Contribution to the design of reconfigurable multi-product assembly systems by architecture solutions generation through a new locating-driven approach

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A B S T R A C T

Production companies are today faced with increasing product varieties, shortened development times and product life cycles, and decreasing lot sizes. Reconfigurable manufacturing and assembly have been developed as new manufacturing paradigm to face this challenging market environment. However, the aspects of enabling multi-product assembly and operational reconfiguration are rarely addressed. This article presents a new approach, aiming at this research potential: the use of component locating in the center of a new assembly system design method around component locating modules. It is detailed how the use of component locating allows the generation of a system architectures solution space. To support the application of locating strategies, a new model, the precedence-locating graph, is introduced. The approach is described with an illustrative example and the new concept has been tested on an industrial case study in the automotive industry which can only be mentioned partially due to confidentiality issues.

Introduction

Today, production companies evolve in an environment which heads from mass production to mass customization, i.e. the development towards a hand craft production on industrial scale [1]. It means that product variety increases, which increases implicitly the number of different product references having different features and functionalities. At the same time, lot sizes decrease. This has an impact on the production system: systems dedicated to one product type without reusability at the end of their lifecycle become more inefficient as the break-even point between investment and return of investment is postponed due to decreasing lot sizes. In addition, a production system has to meet a set of requirements of different nature which is sometimes contradictory. The design of a production system is then in the center of this field of tension as shows Fig. 1, detailing the challenges mentioned.

In the following of this paper, a particular production system type, i.e. assembly systems, is addressed. Concerning assembly, one possibility to face product variety and changing demand is the design of adaptable multi-product assembly lines and their reconfiguration – ideally rapid and less costly. These issues should be addressed when designing the assembly systems, considering at the same time the aspects of product mix definition and analysis, assembly plan generation, and the elaboration and selection of technical solutions.

The related research question is: **How can multi-product assembly system architectures be defined taking into account a given product family and reconfiguration?**

In this research question, two scientific issues are addressed. The first one is the notion of *reconfiguration,* the second is the *identification of a common production system architecture* to produce several products on one system. Those two aspects represent the entrance point for the new methodology. In the following, the paper is structured as indicated in Fig. 2.

Reconfiguration is addressed in *Reconfiguration in literature*. It is a production paradigm allowing the production system to be adaptable for a product variety. A plenty of different literature on reconfiguration has emerged since its definition by Koren in 1999 [3]. This literature can be classified in two ways: either by the reconfiguration type which is considered, or the aspect they address. Concerning the question of the reconfiguration type, three categories are identified:

1) Reconfiguration through routing: reconfiguration is obtained by defining and scheduling different paths for the products through

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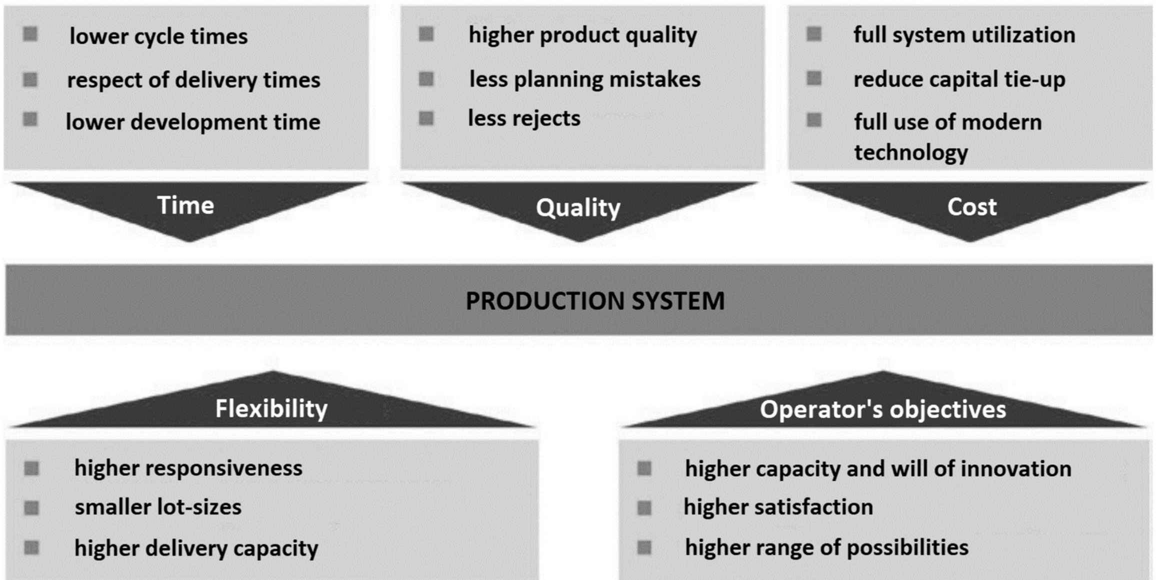


Fig. 1. Requirements on a production system.
Adapted from [2].

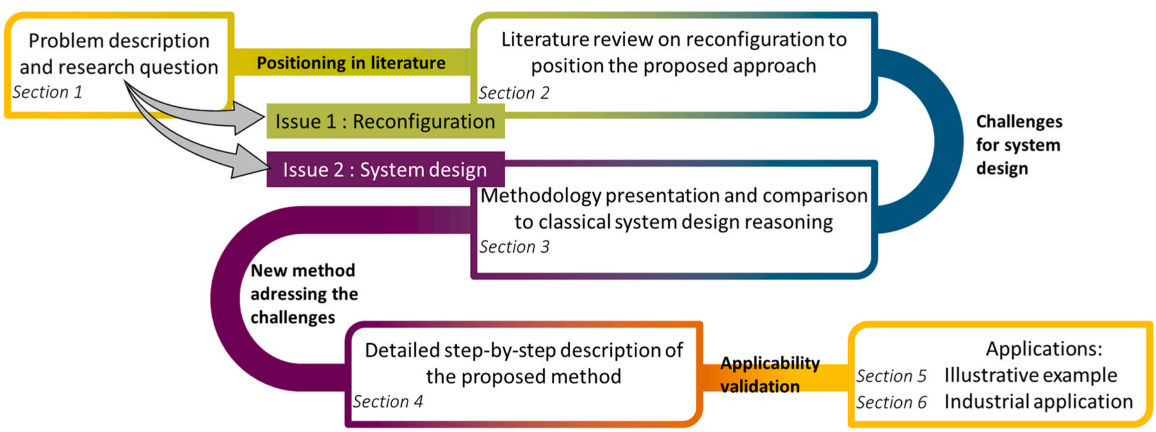


Fig. 2. Article structure and link between the sections.

the workshop which is organized in production cells depending on the operation sequences. The objective is to be able to realize different production plans with the same layout. The key driver enabling reconfiguration is the conveyor system which has to be able to cope with different products and schedules at the same time.

2) Reconfiguration through accessibility and operations: reconfiguration is achieved by the capacity of machines to perform different tasks for different product references. The objective is, as the previous one, to enable the production of different references with the same layout and machines. But the key driver in this case is not the conveyor system but the machine capacities (operations, orientation) and the possibility to change them during the production cycle.
3) End of (production-)cycle reconfiguration/ reconfiguration for reuse: reconfiguration is obtained by the reuse of the production system modules in order to shift from an initial configuration to a new one, in general at the end of the production cycle of one product to produce a new one. The objective is then to extend the lifespan of the system modules. It means implicitly increasing the profitability of these modules. The key driver of this reconfiguration type is the modularity, mobility, and connectivity of the system modules.

The reconfiguration types one and two are considered to be immediate, that means that reconfiguration is carried out without shutting down the production system. In contrast, the third aspect can only be realized during production stops. Therefore, the first two types are more agile in the technical sense of agility than the third type. Concerning the question of addressed reconfiguration aspects, the literature examined in the following section focuses on the two different types of production systems, i.e. reconfigurable assembly systems and manufacturing systems (the latter also includes machine tools). Other aspects as for example supply chain, optimization, or information system frameworks are not considered in this paper.

Then, out of the literature review on reconfiguration, challenges to the system design are identified linking to the second research issue addressed by the research question: *identification of a common production system architecture* to produce several products on one system. In the context of product variety, it is necessary to identify which modules of the production system are common to all products and which one are distinct (and therefore submitted to reconfiguration). It needs an analysis of products at the part level at early stages of the system design in order to identify commonality which can be used in the system. This new method is presented in *A*

Table 1
Reconfiguration addressed in literature.

Ref.	Application (synthesis)	Production type		Reconfiguration type		
		Manufacturing	*Assembly*	*Routing*	*Operation*	*Reuse*
[3]	Machining systems	X				X
[4,5]	Cylinder head machining, Manufacturing in general	X		X		X
[6]	Wheel speed sensors	X		X	X	
[7]	Cylinder head machining	X		X	X	X
[8,9]	Manufacturing in general	X		X		X
[10]	Cylinder head machining	X			X	X
[11–16]	Manufacturing in general, part machining, electronic products	X				X
[17]	Virtual assembly/manufacturing line	X	X			X
[18]	Refrigerator thermostat		X		X	X
[19–23]	Automated assembly cells, automobile assembly, assembly in general		X	X		X
[24–28]	Assembly in general, cycle bell assembly		X			X

new regard on the design of reconfigurable systems in comparison to a common approach.

