared assembly sequences. Especially indicator (2), based on the SCS, indicates if an integration of the smaller assembly sequence to the longer assembly sequence needs more or less additional modules.

Thirdly, the last indicator (3) evaluates the mutuality of the assembly operations. If its value is high, it means that the number of operations used in the common partitions of the assembly plan is close to the overall number of operations used for all different products. This implies a high mutuality of operations and a low number of idle assembly units. For low values, the interpretation is vice-versa.

Globally, there are three application cases for the LCS/SCS analysis. The first case is an analysis for the integration of a new product to an existing assembly line. It consists of an LCS/SCS analysis for the choice of an optimal assembly plan for a new product. It concerns the comparison of an existing assembly plan, i.e. the plan of a product already in production with a set of possible assembly plans for a new product aiming to determine which of the assembly plans for the new product matches the best the one for the existing product.

The second case is the development of a new assembly line for a set of new products which are not yet in production. It is based on the comparison of two or more sets of assembly plans to each other. This comparison has as aim to determine before the production start which combination of assembly plans is the best one. As the products are not yet in production, the comparison has to be done with a set of preliminary assembly plans.

The third case is the parallel analysis of assembly plans for multiple products when determining the preliminary assembly plans. It is an optimisation approach to generate one optimal solution for multiple products. It is in contrast to the two other approaches where first the solution space is generated and explored afterwards.

## 4 Industrial case study

The assembly plan comparison method by LCS/SCS analysis has been applied on three products of the industrial partner company. These are complex mechatronic products (up to 23 technical functions are considered, the products have between 50 and 200 parts, and their complexities reach from low to high). Due to confidentiality issues, the products - called product 1,2, and 3 - cannot be illustrated in detail here. Also, all data has been anonymised.

Starting with product 1, an assembly sequence with the information fixturing, operation and orientation extracted out of the assembly plan is illustrated in Fig. 6. Each column (having its distinct colour) represents a different component for fixturing, indicated by "comp" (component for fixturing).

Analogous, the assembly sequence containing the same information concerning product 2 is shown in Fig. 7. As product 2 is the most basic one, its assembly sequence is as well the simplest one.

For product 3 as well, an assembly sequence with the information fixturing, operation and orientation extracted out of the assembly plan is illustrated in Fig. 8.

Same colours used to highlight the components for fixturing indicate compatibility with other products. To enable the comparison of the three assembly plans (product 1 is compared to product 2 and product 3), Table 3 details the compatibilities of components used for fixturing in the three products. This compatibility has been determined by an expert comparing shape, geometry and size of the different references.

For the comparison driven by fixturing, the assembly plan information is translated into information vectors and gathered in regard of the belonging fixturing. All information vectors are listed in Table 4, gathered for each product according to the component for fixturing. An information vector is expressed as follows: (fixturing reference; operation type; operation orientation).

At this stage, the user of the new method has a complete overview of the assembly plan signatures. Depending on the gathering criteria, which is the predominant criterion for the analysis (for instance the component used for fixturing), the complexity of the product assemblies can be estimated by the number of different components used for fixturing and the length of the sequences. In the example presented in Table 4, it becomes evident that product 1 and 3 are more complex than product 2 and that the principle part of assembly will be conducted using component 7 (for product 1) and component 4 (product 3) for fixturing.

### 4.1 Sequence comparison of product 1 and product 2

For the sequence comparison of product 1 and 2, the sequence transformation method described in the previous section is applied on the information vectors. As granularity level for the analysis, the criteria "fixturing" and "assembly operation" have been chosen but not operation orientations (option (2)). For the identification of compatible fixturing, Table 3 is used. The character list which has been generated according to the flow chart is available in Table 5.

The double listing as presented in Table 5 is needed for manual treatment. In the case of an implementation, one list would be enough. Finally, the input sequences for

