Enabling the identification of multi-product assembly system architectures – a new method and its application in the automotive industry

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ABSTRACT
Product variety, in combination with today's unstable market environment, brings strong challenges to manufacturing firms. Single-product assembly systems become difficult to implement as the return on investment is difficult to obtain with decreasing lot sizes and unstable customer demands. Multi-product assembly systems are a possible solution to this problem, as they allow to compensate demand fluctuations throughout the product mix. However, variety is a strong barrier to this kind of production systems. A new method is presented in this paper to identify multi-product assembly system architectures adapted to a product family, based on the identification of components for common positioning. This method has been applied to a supplier in the automotive industry and a return of experience of this case study is provided, highlighting its potentials and barriers.

1. Introduction

It is today common sense that manufacturing companies are confronted to an ongoing trend of increasing product variety linked to market trends like mass customisation and personalisation (Koren 2010; Vogel-Heuser, Bauernhansl, and Ten Hompel 2017). Personalisation is related to the increasing customer's influence on the product design, requiring to adapt product design specifically to single customer requirements. Therefore, mass customisation requires the ability to produce personalised products at high production rates. In consequence, one impact on the manufacturing companies is the need for adaptable production systems: adaptable in terms of product mix, production lot sizes and used production processes. The last years have been marked by numerous unpredictable events like diseases, geopolitical tensions and an increasing number of natural catastrophes, in addition to customer-induced market challenges. All those events effect globalised markets and supply chains by increasing instability and emphasise even more the need for adaptive production systems as it is more and more difficult to keep production systems profitable which

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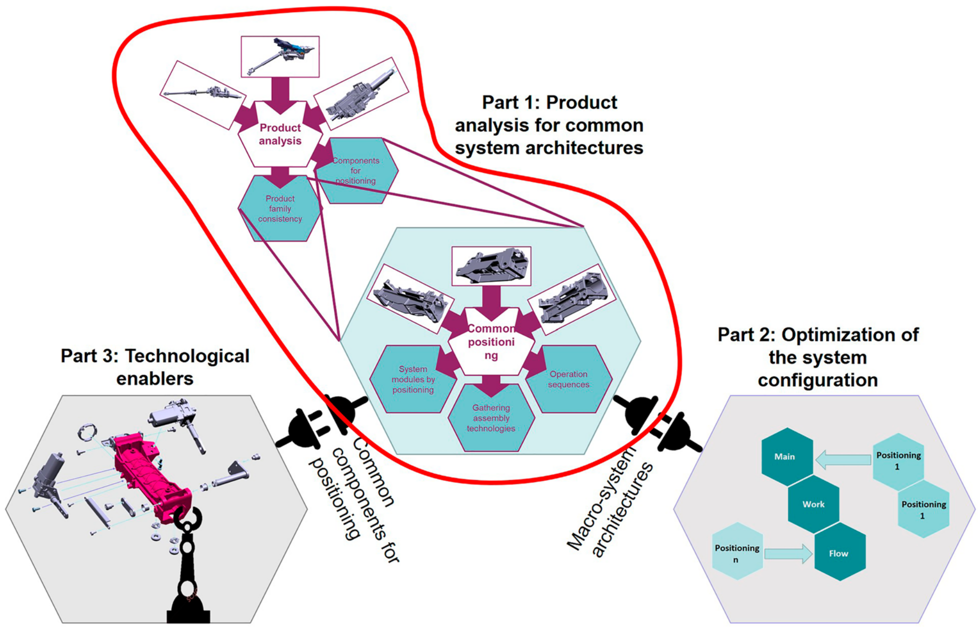

Figure 1. Global scope of the RDI project and scope of this paper (encircled area).

are dedicated to a single product (Backhaus et al. 2017). A possible solution is to outset the same production system for several different products to improve the return of investment.

The present article aims at contributing to the implementation of adaptable production systems in industry. It focuses on assembly systems as one kind of production systems in contrast to manufacturing systems. In this article, 'production system' is used as umbrella term which can designate at the same time a manufacturing system or an assembly system. The results and conclusions presented in the article are based on an industrial research project (project type RDI: Research Development Innovation) between Arts et Metiers and its partner company in the automotive sector, conducted by mixed teams which are composed of academic researchers and industrial engineers.