New locating-based approach for assembly system architecture determination describes step by step the new approach as well as the tools and methods used in this approach. Its application is detailed in two sections. *Illustrative example of the new approach: ball pen assembly* gives an illustrative example based on a simple ball pen application and *Industrial application and perspectives for integration to decision making and optimization approaches* gives an excerpt of an industrial application in the automotive industry.

Reconfiguration in literature

Literature on reconfiguration has been examined concerning the three reconfiguration aspects introduced previously (multiple naming is possible as an article may address more than one aspect). The result is presented in Table 1. This literature review does not pretend to be exhaustive but gives a representative overview. Analyzing the distribution in Table 1, it becomes evident that research on manufacturing systems addresses all the three reconfiguration types, with a focus on *reconfiguration for re-use*. For assembly systems, to whom this research work is dedicated, analogous to manufacturing systems, most of the research is focused on the same reconfiguration type. Concerning assembly systems, it becomes visible that research potential concerns mainly *reconfiguration through accessibility and operation*.

Reconfiguration: manufacturing versus assembly

More in detail, as research on manufacturing systems cannot be translated to assembly systems due to their differences, the presented research is located in the assembly section and focuses afterwards on reconfigurable assembly, its characteristics and enablers. These differences between manufacturing and assembly are due to their divergent characteristics:

- A manufacturing system is outset to process parts beginning with a raw state (initial state) to get them with operation closer to the final state. On each station a set of operations is performed. In general, the product is transferred from one cell to the next one, and then positioned into these cells for processing. Manufacturing cells are nowadays flexible (tool changes, orientation changes, ...) which enables their adaptation for several product shapes. Therefore, the reconfiguration types concerned are mainly *routing* (including scheduling), as well as *end of cycle reconfiguration*.

Fig. 3 illustrates a reconfigurable manufacturing system. In this example, the first product visits a milling station and then the drilling station. And the second product visits the drilling station and a surface treatment station. It illustrates well the two main reconfiguration types: (i) to find a path for the two products and scheduling it, and (ii) to add or remove modules and/or machines at the end of the production cycle. The drilling machine has the capacity to manufacture both products.

- An assembly system works by adding components to the product. Thus, the product changes significantly shape, size and weight during the assembly process, all parameters being increased. Assembly in general is a challenging task as complex products are composed of numerous different subassemblies which all need different locating in the machines (i.e. different parts need to be positioned precisely and maintained during the assembly operations) and which may address a plenty of different operations. Therefore, all the three reconfiguration types are concerned: *routing* (including scheduling), *accessibility and operations*, as well as *end of cycle reconfiguration*.

Fig. 4 illustrates a reconfigurable assembly system (RAS) mentioning its key characteristics which have been identified in literature and which are summarized in Table 2 with their belonging references and a short description of the key concepts. A similar result concerning the key characteristics has been found by [30] who identify the first eight key characteristics regarding the literature review. These are all on the level of the assembly system regarding the assembly module. They concern, as illustrated in Fig. 4, technical solutions for the assembly modules and are oriented to the detailed system design answering questions of how to connect and disconnect modules, how to change the module purposes and how to reuse them.

When dealing with reconfigurable assembly, mainly two reconfiguration types are considered: *reconfiguration through routing* which can be addressed with flexible product flow and the *reconfiguration for reuse* (end of cycle) which is addressed by the other key characteristics. Thus, these types can effectively be matched by the characteristics mentioned in Table 2.

Several propositions exist in literature to make a system reconfigurable. A set of these enablers, concerning reconfigurable assembly systems (RAS), has been identified by [8]. They propose an exhaustive description of enabling technologies synthesized in Table 3. For each technology a short description is given and it is indicated to which reconfiguration type they refer.

Regarding the enablers list in Table 3, the five enablers oriented to *reconfiguration through operation/accessibility* are in interaction with this research. The following statements can be done:

- Design for assembly: this enabler is situated on the product design level. A method to improve assembly similarity of different products has been introduced in [36].

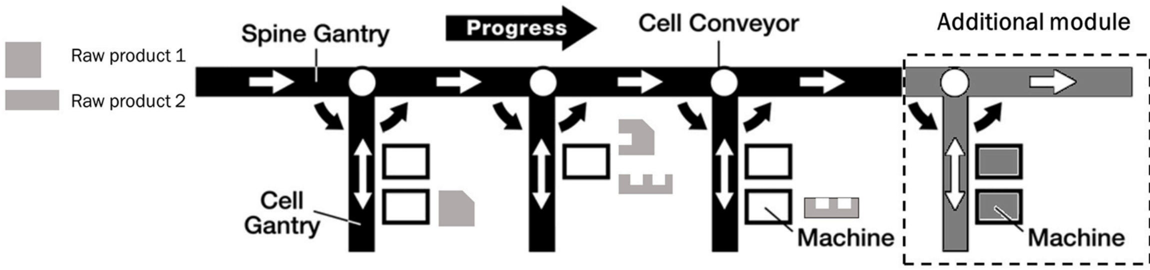


Fig. 3. Illustration of a reconfigurable manufacturing system with two products. Adapted from [5].

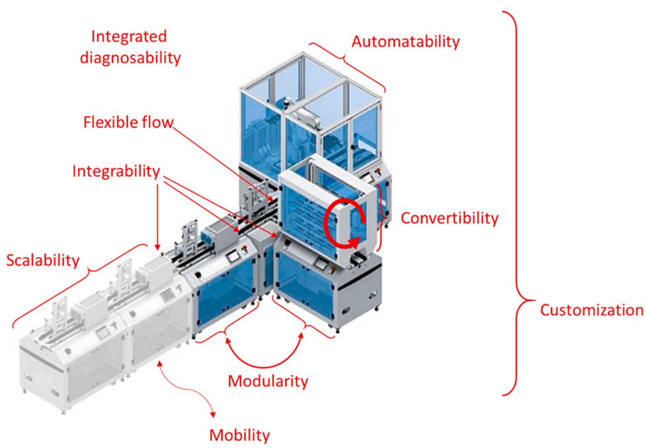


Fig. 4. Illustration of RAS enablers (illustration modified from [29]).

- Human being in assembly and robots for reconfigurable assembly: these two enablers are on the level of the detailed system design. This is the step after the system architecture determination, deciding which technical solution (robotized assembly, manual assembly, automated conveyors, manual part handling,.) is applied to the system modules.
- Flexible fixturing and fixtureless assembly processes: The aspects of fixturing**, in particular component locating**, are one key element for the determination of reconfigurable assembly system architectures. The question addressed by this research work **is which components** are to be located **when** and **how** during the assembly process. This question is an essential strategic issue for the design of multi product assembly systems.

Research gap, addressed reconfiguration aspect and enablers

However, one important aspect of reconfigurable assembly is missing in this picture: the product. Because assembly is strongly linked to product design. This implies the need of *operation and accessibility reconfiguration* for the assembly of multiple products with the same assembly equipment. As result, a research gap has been identified throughout this literature review concerning reconfigurable assembly systems with *operational reconfiguration*, that means reconfigurable multi-product assembly systems for product variety assembly. A product variety may differ in many points. For assembly, the important aspects are:

- Product design – component types (mechanical, electric, electronic), number and their connections (depending implicitly on the product functions).
- Product assembly – the operations performed and their orientation referring to the product coordinate system.

As mentioned in the introduction, the according research question is "**How can multi-product assembly system architectures be defined taking into account a given product family and reconfiguration?**". To answer this question, a new approach focusing on component locating has been developed. The focus of this paper is therefore put on the last point of the concerned enablers: Flexible locating and intelligent locating (intelligent in the sense of choosing intelligently the most adapted components to be located during the assembly process) are identified as key enablers for generation of architectures for reconfigurable multi-product assembly systems. The next section compares a common approach and details the advantages of a locating oriented method.

A new regard on the design of reconfigurable systems

The classical view on changeability, containing reconfiguration as part of it, is illustrated in Fig. 5. This view is strictly hierarchical. A changeability class is assigned to each product-production level, following the theory of systems engineering that each system can be composed into sub-systems [34,37].

This system design approach starts on the product side and, through the determination of reconfigurable process plans (RPP), determines the elements in the factories of the production network, as indicated by the arc. It goes top-down for the product and bottom-up for production. This way of reasoning is determined by operations: for each product, part elements are analyzed, the needed operations are identified (stations on the production level), and all is assembled to operation modules (cells) whose sequences form the

Table 2
Synthesis of RAS key characteristics.

Key characteristics	Concept	Ref.
Convertibility	Ability to convert system elements to adapt their use	[5,16,25,31–33]
Scalability	Ability to easily change size/capacity of the system	[5,16,25,31–33]
Customization	Ability to easily adapt the system to specific user needs	[5,16,25,31,32]
Modularity	System being composed of (inter)changeable modules	[16,25,31]–[33]
Diagnosability	Self-diagnostics provided	[5,16,25,31,32]
Integrability	Easy integration of new elements: "Plug-and-play" and standard interfaces	[5,16,25,31,32]
Mobility	Ability to easily move system elements	[33]–[35]
Automatability	Ability to switch between automatized and manual task realization	[33–35]
Flexible flow / Modular conveyor system	Ability to change material flow instantly	[5,21]

Table 3
Enabling technologies for reconfigurable assembly and addressed reconfiguration types.