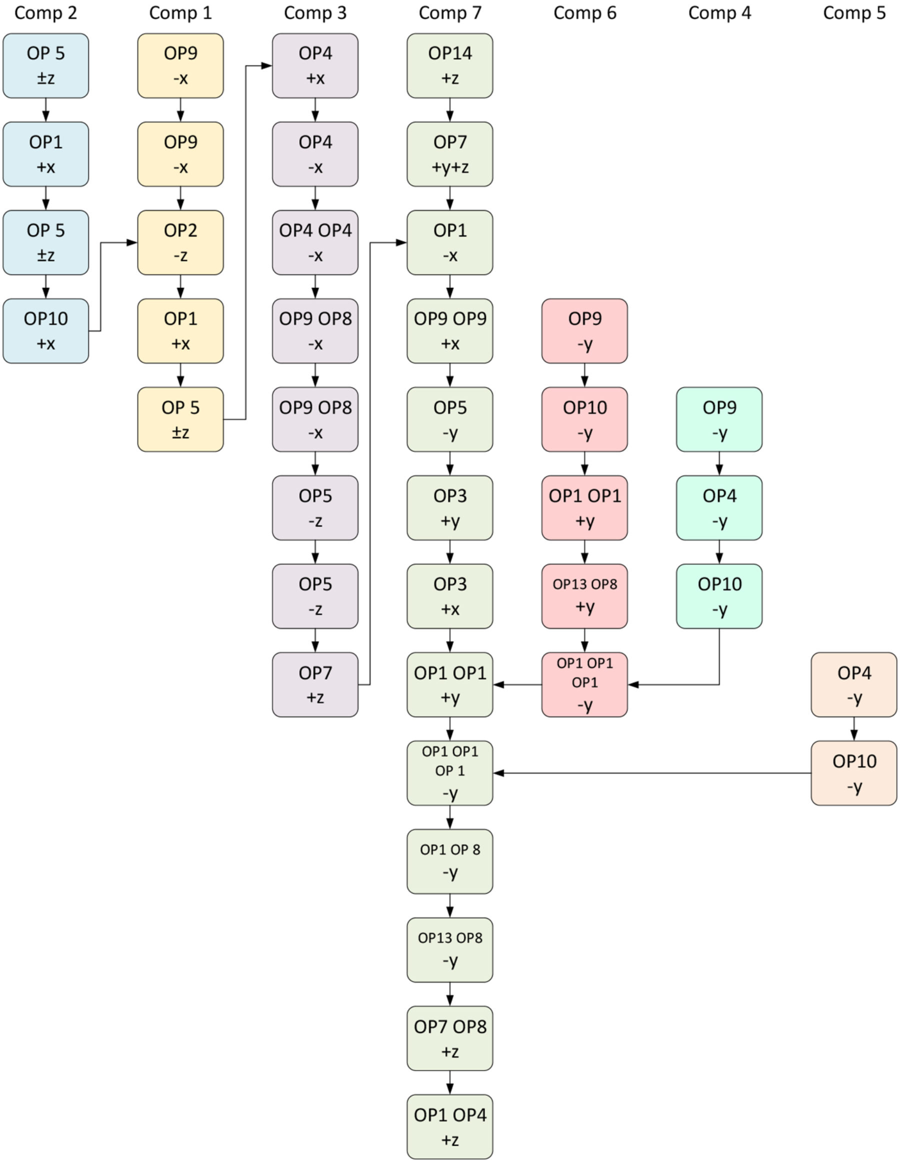
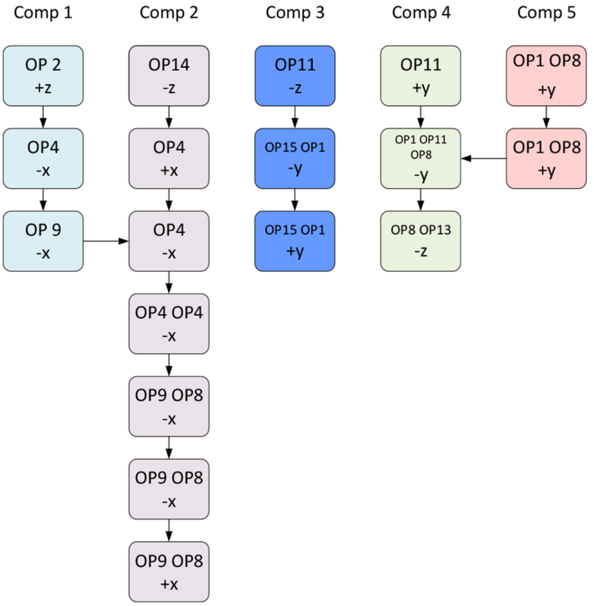


**Fig. 6** Illustration of an assembly sequence for product 1

the LCS/SCS analysis are shown in Table 6. It is the translation of the information vectors in Table 4 with help of the character list in Table 5. At one glance it becomes evident that the preliminary assembly plans of the two products differ largely. The number of generated LCS/SCS input sequences and their length differs, as well as the used characters. In this particular case, and as the comparison is up to now still conducted manually, a detailed analysis of all LCS/SCS indicators is not necessary as the only sequences which does *not* differ are the ones in line 2, line 3, and line 4.

**Fig. 7** Illustration of an assembly sequence for product 2



Their analysis is detailed in the following. For the lines 1, 5, 6, 7, and 8, all indicators are equal to zero.