Figure 1 illustrates the overall scope of the RDI project which is divided into three parts. This article focalises on the first part, i.e. the identification of an assembly system architecture which is shared for a product family including variant products. The term 'assembly system architecture' defines a macroscopic line layout by determining the sequence of workstations (which must match with the assembly operation sequences of each product variant), each workstation having the capability to perform pre-defined tasks. The material handling system is not analysed.

1.1. Industrial motivations

The industrial partner in this research project has conducted a preliminary analysis to determine the most important industrial challenges. In general, it is stated that there is an exponential correlation between investment in assembly machines and the desired cycle time. The investment can reach from some hundred thousand euros for manual work stations up to millions for highly automated machines. However, for manual work stations, the high operator costs in France must be considered. These factors make it difficult to obtain the return of investment on assembly systems dedicated to a single product or on highly flexible assembly systems which need a high number of operators. The idea of multi-product assembly lines is to be able to compensate the fluctuations of lot sizes of one product with another one by changing the product mix or the production plans.

In the second step, the impact of the variety in a product family on the assembly system has been examined. In particular, the variability of semi-finished products is challenging. Across a product family, the assembly sequences are not identical, there is a big number of variant components, and many different assembly processes are used (e.g. joining, screwing, clipping, greasing, etc.).

This has a great impact on tools, operations and especially the positioning of the semi-finished product during the assembly operations: when assembly operations differ, additional returning tasks have to be added to the assembly sequences, different tools and fixtures are needed for each product variant, and the process variety leads to idle (i.e. unused) process modules in 100% flexible machines because they provide more process flexibility than actually needed. Facing the process variety, the question of developing universal machines for each process emerges, which can conduct all assembly operations having the same assembly process for a given product family.

1.2. Research questions

The associated main research question is **how can a multi-product assembly system architecture be determined in an industrial company evolving under constraints in a competitive environment?** It is subdivided into three detailed questions:

(1) How to identify a consistent product family concerning design similarity and process similarity?
(2) How to determine common positioning and fixturing which is an enabler for a multi-product assembly system?
(3) How to determine the global architecture of the final multi-product assembly system?

To answer the main research question, a method is presented which uses process similarity, precedence analysis and common positioning as drivers for the assembly system design. The term of ‘common positioning’ describes the hypothesis that the design of a multi-product assembly system relies on the use of similar components which have to be positioned during the different assembly operations. These components are a ‘platform’ for a subassembly which is based on them. For each similar subassembly, a solution for positioning which is unique and shared in the product family is needed to support the shared use of the assembly system. The term ‘multi-product assembly system’ designates then a same assembly system which can be used to assemble different products. The novelty in this paper is twice: it proposes at one hand an industry-oriented method for the design of multi-product assembly system architectures, and on the other hand the return of experience of a complete industrial case study. The paper focuses on the return of experience of the industrial application, addressing the following elements:

- How to implement a comprehensive approach in an industrial company? – The used method and tools are presented to answer the question.
- What are the benefits? – The term 'benefits' is here used in the sense of how the application has enriched the industrial reasoning processes and not in the sense of quantifying a financial impact.
- Which problems have been identified? – A return of experience is given.

The objective is to provide feedback on the benefits which have been brought to the company, and to emphasise the problems and barriers which have been met. The research work aims to contribute in this way to expand knowledge on industrial implementation of scientific methods for product family analysis applied to the identification of multi-product assembly system architectures. From a scientific viewpoint, adaptable assembly systems based on product platforms and families are an important enabler of mass customisation. They allow to design multi-product assembly systems which are able to assemble a product platform with high production rates, and specific product features in smaller volumes (ElMaraghy et al. 2021). As a further perspective, continuous adaptation and resilience improvement of those adaptable systems can then be achieved by the use of digital twins and scenario forecasts (Nassehi et al. 2022).