Enabling technology	Example	Reconfiguration types		
		Operation/accessibility	*End of cycle/reuse*	*Routing*
Design for assembly	Adapt product design to minimize changes in the production system	X		
System modularization	Allow easy layout reconfiguration thanks to module change		X	
Robots for RAS	Use the adaptability of robots for adaptation	X	X	
Fixtureless assembly processes	Eliminate product dedicated fixtures to facilitate change of product references	X		
Material-handling system	Allow to change easily the production flow in function of production needs			X
Flexible fixturing	Adapt one fixture easily to different products	X		
Auxiliary machines for reconfiguration	Facilitate reconfiguration with machines which intervene during the reconfiguration process		X	
System configuration design	Foresee the system configurations during system design		X	
System control	Allows the control system to follow changes in the system structure (plug-and-play)		X	
Human being in assembly	Use the adaptability and flexibility of human operators	X		

system. It fits perfectly to the *reconfiguration for re-use,* because when changing products at the end of a cycle, the need of changing stations or cells in the system can be analyzed. But it gives no answer to the question of how to enable the assembly of multi-products, where the reconfiguration is required, and which components are used for locating. Therefore, the classical approach lacks to answer the identified research question and research gap.

In this gap, the contribution of the newly developed approach is situated. Its key element is the strategic locating of components. We define in this paper *locating* as action which *aims to remove degrees of freedom of a part in order to locate it in the three-dimensional space and in relation to other parts and to assure a needed orientation towards the assembly or manufacturing operation tool.*

In this context, the objective of *strategic locating* is to determine which combination of components selected for locating enables the assembly of multiple products on the same production line. At the same time, it can be identified where reconfiguration is needed in this line.

An overview of this new approach is illustrated in Fig. 6. It is based on the analysis of products and their assembly processes. Out of it, components for common locating are identified and processes are defined for each common component locating. This information is used on one side to determine the overall system architecture (sequence of components for locating) and on the other side to determine in global the operations needed to be performed, then operations for each locating and reconfiguration needs.

Therefore, locating is the key for generating assembly system architecture solutions which are adapted to multi-product-assembly. It allows to address three objectives:

i. Ensure the compatibility between multiple products.
ii. Define the macro system architecture solutions driven by locating.
iii. Generate preliminary assembly plans by allocation of assembly operations to the system modules.

These three objectives are illustrated by Fig. 7, linking them to the main items of the new approach. The products representing the product family used in the industrial application.

The first point (compatibility) addresses system design difficulties due to the fact that different products may have different sizes and shapes. Also, assembly operations may be performed on different areas of the products which means that for each product the coordinates of a same assembly operation can differ. The multi-product assembly system has to cope with this. The question for the system designer should be: which components of a product mix allow the definition of a generic locating limiting changes in the production system? This question concerns all types of assembly

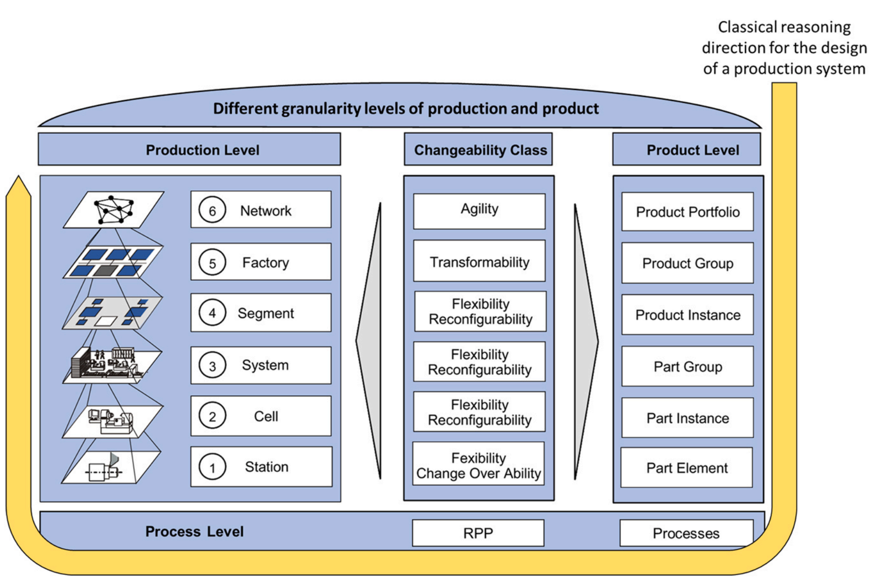


Fig. 5. Classical view on changeable systems and reconfiguration.
Adapted from [37].

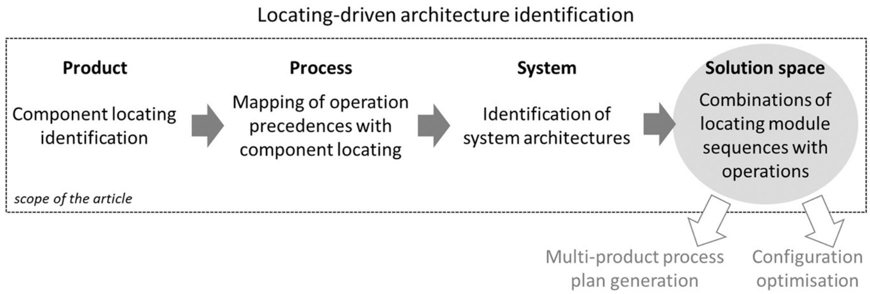


Fig. 6. Framework of the new approach for locating-oriented generation of system architectures and scope of the article.

systems, from linear rigid systems to highly flexible ones using for example collaborating mobile robot units (for transfer and assembly operations) as proposed by [38]. The key is to determine the components used for locating with the aim that the locating is valid to assemble the entire product mix. We call then the sequence of different components used for locating for one single product a *locating sequence* for this product.

Afterwards, on the product family level, the compatible locating sequences have to be identified across all products. Then, the second point (system architecture) is addressed: the macro assembly system architectures are in a first time defined by the identified compatible components for locating. Their sequence determines the generic modules of the system. These modules, representing the different components used for locating in the sequence, are here called the *locating modules*. Depending on the product complexity, a solution space which contains several different combinations of used components for locating and their order can be generated. This solution space is therefore containing different valid macro architecture solutions.

The third point (grouping operations) is addressed at last. Operations can be gathered to their corresponding locating module. It ensures that the operations are compatible for the product mix and enables the application of different strategies. For example, to gather the operations by minimizing at the same time operation changes or orientation changes.

The following section details the tools and models used to achieve the three objectives.

New locating-based approach for assembly system architecture determination

This section presents the different steps which are applied to go from product and process information to the architecture of multi-product assembly systems. Fig. 8 details these steps and illustrates

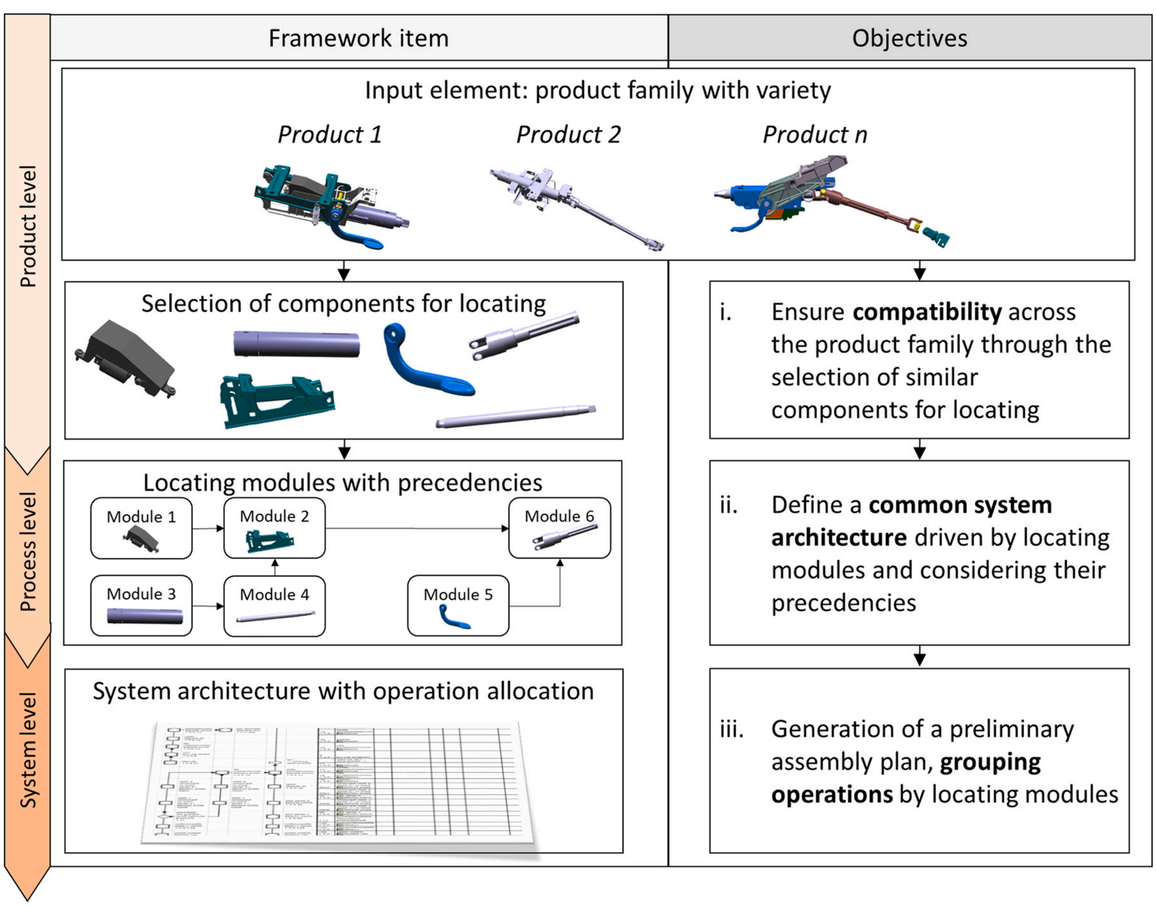


Fig. 7. Framework items and their objectives (the product references are reflecting the products used during industrial case study).