- Indicator 1 (LCS vs. shortest initial sequence) = 1/3 = 33% < 100%.
- Indicator 2 (longest initial sequence vs. SCS) = 5/7 = 71% < 100%.
- Indicator 3 (characters in LCS vs. different used characters) = 1/5 = 20%.

Analysing the three indicators allows at a glance to state about the pertinence of a common assembly plan for line 2: the first and the second indicator tell the user that neither product 2 can be realised with the LCS, nor that the sequence of product 1 englobes the one of product 2. A closer look emphasises that in a mutual sequence either operation type D or operation type E would be redundant. Finally, the third indicator expresses that the mutuality of a common sequence will be poor. In a common assembly line, only one of the five assembly operation modules would be used mutually and the redundancy leads either to duplication of same modules or material flow complexity as a same module has to be visited twice. It is therefore not recommended to combine both products for this part of the assembly.

Sequence comparison of line 3:

- LCS = {H H I J J}, length 5.
- SCS = {j H H I J J K K L}, length 9.
- Indicator 1 (LCS vs. shortest initial sequence) = 5/6 = 83% < 100%.
- Indicator 2 (SCS vs. longest initial sequence) = 8/9 = 89% < 100%.
- Indicator 3 (characters in LCS vs. different used characters) = 3/6 = 50%.