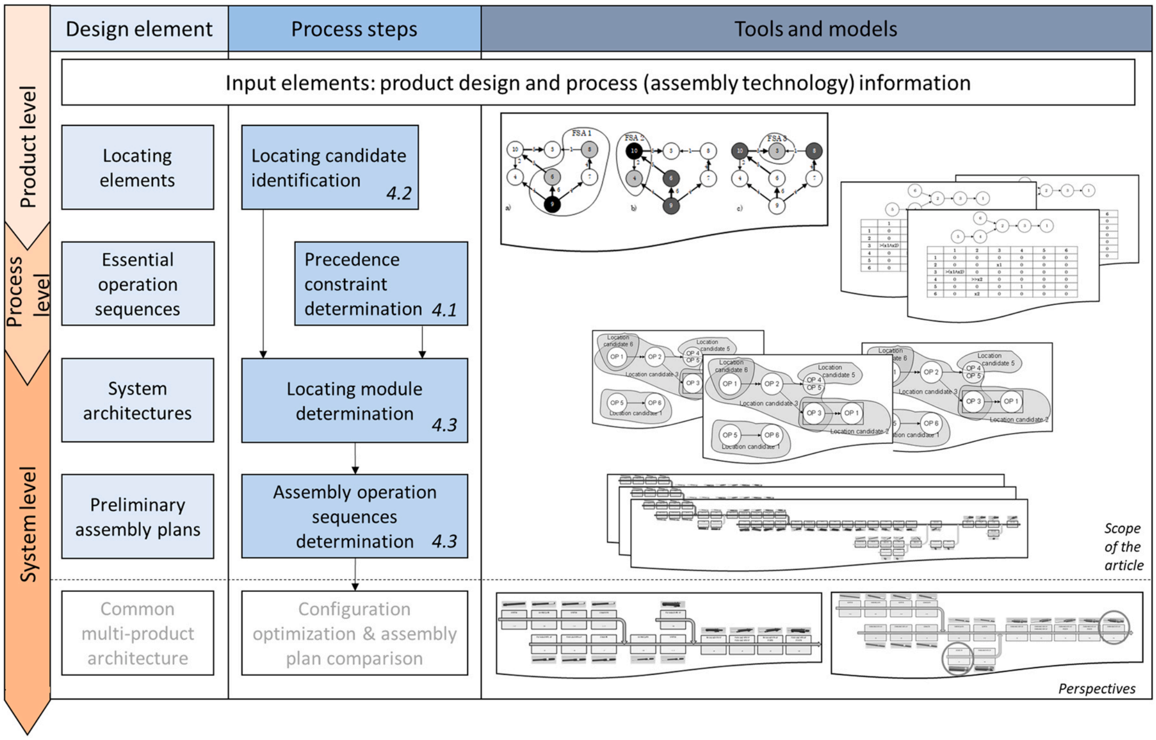


Fig. 8. Overview of the locating-oriented system architecture design approach and scope of this article.

the structure of this section. The belonging sub-section is indicated for each process step.

As illustrated in this figure, the input element is information related to product design, i.e. the components and their mechanical links, and information related to the assembly processes. The latter addresses the assembly technologies used for the mechanical links and their specific parameters. This analysis can be applied to already industrialized products or to newly developed ones. In the first case, completely defined assembly information can be used. In the second case, the analysis can be done based on the predefined product (preliminary product design).

Precedence constraint determination

By using product design and assembly information, precedence constraints between assembly operations are determined. Two different groups of precedent constraints can be distinguished:

i. First, discriminant precedence constraints are defined: i.e. precedence constraints which are necessary to assure the feasibility of an assembly. These are for example accessibility constraints or the interdiction of certain operation sequences.
ii. Second, supplementary precedence constraints can be added:

these are not essential, as for example constraints linked to weight or dimension variations, material constraints and strategic constraints of the company.

In general, it is recommended to determine as less precedence constraints as possible. This avoids that the solution space is unnecessarily reduced. Several different methods to express precedence constraints exist, from logical expressions to graphical representations. At this stage no recommendation is given which approach to use. For the next step of the approach it is only important to distinguish between normal precedencies (operation 1 must be performed somewhere before operation 2) and immediate precedencies (operation 1 must be realized immediately before operation 2). Immediate precedencies mean in this case that two operations cannot be dissociated.

Identification of components which are suited for locating

After the precedence constraint identification, the next step towards the generation of assembly system architecture solutions is the identification of components which can be used to locate product (sub)assemblies. These components for locating are here defined as "*components of the product or one of its subassemblies which can be a base part for other assemblies. That means a component for locating is situated at the beginning or the end of a sequence of valid mechanical links.*" In the following, we call the components for locating "locating candidates" as they represent different possibilities to realize assembly locating.

The related industrial problem is: how to define assembly sequences and how to design a multi-product assembly line for product varieties? In this context, the identification of locating candidates is a key element for the assembly sequence generation as they are the enabler (and discriminant element) for multi-product assembly.

The components for locating can be identified out of the product model when using a component-based representation as for example Datum Flow Chains [39,40] or any similar ordered graph, e.g. [41,42]. The hypothesis is that a locating component has to be situated either in the beginning or at the end of an ordered sequence of mechanical links. This means that the components which are supposed to be in the beginning or at the end of this sequence are supposed to be candidate for positioning their belonging assembly during the assembly process. In the case of the industrial subassembly illustrated in Fig. 9, the body is starting point of a positioning logic (blue dotted arrows) as it locates the two components which are assembled with screws as well as the screws themselves. According to the presented reasoning, for this subassembly, either the body can be used as component for locating or the lock or the command module. The red arrows indicate the assembly direction if

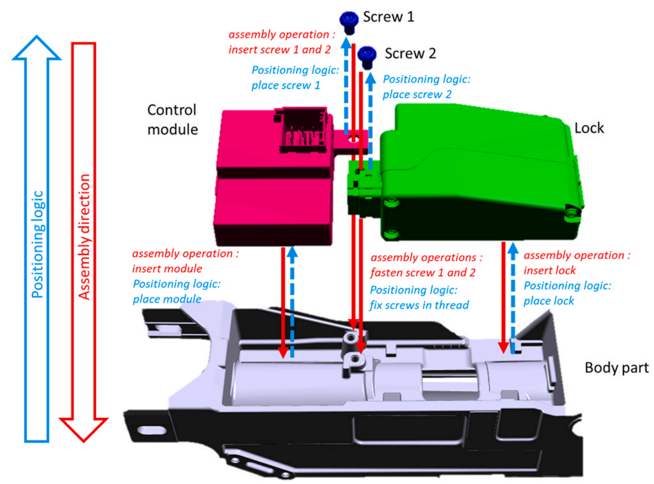


Fig. 9. Positioning logic and assembly operations in one of the industrial subassemblies.

the body part is chosen to be used for the locating of the subassembly. If the lock or the command module had been chosen as component for locating, the assembly direction would be inverse.

The locating must be supported by available surfaces of the identified components. These are the surfaces which will not be used during the product assembly process. Furthermore, the locating candidate must fulfill three criteria to assure that its according subassembly is feasible:

1) The accessibility and orientation criterion: it defines if the assembly is possible. This is not the case if the locating blocks the tool and component trajectories.
2) The degree of freedom criterion: it defines whether an assembly operation achieves a stable subset or not. If a connection achieves too few degrees of freedom the connection realized is not stable and therefore is not feasible. Parts could fall apart during transfer or assembly operations.
3) The force criterion: it indicates whether the locating is in accordance with the necessary efforts to achieve the connection (e.g. press fitting) or not. If the completion of an assembly step requires a force but there are degrees of freedom left between the components in question, the assembly operation cannot be performed.

Based on these criteria, all locating candidates are determined for a product assembly. For each of them, the feasible mechanical links, used assembly operations (e.g. press fitting, adhesive bonding, etc.), and their orientation in the product coordinate frame have to be gathered. Of course, not all accessible parts can be locating candidates: their flexibility, robustness or even their size can be a constraint which prohibit their use as locating candidate. Also, assemblies may have surfaces with quality constraints (e.g. surfaces visible to the customer) which needs to be protected and which should therefore not be used for locating. The method presented for the identification of locating candidates aims at identifying a maximum of theoretically possible candidates based on a product representation. However, an expert has still to validate the final choice of locating candidates for the further steps of the approach.