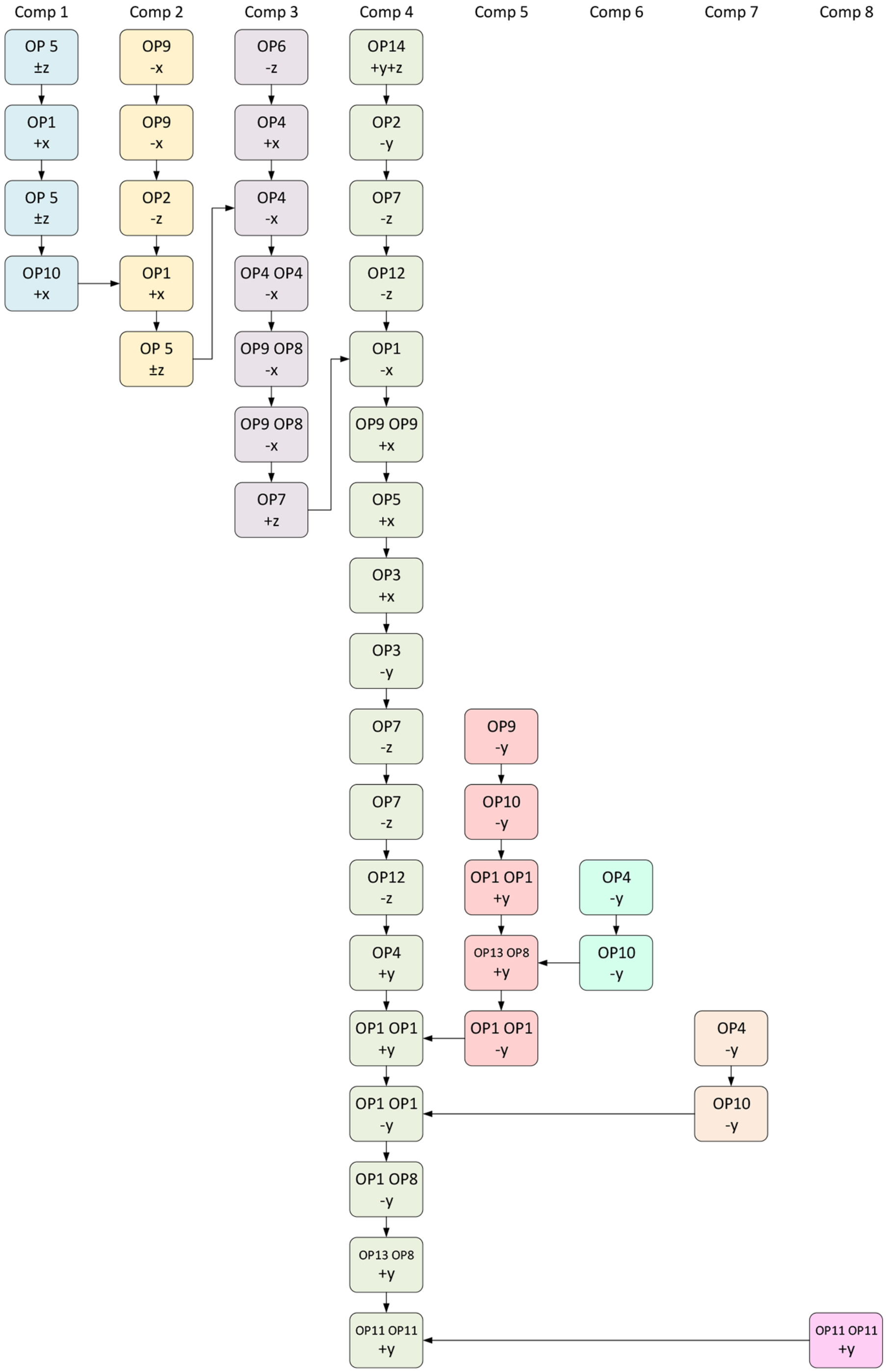


**Fig. 8** Illustration of an assembly sequence for product 3

**Table 3** Fixturing compatibilities for the three analysed products

| Products | Component compatibility for fixturing | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Product 1 | 2 | 1 | 3 | 7 | 6 | none | 4 | 5 | none |
| Product 2 | 1 | 1 | 2 | 5 | 4 | none | none | none | 3 |
| Product 3 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | none |

**Table 4** Expression of assembly sequences in information vectors (entries according to the previous assembly sequence illustrations)

**Product 1**

(2; op5; ±z) (2; op1; +x) (2; op5; ±z) (2; op10; ±z)

(1; op9; -x) (1; op9; -x) (1; op2; -z) (1; op1; +x) (1; op5; ±z)

(3; op4; +x) (3; op4; -x) (3; op4 op4; -x) (3; op9 op8; -x) (3; op9 op8; +x) (3; op5; -z) (3; op5; -z) (3; op7; +z)

(7; op14; +z) (7; op7; +y+z (45°)) (7; op1; -x) (7; op9 op9; +x) (7; op5; +x) (7; op5; +x) (7; op3; -y) (7; op3; +y) (7; op1 op1; +y) (7; op1 op1 op1; -y) (7; op1 op8; -y) (7; op13 op8; -y) (7; op7 op8; +z) (7; op1 op4; +z)

(6; op9; -y) (6; op10; -y) (6; op1 op1; +y) (6; op13 op 8; +y) (6; op1 op1 op 1; -y)

(4; op4; +y) (4; op10; +y)

(5; op9; -y) (5; op4; -y) (5; op10; -y)

**Product 2**

(1; op2; +z) (1; op4; -x) (1; op9; -x)

(2; op14; -z) (2; op4; +x) (2; op4; -x) (2; op4 op4; -x) (2; op9 op8; -x) (2; op9 op8; +x)

(3; op11; -z) (3; op15 op1; -y) (3; op15 op1; +y)

(4; op1; +y) (4; op1 op8; +y) (4; op1 op8; +y)

(5; op11; +y) (5; op1 op11 op8; +y) (5; op8 op13; +y)

**Product 3**

(1; op5; ±z) (1; op1; +x) (1; op5; ±z) (1; op10; ±z)

(2; op9; -x) (2; op9; -x) (2; op2; -z) (2; op1; +x) (2; op5; ±z)

(3; op6; -z) (3; op4; +x) (3; op4; -x) (3; op4 op4; -x) (3; op9 op8; -x) (3; op9 op8; +x) (3; op9; +x)

(4; op14; +y+z (45°)) (4; op2; -y) (4; op7; -z) (4; op12; -z) (4; op1; -x) (4; op9 op9; +x) (4; op5; +x) (4; op5; +x) (4; op3; -y) (4; op3; +y) (4; op7; -z) (4; op7; -z) (4; op12; -z) (4; op4; +y) (4; op1 op1; +y) (4; op1 op1; -y) (4; op1 op8; -y) (4; op13 op8; -y) (4; op11 op11; -z)

(5; op9; -y) (5; op10; -y) (5; op1 op1; +y) (5; op13 op 8; +y) (5; op1 op 1; -y)

(6; op11 op11; -y)

(7; op4; +y) (7; op10; +y)

(8; op4 ; -y) (8 ; op10 ; -y)

As well as for the analysis of line 2, the first and second indicator show the user at a glance that neither the shorter assembly sequence is included in a common one, nor the longer assembly sequence allows to assemble both products. However, the high value of indicator 1 signals that an integration of the shorter sequence of product 2 to the assembly sequence of product 1 is feasible without major modifications. For instance, as the LCS is uncut, the assembly can be mutualised for both products using