Locating module determination with the precedence-locating graph (PLG): its generation, solution space description, and possible exploration

This step relies on a new assembly model, **the precedence-locating graph** (PLG) which is the core element of the new approach. The novelty of the PLG compared to classical precedence graphs is that it combines information of precedence constraints with available locating candidates. It displays all assembly operations, all their precedencies, and the belonging locating candidates which can be used to realize the operations. Compared to classical component-based product representations as for example Datum Flow Chains or classical precedence graphs (e.g. [43–45]), it represents a shift of the point of view: In component-based models, the nodes of the graph are the product components and the arcs represent mechanical links. This representation is very useful for product design analysis [36] but less adapted for assembly-system-oriented analysis. At the same time, precedence graphs, as oriented graphs, only display obligatory sequences. These can be either between parts or operations. But also here, no link between component and operation is done. This gap is closed by the modeling viewpoint in the PLG using – as new feature – locating candidate information. It is the core element of the new approach for assembly system architecture generation driven by locating candidates as it (i) supports the combination of information concerning at the same time assembly operations, their precedences, and locating and (ii) enables the application of strategies for the assembly system design.

The PLG is the key element for the generation of assembly system architecture solutions. The detail level goes form a macro view of locating modules and their sequences to a micro view of operation sequences in the locating modules as illustrated in Fig. 10. In the PLG of a product (i.e. a mechanical assembly), all possibilities to allocate operations to locating candidates are synthesized in a single representation. It represents therefore a solution space. Different alternative system architectures can now be determined in two steps:

1. First on the macro level by determining the locating modules (i.e. choosing a final allocation of operations to locating candidates when different options exist). A locating module is considered to be the final allocation of operations to locating candidates. It is here defined as "*the combination of locating candidates with at least one operation. All operations which are allocated to the same location module are supposed to be realized using the same locating candidate. In a locating oriented assembly system, locating modules may also represent its assembly modules.*" Beside the special case of parallel operations with multiple locating candidates, an operation is allocated to only one locating candidate.
2. And second on the micro level by sequencing locating modules and operations. For this step, precedence constraints are transposed to the locating modules. They give an obligatory sequence of locating modules and operations in those locating modules. The final sequencing can then be determined by applying additional criteria (see *Industrial application and perspectives for integration to decision making and optimization approaches*, Table 6).

The main steps to generate the PLG are pictured in Fig. 11. The input is information on precedence constraints (*Precedence constraint determination*) and locating candidates (*Identification of components which are suited for locating*). If a multitude of locating candidates has been identified, a preselection may be done in addition to the expert selection which eliminates unsuited candidates. Afterwards, the graph is built by generating at first its nodes representing the assembly operations belonging to the mechanical links of the product. Then, the immediate precedencies are added if required. Next, all other precedencies are defined. Last, the locating candidates are allocated to the assembly operations.

Fig. 12 illustrates the new precedence-locating graph (PLG). This graph represents a real product of our industrial partner company, but due to confidentiality, the operation names have been replaced by numbers. Each of its nodes represents either a single operation or a parallel operation (two or more operations are carried out at the same time). The arcs display two different kinds of precedence

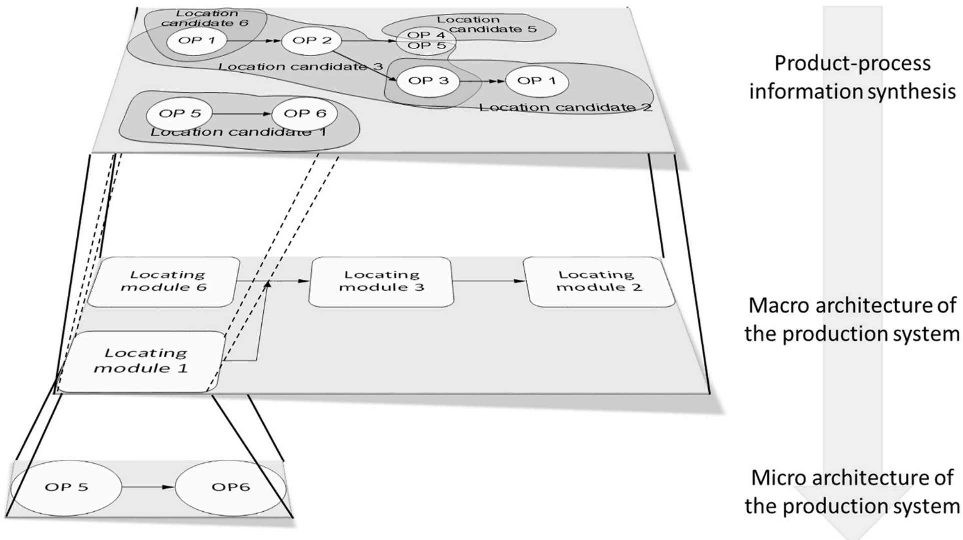


Fig. 10. From the PLG to the micro architecture of the production system.

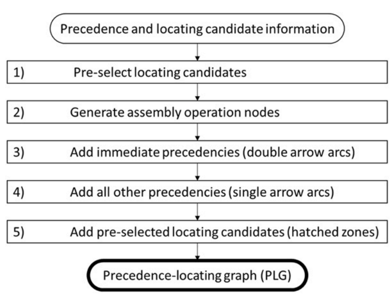


Fig. 11. PLG generation sequence.

information: standard precedencies (arcs with single arrow) and immediate precedencies (arcs with double arrow). If there is no arc, no precedence constraint exists between the operations. Therefore, operations which are independent in terms of precedencies are represented by non-connected graphs: in Fig. 12, these are operation 14 using locating candidate 2 and the operations using locating candidate 3. Thus, one product assembly can be represented by several unconnected graphs if its subassemblies are not linked by precedence constraints. All available locating candidates are represented by zones covering the nodes of the PLG (gray hatched zones in Fig. 12). Each zone stands for one locating candidate.

A special case occurs, when a node includes two or more parallel operations and has different locating candidates (as illustrated in Fig. 12: operation 4 with locating candidate 1 and 2). In this case, two actions are available: either one of the locating candidate can be used for all operations if the assembly allows it, or the two operations have to be carried out using both locating candidates at the same time as they are parallel operations.

By determining the locating modules (i.e. the final allocation of an operation to a locating candidate), the macro architecture of the assembly system organized around locating modules is determined. As mentioned, the PLG synthesizes all possible combinations of operation-locating candidate allocations, locating module sequences and operation sequences. Two different possibilities then exist for the generation of system architecture solutions: either the exploration of the entire solution space which means that all possible combinations are explored and all possible different preliminary

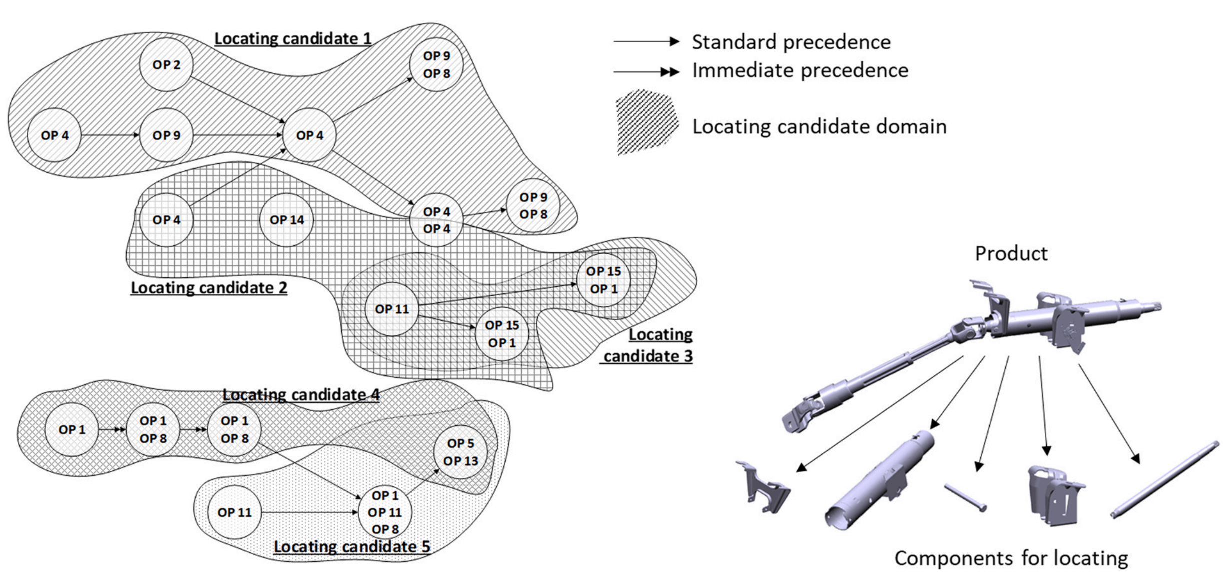


Fig. 12. Schematic illustration of the precedence-locating graph with its product and the five identified locating candidates (lower right corner).

Table 4
Locating module strategies characteristics.

Characteristics	Locating strategy (1)	Locating strategy (2)
Operation	Flexible directions	One-directional
Locating	Flexible directions	Static
Transfer	Low	High
Expected module cycle-time	High	Low
System layout	Cellular	Linear

assembly plans are generated. Or generation strategies are applied to restrain the solution space which can become very complex due to combinatorial possibilities. The application of strategies to orient the solution generation into a predefined direction is possible. Two opposite strategies have been identified and are described in the following:

(1) The maximization of operations which are realized with a minimum number of locating candidate, i.e. a minimum of reconfigurable modules (high operation commonality, mutual use and low module number).
(2) The decomposition of the assembly system according to different locating candidates in separate modules with high throughput (low operation mutuality and high module number).