**Table 5** Character list for product 1 and product 2

**Character list for product 1**

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **A** | (2; op5;) | **J** | (3; op9 op8;) | **S** | (7; op1 op1;) | **b** | (6; op13 op 8;) |
| **B** | (2; op1;) | **K** | (3; op5;) | **T** | (7; op1 op1 op1;) | **c** | (6; op1 op1 op 1) |
| **C** | (2; op10;) | **L** | (3; op7;) | **U** | (7; op1 op8;) | **d** | (4; op4;) |
| **D** | (1; op9;) | **M** | (7; op14;) | **V** | (7; op13 op8;) | **e** | (4; op10;) |
| **E** | (1; op2;) | **N** | (7; op7;) | **W** | (7; op7 op8;) | **f** | (5; op9;) |
| **F** | (1; op1;) | **O** | (7; op1;) | **X** | (7; op1 op4;) | **g** | (5; op4;) |
| **G** | (1; op5;) | **P** | (7; op9 op9;) | **Y** | (6; op9 ;) | **h** | (5; op10;) |
| **H** | (3; op4;) | **Q** | (7; op5;) | **Z** | (6; op10 ;) | | |
| **I** | (3; op4 op4;) | **R** | (7; op3;) | **a** | (6; op1 op1;) | | |

**Character list for product 2** (checking fixturing compatibilities)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| **A** | (1; op5;) | **K** | (2; op5;) | **U** | (5; op1 op8;) | **j** | (2; op14;) |
| **B** | (1; op1;) | **L** | (2; op7;) | **V** | (5; op13 op8;) | **k** | (3; op11;) |
| **C** | (1; op10;) | **M** | (5; op14;) | **W** | (5; op7 op8;) | **l** | (3; op15 op1;) |
| **D** | (1; op9;) | **N** | (5; op7;) | **X** | (5; op1 op4;) | **m** | (4; op1;) |
| **E** | (1; op2;) | **O** | (5; op1;) | **Y** | (4; op9 ;) | **n** | (4; op1 op8 ;) |
| **F** | (1; op1;) | **P** | (5; op9 op9;) | **Z** | (4; op10 ;) | **o** | (5; op11;) |
| **G** | (1; op5;) | **Q** | (5; op5;) | **a** | (4; op1 op1;) | **p** | (5; op1 op11 op8 ;) |
| **H** | (2; op4;) | **R** | (5; op3;) | **b** | (4; op13 op 8;) | | |
| **I** | (2; op4 op4;) | **S** | (5; op1 op1;) | **c** | (4; op1 op1 op 1) | | |

**Table 6** LCS/SCS input sequences for product 1 and product 2

| # | Product 1 | Product 2 |
|---|---|---|
| 1 | A B A C | |
| 2 | D D E F G | E i D |
| 3 | H H I J J K K L | j H H I J J |
| 4 | M N O P Q Q R R S T U V W X | o p V |
| 5 | Y Z a b c | m n n |
| 6 | d e | |
| 7 | f g h | |
| 8 | | k l l |

Sequence comparison of line 2:

- LCS = {E} or {D}, length 1
- SCS = {E i D D E F G} or {D D E i D F G}, length 7

the assembly modules present in the LCS and afterwards the production flow could be separated for the other ones (j for product 2 and K K L for product 1). As result of the LCS/SCS analysis, product 2 could be integrated partially to the line of product 1 by adding one assembly operation module. It should be noted that mutuality (indicator 3) for a complete common assembly plan remains weak as only the half of the sequence can be shared.

Sequence comparison of line 4:

- LCS = {V}, length 1.
- SCS = {o p M N O P Q Q R R S T U V W X}, length 16.
- Indicator 1 (LCS vs. shortest initial sequence) = 1/3 = 33% < 100%.
- Indicator 2 (SCS vs. longest initial sequence) = 14/16 = 88% < 100%.
- Indicator 3 (characters in LCS vs. different used characters) = 1/14 = 7%.

The comparison of the sequences in line 4 gives similar results as the one of line 2, and indicator 3 has an even weaker value. The user can quite easily take the same conclusion: It is not recommended to combine both products for this part of the assembly.

Out of these three detailed analyses and in regard of the heavy differences concerning the other sequences (zero commonality), the following deductions about a multi-product line for product 1 and 2 can be taken:

- The assembly plans (i.e. the assembly plan signatures) of product 1 and product 2 differ too much to allow a complete integration of the two products to one common multi-product assembly line.
- The only partial assembly sequence which could be mutualised is the one in line 3 of Table 6.

These findings have been validated by industrial experts.

## 4.2 Sequence comparison of product 1 and 3

For the sequence comparison between product 1 and product 3, the character list for product 1, which has been defined in Table 5, can be reused. Only the characters of product 3 need to be newly defined during the manual input. Table 7 illustrates this new character list which shows all characters relevant for the SCS/LCS input sequence generation.

Similar to the previous comparison of product 1 and product 2, only fixturing references and operation types have been compared. No operation orientation has been considered for the character generation. The obtained LCS/SCS input sequences are shown in Table 8, ordered by compatible fixturing references. It is emphasised that the sequences in line 1, 2, and 6 are identic: it means that there is a perfect match between compatible fixturing references and operation types for the two products. As consequence, the same assembly modules can be used in these cases.

The sequence comparison in line 5 highlights that the last operation in the sequence differs. In consequence, for a common assembly, a reconfigurable assembly opera-

**Table 7** Character list for LCS/SCS input sequence generation

| Character list for product 3 (checking fixturing compatibilities) | | | | | | | |
|---|---|---|---|---|---|---|---|
| A | (1; op5;) | M | (4; op14;) | Y | (5; op9 ;) | k | (4; op2;) |
| B | (1; op1;) | N | (4; op7;) | Z | (5; op10 ;) | l | (4; op12;) |
| C | (1; op10;) | O | (4; op1;) | A | (5; op1 op1;) | m | (4; op4;) |
| D | (2; op9;) | P | (4; op9 op9;) | B | (5; op13 op 8;) | n | (4; op11 op11;) |
| E | (2; op2;) | Q | (4; op5;) | C | (5; op1 op1 op 1) | o | (5; op1 op 1 ;) |
| F | (2; op1;) | R | (4; op3;) | D | (7; op4;) | p | (6; op11 op11;) |
| G | (2; op5;) | S | (4; op1 op1;) | E | (7; op10;) | | |
| H | (3; op4;) | T | (4; op1 op1 op1;) | F | (8; op9;) | | |
| I | (3; op4 op4;) | U | (4; op1 op8;) | G | (8; op4;) | | |
| J | (3; op9 op8;) | V | (4; op13 op8;) | H | (8; op10;) | | |
| K | (3; op5;) | W | (4; op7 op8;) | i | (3; op6;) | | |
| L | (3; op7;) | X | (4; op1 op4;) | j | (3; op9;) | | |

**Table 8** LCS/SCS input sequences for product 1 and product 3

| # | Product 1 | Product 3 |
|---|---|---|
| 1 | A B A C | A B A C |
| 2 | D D E F G | D D E F G |
| 3 | H H I J J K K L | i H H I J J j |
| 4 | M N O P Q Q R R S T U V W X | M k N l O P Q Q R R N N l m S S U V n |
| 5 | Y Z a b c | Y Z a b o |
| 6 | d e | d e |
| 7 | f g h | g h |
| 8 | | p |

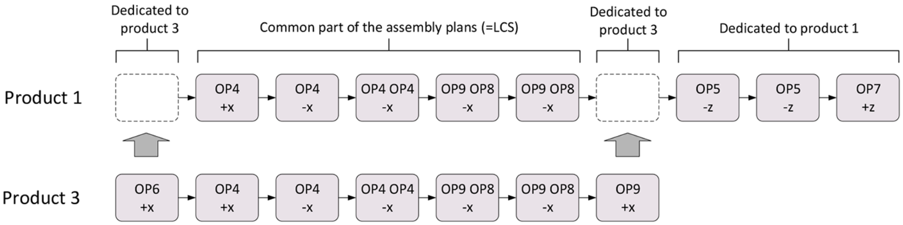


**Fig. 9** Assembly plan adaptation of product 1 to integrate product 3

tion module can be used, performing **c** and **o**. Or, the module can be doubled with an operation dedicated to each product.

Concerning the other sequences, the one in line 7 needs an additional operation in the beginning for product 1. And the sequence in line 8 is proper to product 3. The rest of the sequences (line 3 and 4) are submitted to the detailed LCS and SCS analysis.

Sequence comparison of line 3:

- LCS = {H H I J J}, length 5.
- SCS = {i H H I J J j K K L}, length 10.
- Indicator 1 (LCS vs. shortest initial sequence) = 5/7 = 71% < 100%.
- Indicator 2 (SCS vs. longest initial sequence) = 8/10 = 80% < 100%.
- Indicator 3 (characters in LCS vs. different used characters) = 3/7 = 42%.

Indicator 3 highlights that the sequences are composed of almost half-half the same characters and characters which are particular to one of the two products. Mutuality is therefore not very high but as the SCS is very close to the sequence of product 1 (indicator 2 is high), one may deduce that product 3 can possibly be integrated to the assembly line of product 1 with less efforts.