These philosophies correspond to the choice between flexible and modular systems versus high performance specific and dedicated systems. Table 4 synthesizes the expected characteristics of an assembly system depending on the chosen locating strategy.

In strategy (1), a module gathers more operations, and the operations or locating candidates are mobile (movement flexibility) in order to realize all operations on the same locating candidate. Strategy (2) has more and different modules with static locations and gathers less operations which allows the adaptation of the modules to the operations and requires only less kinematic flexibility.

Illustrative example of the new approach: ball pen assembly

To illustrate the application of the new approach and the use and benefits of the PLG, this section presents an illustrative example based on a ball pen assembly presented in [46]. The components of the ball pen and its according assembly operations in are illustrated in Fig. 13.

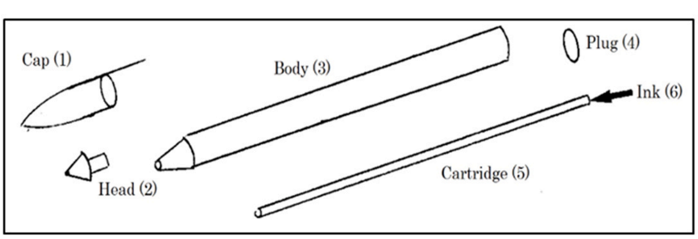
The PLG generation sequence illustrated in Fig. 11, has been applied to this example. It is illustrated from beginning to the end in Fig. 14. The numbers in Fig. 14 refer to the steps of the PLG generation sequence.

The first step in the PLG generation is the pre-selection of locating candidates. To illustrate this step, a simple product representation as oriented graph has been generated. For the ball pen example, there are several possibilities as it is a quite simple assembly. According to the selection criteria described in *Identification of components which are suited for locating* one may choose components in the beginning of an assembly sequence: those would be the body (3) and the cartridge (5). Or the components at the end of an assembly sequence can be selected, i.e. cap, plug, head and ink. In this case, ink has to be removed from the list because as a liquid it is not suited for locating. One may also choose a mix of those two possibilities. In the further example, the components 1,2 and 5 have been selected, because they allow to illustrate best the application of different locating strategies in the PLG.

Based on the generic PLG shown at the bottom of Fig. 14, locating strategies can be applied to the ball pen assembly. To remind, strategy one aims at minimizing the number of different locatings and at maximizing the number of operations by locating module. Strategy (2), in opposite, aims at distinguishing at maximum the locating modules with less operations per module. To conduct strategy (1), the following transformation rule is applied: the area of locating candidates should be extended following the precedence sequences, i.e. up to the operation at the end of a sequence of directed arcs. Then, analyzing the possible combination of locating candidates with operations, their final allocation is done. The modified graph which shows the accumulation of locating candidates according to strategy (1) is illustrated in Fig. 15 a). Locating candidate 5 has been discarded as it could not be extended due to accessibility issues. One should note that the operation "press fit cartridge" has got a more restrictive precedence constraint to enable unique location with component 2 (it has been integrated into the precedence sequence).

For strategy (2), the information of precedence sequences and overlapping or separated locating candidate areas is used as follows: whenever possible, different locating candidates are selected and it is preferred to change locating candidates when possible. This strategy aims at avoiding accumulations or the reuse of locating candidates. It uses the following transformation rule: the area of locating candidates is cut as much as possible. This means that the change of locating candidates should be done when possible, under condition that already locating candidates are not selected again. It is represented in the PLG by splitting the zones of locating candidates. No overlap of locating candidate areas exists at the end of the transformation. Last, the final allocation of operations to locating candidates is done.

This locating candidate selection method allows to identify operation sequences with the most appropriate locating candidate and eases the identification of differentiation points in the assembly sequence. In contrast to strategy (1), two possible solutions exist for strategy (2), illustrated in Fig. 15 b) and c). Either the operation "press fit cartridge" is realized with locating candidate 3 or with locating candidate 5. The next section shows how to determine the operation precedencies in this case. It can be seen that all locating candidates are distinct for a set of operations: no candidate is used more than one time and no accumulation is done. With help of the different PLG, possible architecture solutions can be deduced. The



N°	Assembly operation description
i	Fill ink into cartridge
ii	Control filling
iii	Clean cartridge
iv	Press fit cartridge into head
v	Clean head
vi	Screw head with cartridge on body
vii	Press fit plug on body
viii	Seam plug
ix	Clip cap on body

Fig. 13. Ball pen assembly: components and assembly operations.

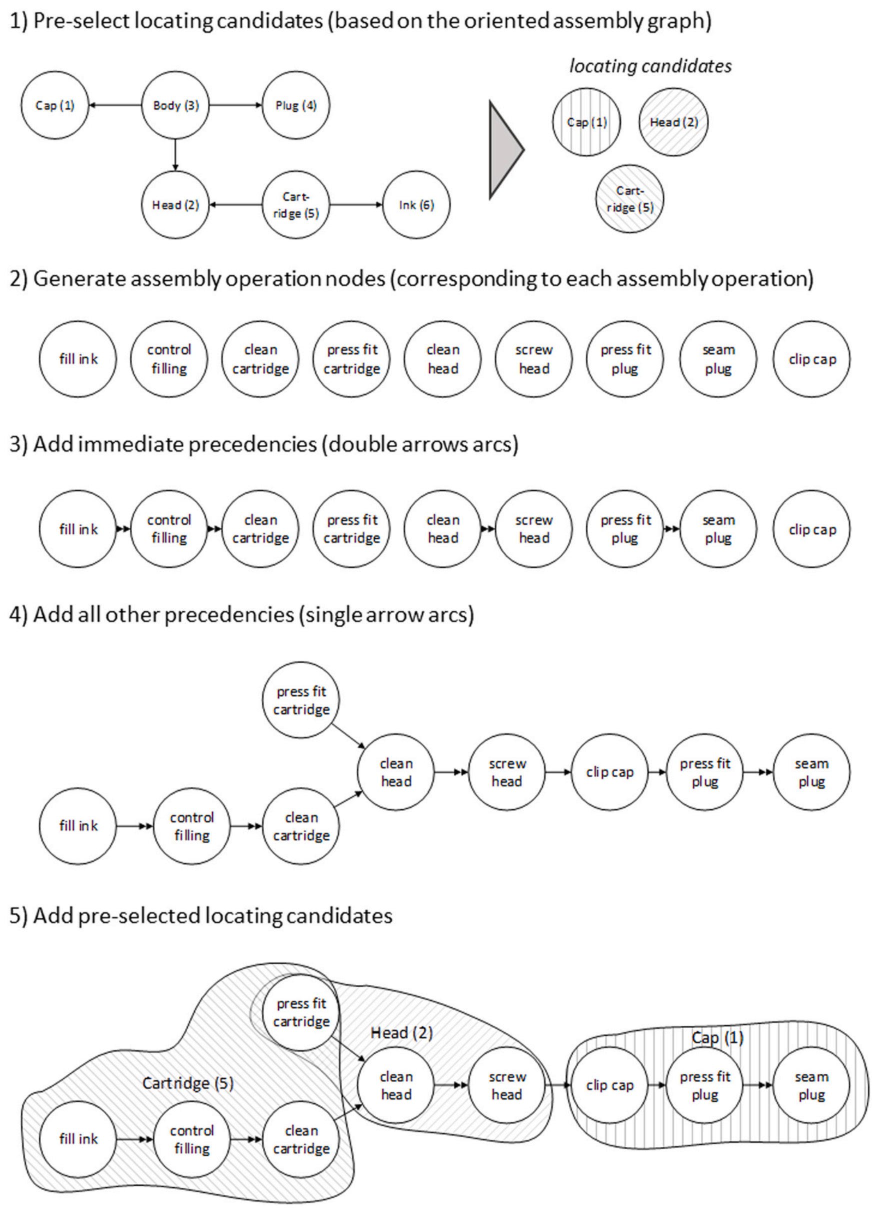


Fig. 14. Illustration of the PLG generation for a ball pen.

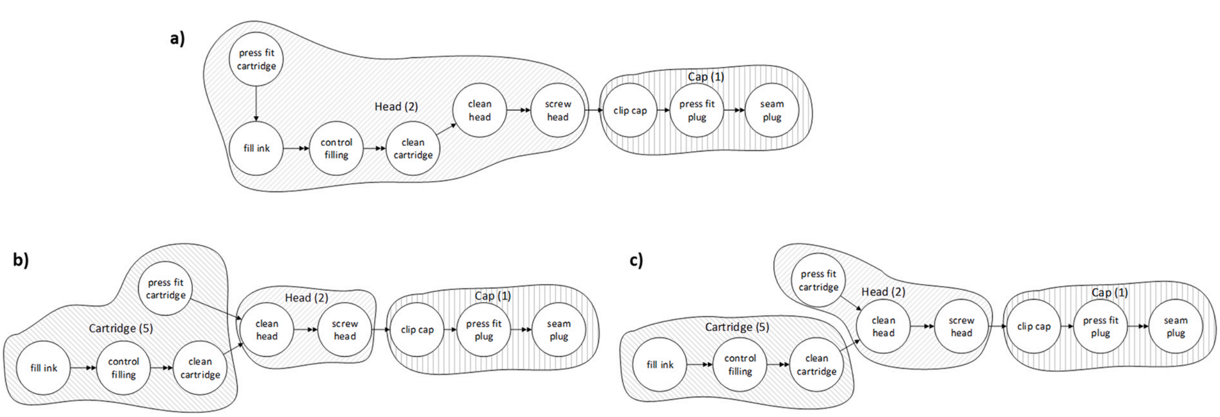


Fig. 15. Ball pen example – locating strategies.