Figure 9 provides an illustration of this possible integration. In the figure, the LCS sequence is put into evidence. It represents the mutually used part of the assembly sequence. The global common assembly sequence (LCS plus parts dedicated to product 3 and to product 1) is equal to the SCS. The user of the methodology has at this point two possibilities: Either one may tend towards a single assembly system (one common assembly plan) for product 1 and product 3, knowing that there will be about 50% of the modules which are only used for a single product. Or one may imagine a mixed flow assembly system where the LCS sequence is used for both products (main flow) and the dedicated assembly modules are separated from the main flow into secondary flows.

Sequence comparison of line 4:

- LCS = {M N O P Q Q R R S U V}, length 11;
- SCS = {M k N l O P Q Q R R N N l m S S T U V n W X}, length 22.
- Indicator 1 (LCS vs. shortest initial sequence) = 11/14 = 78% < 100%.
- Indicator 2 (longest initial sequence vs. SCS) = 19/22 = 86% < 100%.
- Indicator 3 (characters in LCS vs. overall used characters) = 9/17 = 53%.

As in the previous analysis, the indicators 1 and 2 are high but not equal to 100%. It means that the product 1 and 3 have not a completely common sequence and modifications are needed to generate a common assembly plan. Indicator 3 shows that the sequences are almost half-half composed of dedicated characters and common characters. However, as the SCS is close to the sequence of product 3, product 1 can be integrated to product 3 with less efforts.

Only three assembly modules have to be added (characters T, W, X of product 1) as shown in Fig. 10. The representation has been cut into an upper and a lower part due to space limitations. As the figure illustrates, assembly flow in a common assembly plan will be complex as there are alternating dedicated and shared parts in the assembly plan and, furthermore, there are some idle machines in the shared parts.

Out of these analyses, the following deductions about a multi-product line for product 1 and 3 can be taken:

- The assembly plan signature for the first two compatible fixturing components listed in the first two lines in Table 8 is identical. Therefore, no modifications have to be made in the common assembly plan.
- For the third line, the signature of product 1 can be chosen; then two additional assembly modules for product 3 have to be added (these will be idle when for

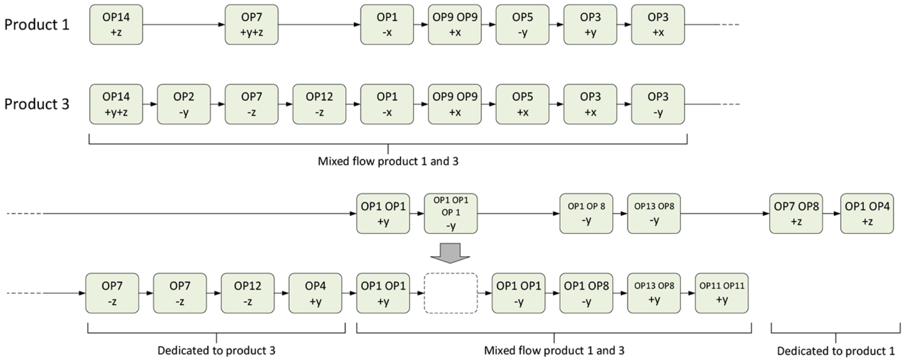


**Fig. 10** Integration of product 1 to the assembly plan of product 3

product 1 assembly); however, overall mutuality is quite low (<50%) which means that 50% of the stations will not be used at full charge – the application of reconfigurable assembly modules should be examined. Alternatively, the assembly flow can be mutualised for the LCS only and then separated as the LCS exists uncut in both sequences (thus the separating points are before and after the LCS).
- For the fourth line, the signature of product 3 may be chosen adding three supplementary assembly modules for product 1; however, mutuality is quite low (<50%) which means that 50% of the stations will not be used at full charge – similarly to the previous case, applying reconfigurability should be examined.
- Concerning the fifth line, there are three options: (i) differentiating assembly flow for the last assembly module (after the LCS), (ii) doubling the last assembly module which is then dedicated to each product, or (iii) having a reconfigurable assembly module able to switch between two different assembly operations.
- The sixth line is identical, so no modifications have to be made for common assembly.
- Concerning the seventh line, there exist two options: differentiating the assembly flow for the first assembly module (before LCS), or integrating the first module to the common assembly flow (which is then only used for one product).
- Last, the eighth line is dedicated to product 3 only.

This information can be used now by the system designer to orient decision making concerning merging the assembly, partially or completely of the two products.

## 5 Discussion

This section aims at discussing the generalisability of the findings from the single case study, presenting some managerial implications, and providing some analysis of the results.