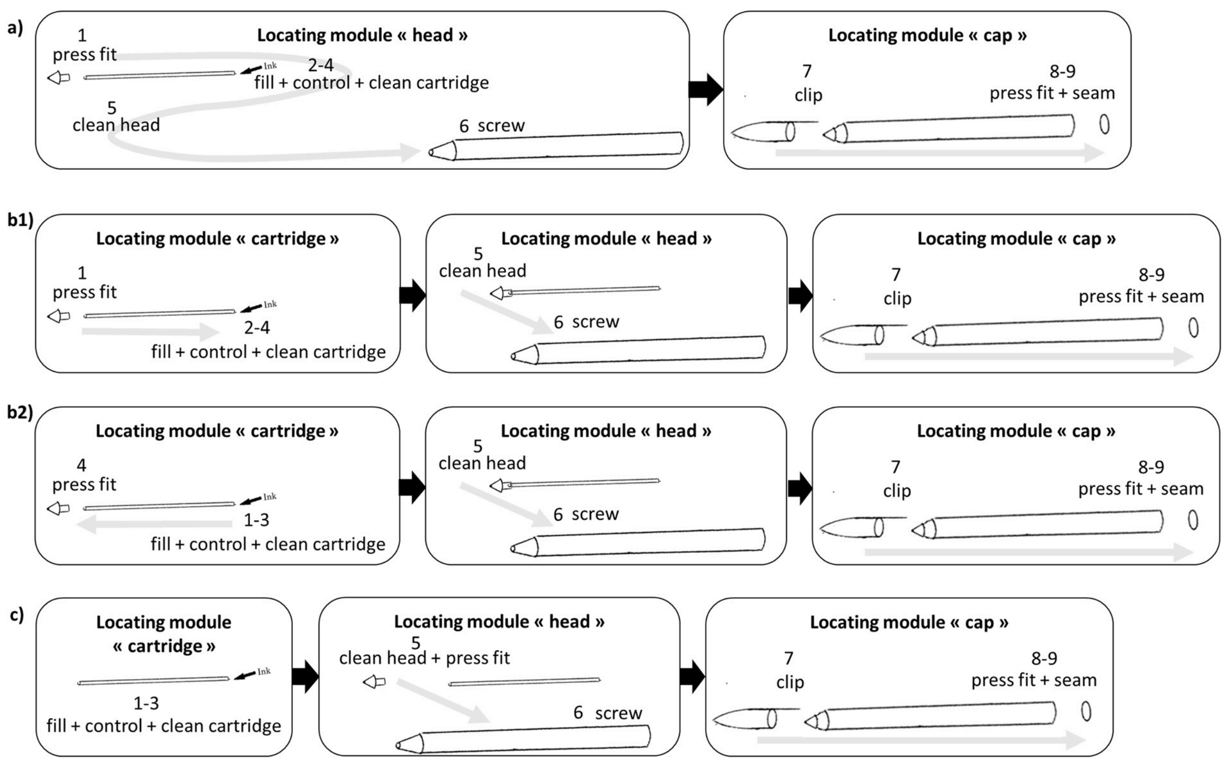


Fig. 16. System architecture solutions for ball pen assembly.

hypothesis, as described previously, is that a locating candidate with its allocated assembly operations forms a so called locating module which corresponds to a module of the production system. It can be seen that the macro architecture of the assembly system using strategy (2) contains three different locating modules (a first module using cartridge for locating, another module using the head and a third module using the cap). This is one module more than with strategy (1). It uses the head and the cap in two modules. By allocating the assembly operations to the locating modules, the micro architecture can be deduced. For the simple ball pen assembly, all different architecture solutions based on the PLG use are illustrated in Fig. 16. The letters refer to the according PLG in Fig. 15. For the PLG b), two different architectures exist because the operation “press fit” in the locating module “cartridge” can be carried out before or after filling the ink. In this case, the final allocation conducts to two possible solutions.

To conclude, the ball pen example showed how to generate and use the PLG for the generation of a solution space for assembly system architecture solutions. For a simple assembly of five components and nine assembly operations, three different architecture solutions could be identified using the new component locating centered approach. For a multi-product assembly, the architecture solutions of different products have to be compared by identifying compatible locating modules.

Industrial application and perspectives for integration to decision making and optimization approaches

The overall approach has been carried out in an industrial case study on three products in the context of an analysis for a common multi-product assembly system. The partner company is a supplier in the automotive sector. Due to confidentiality issues, the intermediate steps and results of the case study cannot be shown in detail. The complexity of the industrial problem (products with 17–54 components) underlines the need to apply decision making logics and/or optimization approaches. This problem is addressed in *Towards an integration to optimization approaches: additional decision making criteria.*

Example for an industrial PLG application and a possible assembly system architecture defined by manual exploration

For the industrial case shown briefly in this section, the PLG shown in Fig. 12 is used as starting point. The product is the simplest mechanical product out of the three products examined. It has 17 different components and needs 28 assembly operations for final assembly of all components. During the case study, it has been decided to apply the second locating strategy (decomposition of the assembly system according to different locating candidates) to reduce the solution space. The adapted PLG is pictured in Fig. 17.

This locating candidate selection method allows to visualize operation sequences with an appropriate locating candidate and eases the differentiation point identification. Fig. 17 shows the differentiation. The obtained operations list with differentiated locating candidates, the so called locating modules, are also illustrated in this figure. It can be seen that all locating candidates are distinct for a set of operations. No candidate is used more than one time and no accumulation is done. By manually sequencing the operations for each locating module, one architecture solution has been generated. This solution is shown in at the bottom of Fig. 17. It illustrates an operation sequence for a locating module sequence (same hatches as in the PLG) determined with the application of the PLG and strategy (2). When combined with information about operation parameters and operation orientation (which has been removed for confidentiality reasons), this illustration can be extended to a preliminary assembly plan with the locating module sequence as macro architecture of the assembly system and the operation sequence by locating module as its architecture on the micro level. The aim of the industrial application is to validate the PLG based approach on several complex industrial assemblies. Through the application on three different industrial products out of different product families,

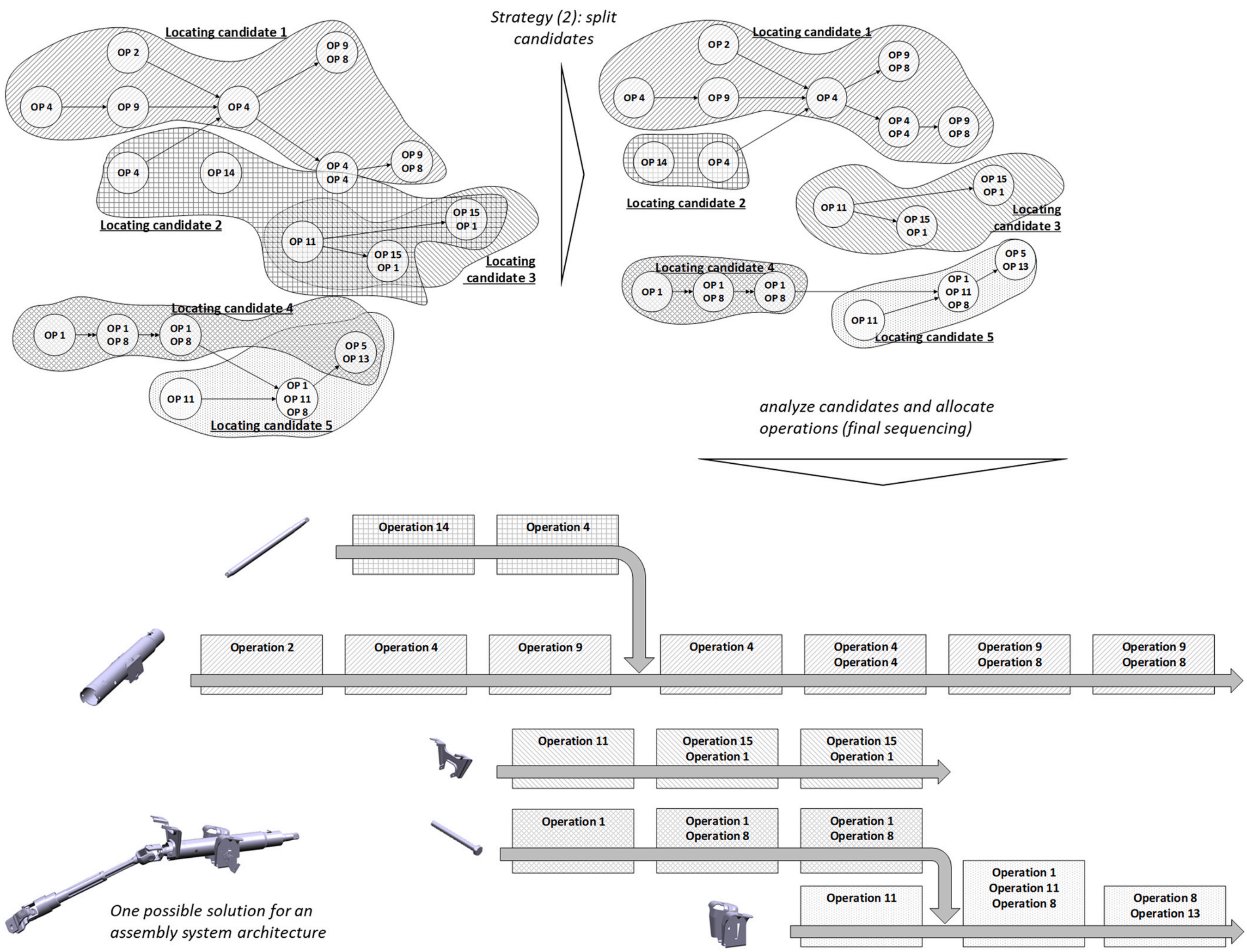


Fig. 17. Application of strategy (2) for the determination of a locating module sequence.

it has been proven that the PLG is adapted for a use on assemblies of industrial scale.