During the case study, the new method has been applied to three different industrial products of a partner company. These products belong all to a same product family, and the case study has demonstrated the applicability of the new method to a complex industrial case. However, the method itself has been developed with the aim to be generalisable in the limit of the domain of assembly engineering (it means it is not transferable to process industries for example). This generalisability in its domain is achieved on two levels: At first, the input of assembly information to generate the information vectors is per definition agnostic from the application. The approach does not distinguish between for example a pen assembly, a gear box assembly and a mechatronic actuator assembly. The flexibility is achieved by the complete liberty to add any information to the information vector which might be pertinent for the comparison. The coding with character chains enables an application to other product assemblies.

In the case of fixturing-driven comparison of assembly sequences it is of course necessary to define the compatible fixturing information as predominant element for the comparison. But if another orientation should be given to the comparison, one may perhaps be interested in an assembly operation driven analysis, even this criterion can be modified. In conclusion, the framework in Fig. 2 aims to be general, as well as the flowchart in Fig. 3 and the indicators presented in Sect. 3.2. If another predominant criterion is chosen instead of fixturing, then the term of fixturing has to be replaced by it in the two figures.

Concerning the managerial implications, the here presented method provides an objective analysis and aims therefore at giving a decision-making aid based on technical information as input. It is therefore more oriented to support assembly plan generation and assembly system design based on technical criteria. From an applicative viewpoint, the compatibility decision for fixtures needs human intervention because it is a complex task considering materials, geometry, accessibility, shape and other constraints. Before using the method, it should be clarified which aspects are the most pertinent for the comparison. This decision may vary from case study to case study but has to remain unchanged during a same case study.

Concerning the internal processes in a company, low indicator values and high disparity in the assembly plans can also be a starting point for an improvement process including the assembly plan design and which may reach the product design in order to achieve higher similarities and to facilitate the generation of common assembly plans. This is what happened to the partner company at the end of the study, as the results led to new reflections about the future assembly systems and assembly processes.

## 6 Conclusion and perspectives

Beside the generation of (reconfigurable) assembly plans, their comparison is of high importance for decision making concerning the structure of the assembly systems and the product mix to send on the assembly lines. A new fixturing-driven reasoning is introduced to face product variety and propose a fixturing-oriented view of assembly. Based on this fixturing-driven approach, a new comparison method is presented, using the theory of longest common subsequences (LCS) and shortest common super-sequences (SCS) analysis for sequence comparison. Assembly plan information is extracted and transformed into information vectors. Their comparison generates character sequences which are used as input to the LCS/SCS analysis. In addition to the direct LCS/SCS string comparison, three indicators are proposed. The developed method allows to compare assembly sequences by their belonging fixturing and points at commonalities as well as it indicates differences in terms of component fixturing and assembly operations. The entire approach has been worked through manually and its applicability has been verified throughout and industrial case study in the automotive industry. It has been shown how the LCS/SCS analysis, proposed only for manufacturing comparisons, can be used in assembly and how this approach can support the development of agile and reconfigurable multi-product assembly systems.

Based on the presented approach, two main perspectives for further developments exist: First, an implementation of the approach has not begun yet. The manual treatment of the information is heavy, time consuming and human errors can easily be made. Based on the presented process flow chart, a partial implementation of the methodology should be possible. Especially the information vectors, the comparison and LCS/SCS input sequence generation, and the LCS/SCS calculation are supposed to be implementable. An implementation would then enable the easy generation of the three indicators. To get an even quicker overview of the results, an aggregation of the indices which are initially calculated for each subsequence should be elaborated to provide information for the overall assembly sequence as well.

Second, the presented approach is oriented the evaluation of a set of input information to generate a set of possible solutions. Therefore, the solution quality depends on the quality of the input. It has to be assured that the assembly plan used as input is of a good quality. To do so, especially in the case of new product assemblies, an optimisation approach can be coupled in a preliminary step. Analogous, the solution set generated by the approach gives no recommendation which solution has to be chosen (for examples for choices between reconfigurable modules vs. dedicated doubled modules or between a common flow with idle modules vs. dedicated separated flow). It can be coupled to decision-making methods like analytic hierarchy process or simulation tools in order to give a decision support to the assembly system designer. In addition, when combining the technical information with economic information, especially estimated time and cost for each operation, the methodology may pave the way for a new approach for assembly process plan optimisation for multi-product assembly.

**Acknowledgements** The authors gratefully acknowledge the support from the members of the research chair entitled “reconfigurable, safe, and efficient production systems”, co-founded by Thyssenkrupp, the European Regional Development Fund “Programme opérationnel FEDER-FSE Lorraine et Massif des Vosges 2014–2020”, UIMM F2I and UIMM Lorraine.

**Data availability** As only real production data of the industrial partner company has been used, no data set can be provided due to confidentiality issues.

## Declarations

**Ethical approval** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. The research is not involving Human Participants and/or Animals.

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