Towards an integration to optimization approaches: additional decision making criteria

Throughout the industrial case study, the application of the new approach to complex mechanical assemblies has revealed that a manual exploration of the solution space (i.e. the generation of all possible assembly system architecture solutions) is by far too time consuming. Examining the case of a complex product with 34 components and 47 assembly operations has conducted to an estimation that around $2{,}73 \times 10^{14}$ assembly system architecture solutions exists.[2] This section aims therefore at proposing decision making criteria which can be used to reduce the solution space and at building a bridge to decision making and optimization approaches. Displaying the assembly architecture generation process in detail, decisions to reduce the solution space can be taken at two points as illustrated in Fig. 18.

The first application point for strategies is the determination of locating modules by final allocation of operations to locating candidates. And the second application point is the selection of assembly operation sequences for each locating module.

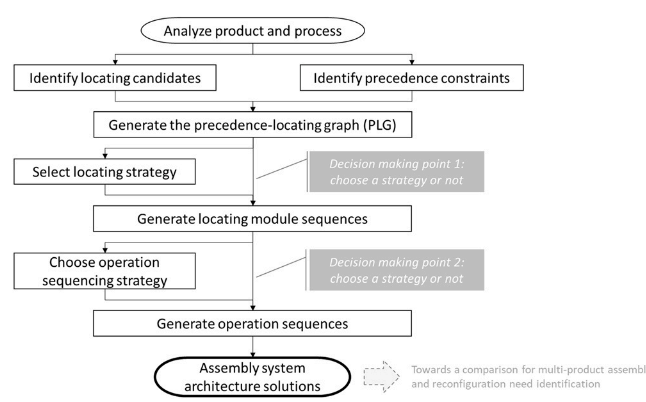


Fig. 18. Assembly system architecture solutions generation process with strategy application points.

In complex assemblies, it may happen that an independent locating module exists which uses the same locating candidate as modules embedded in a precedence sequence. It means that there is an operation without any precedence constraints which uses the same locating candidate as other operations embedded in a precedence sequence. In this case, the independent module should be

[2] For the examined product, there are 288 possibilities of selecting 8 locating candidates multiplied with $3 \times 41 \times 42 \times 43 \times 44 \times 45 \times 46 \times 47$ possibilities of placing 3 subassemblies and 7 operations without precedence constraints.

Table 5
Gathering criteria for locating modules.

Gathering criteria (locating candidates)	Expected impact on assembly system
Gather with the ones having the same locating candidate	Minimize module number and redundant location candidates: • System complexity decreases
Gather with the ones having operations of the same type	Minimize operation changes: • System complexity decreases
Gather with the ones having operations with the same orientation	Minimize orientation changes: • System complexity decreases • Module complexity decreases

mutualized with the embedded ones. The question is on which embedded one it should be integrated. Table 5 proposes an example of decision-making criteria which can be used to answer this question. Depending on the industrial application, the application of all criteria at the same time could be contradictory. Or, as the list is not supposed to be exhaustive, supplementary criteria could be needed. Once the PLG generated and possible operation-locating candidate allocations are gathered, an optimization approach using mathematical modeling may help to choose the best solution.

After operation allocation and the generation of locating module sequences, operations have to be sequenced as well, going from the macro level of locating modules to the micro level of their belonging operations. This is the second decision point as illustrated in the process overview in Fig. 18. Either criteria are applied for operation sequencing, or all possible sequences are generated to have an unlimited solution space. Concerning those criteria, Table 6 gives an overlook.

Analogous to the gathering criteria for locating modules, the list does not pretend to be complete and may vary depending on application cases. And the application of all criteria at the same time is also likely to give contradictory results. One should choose the most relevant ones and define priorities to avoid contradictions. To add the locating oriented approach to an optimization approach as used in operations research (OR), the selection of locating modules can become an additional decision variable. Also, the criteria presented in the tables above can be added to the constraints section of the mathematical OR model.

In the context of a multi-product assembly system design, based on the assembly system architecture solutions, a comparison has to be carried out which aims at examining the similarity of locating modules and their operation sequences. For multi-product analysis, the comparison should be conducted by the locating modules which have been identified as compatible. Compatible locating modules can be identified by a morphological and geometrical analysis of the components selected for locating. Also, using product bill of materials, similar locating candidates can be found by an etymological analysis of product references. For each locating module, it has to be determined if the operation sequences are common or different. If there is commonality, it means that the analyzed products can be assembled on the same assembly system without any adaptation. If there are differences, three possibilities exist:

1) If the differences are situated in the beginning or at the end of an operation sequence, the belonging operations can be outsourced into a supplementary locating module dedicated to one product.
2) If the differences concern supplementary operations in the assembly sequence, supplementary operation modules, dedicated to only one of the products, have to be added in a locating module which means that these modules will not be used at full charge.
3) If the differences concern different operations at the same point of the assembly sequence, a reconfigurable operation module which is able to switch between the needed operations, should be used.

In this way, the comparison of assembly system architecture solutions generated around locating modules allows the generation of a common assembly plan for multi-product assembly. The here newly introduced notion of locating modules supports three actions: (i) the identification of compatible components for the assembly of a product variety, (ii) the definition of the macro architecture of the assembly system, (iii) and the identification of commonality, differences and reconfiguration needs in the modules.

Conclusion and perspectives

In this paper, a new way of thinking an assembly system has been presented. It addresses the importance of locating during the assembly process, especially for multi-product-assembly. In literature on reconfiguration, these aspects lack of investigation. Also, they are not addressed by classical system design approaches. To close this gap, the benefits of a component locating based approach have been underlined and a framework for the application of this approach to assembly has been presented. The use of locating candidates and locating modules has been introduced. Further, the precedence-location graph (PLG) has been developed as core part of the new

Table 6
Operation sequencing criteria.

Sequencing criteria (operations)	Expected impact on assembly system
Add operations according to their type	Minimize operation changes: • System complexity decreases • Module complexity decreases
Insert operations according to their orientations	Minimize operation orientation changes: • System complexity decreases • Module complexity decreases
Insert operations according to their value added to the assembly or risk	Minimize reject costs: • Production costs decrease
Insert operations according to the size increase of the assembly	Minimize subassembly size: • Needed workspace decreases • Module complexity decreases
Insert operations according to the weight increase of the assembly	Minimize subassembly weight: • Actuator requirements decreases • System complexity decreases
Number of loose parts in the subassembly	Minimize the number of clamping: • Module complexity decreases
Insert operations according to their reliability (less reliable at first)	Minimize reject costs: • Production costs decrease
Insert operations to obtain a linear assembly flow	Minimize flow management complexity: • System complexity decreases

approach, combining precedence constraints and locating candidates. This graph is the departure point for the preliminary assembly sequence generation. By synthesizing in a single representation the whole solution space of assembly system architectures for a product, it enables the application of sequencing strategies which are based on locating decisions. Either all possible assembly sequences can be generated or, by application of refinement criteria concerning locating module sequences and operation sequences, a more restricted set of solutions may be generated. However, the viability and the reliability of the precedence-locating graph depends strongly on the information input which has been realized beforehand. This implies that these steps have to be carried out very carefully by putting the focus on the completeness and consistency of the gathered information. The entire approach has been tested on industrial products throughout a case study to validate the applicability of the new approach and model on complex industrial assemblies. However, as it cannot be detailed here due to confidentiality issues, an illustrative ball pen example is used to describe the approach and its benefits.

As this paper focuses on the general interest of the new approach and the new model allowing the application of locating strategies (the precedence-locating graph PLG), further work will consist in detailing the methods used for the identification of locating candidates in the product model (*Identification of components which are suited for locating*) and their selection. A research project is ongoing in cooperation with the industrial partner applying the locating based approach to the macro design of a multi-product system architecture proposing a detailed methodology for application. In this methodology, which will be issue of a future publication, the problems of locating candidate selection will be addressed. Furthermore, the complete approach from precedence constraints to architecture generation is for instance oriented to technical solutions. It generates solution spaces based on a set of generation criteria. No decision-making logic has been integrated yet, although possible connection points exits. Thus, it needs to be coupled with evaluation and decision-making approaches. As mentioned, a coupling with mathematical modeling and operations research optimization methods should be tested. Also, no evaluation is integrated which gives a statement about the fitness of the proposed solutions. To improve this point, the optimization approaches could be extended by cost and time considerations which are not considered for the moment. Concerning the technical solutions, in the context of multi-product assembly, coupling to delayed product differentiation approaches [9,47,48] can be done in order to identify differentiation based on common and different assembly locatings.

Declaration of Competing Interest

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.

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