In order to clarify the meaning of the terms 'product architecture', 'physical and functional product architecture' and 'assembly system architecture' used in this paper, the following three definitions are proposed:

- the product architecture defines the product by structuring it into physical subassemblies (components and their mechanical links) and functional subassemblies (set of components which fulfil the same technical function)
- the physical and functional product architecture is a previously developed product representation considering at the same time the mechanical links between components and the relations between the functional subassemblies which map components to technical functions. The aim is to provide a common product architecture representation within a product family.
- the assembly system architecture defines the structural layout of the assembly systems by defining the sequence of system modules gathering positioning and operation information and the macroscopic flow between these modules respecting the precedence constraints. The final physical implementation in a factory building may differ in its detailed layout but the module content and workflow remain the same.

The article is structured as follows: the next section gives an overview of related topics addressed in scientific literature. Section three details the method and tools used in the industrial application. The industrial case study itself is detailed in the fourth section and a return of experience is given step by step. Section five discusses the case study and gives answers to the research question. Conclusion and perspectives are provided in the sixth section.

2. Related work

In order to face the previously described instable market environment and to remain competitive, a need for co-evolution of products and their production systems has been identified in literature. An exhaustive literature review concerning co-evolution of products, processes and production systems has been proposed by the SPECIES working group within the CIRP (Tolio et al. 2010). They state that the company's performance is related to its capacity to manage co-evolution. Bryan et al. (2007) propose a methodology for assembly system co-evolution based on two phases, which are the co-design of a product family with its assembly system and the further co-evolution of both. More recent work has been carried out by Brunoe et al. (2019), focusing on an ontology for product-process co-evolution in the context of manufacturing. Concerning manufacturing as well, an original approach has been introduced by AlGeddawy and ElMaraghy (2011) who use a biological analogy based on cladistics. The co-evolution is managed by the comparison of production system and product cladograms. Those cladograms represent respectively the product features (in the sense of manufacturing) and the corresponding production system capabilities (ElMaraghy and AlGeddawy 2012). By determining missing associations between both cladogram types, further evolution possibilities can be identified (AlGeddawy and ElMaraghy 2012). However, all the approaches remain on low Technology Readiness Level (TRL, (EURAXESS n.d.)) and are hard to implement in industry. Beside co-evolution, several other approaches for analysing product variety in the context of assembly exist, in particular Design for Assembly (DfA) approaches, Design Structure Matrix (DSM) methods and applications and the concept of Delayed Product Differentiation (DPD).

Delayed Product Differentiation (DPD) seems a promising approach for the identification of shared assembly system structures. The aim of DPD is to postpone the point where a product obtains its specific shape and functionalities ('it develops its own identity' (AlGeddawy and ElMaraghy 2010)). To achieve the postponement of differentiating points, He, Kusiak, and Tseng (1998) propose three product design strategies to avoid complex and redundant choices in product family design. Already at the beginning of DPD research, it has been theoretically shown that postponement and the use of common subassemblies are potentially beneficial in comparison to make-to-order systems (Swaminathan and Tayur 1998). However, the DPD approach, which is based on common subassemblies, has been identified as less adaptive to changing market demands in comparison to competitors with early product differentiation (Anand and Girotra 2007). Modularity plays an important role in DPD as product modularity eases postponing the differentiation (Blecker and Abdelkafi 2007). In this context, an important question is the way of how to define optimal modules (Song and Kusiak 2010). Having already been studied for agile systems (He and Babayan 2002), recent work aims at combining DPD with reconfigurable manufacturing (Huang and Yan 2019; Huang, Wang, and Yan 2018). The DPD application eases the shared use of assembly systems as it enhances the commonality of products and in consequence, the possibility to use a big part of the same system to assemble different products. Only the product-specific assembly stations need to be dedicated to single products and by means of the delayed differentiation. They can be added at the end of a shared multi-product workflow. However, the application of DPD depends on the possibility of designing products based on a platform with a strong commonality share in the product family. There can be cases where the products have the same functions but cannot be built out of a shared platform. This is the case, for example, for the industrial partner which is the supplier in the automotive sector where the OEMs (original equipment manufacturers, i.e. the motor companies in the automotive sector) have a very strong influence on the constraints of 'their' product design. In this case, DPD seems very difficult to realise. Another shortcoming of the DPD approach is that is constructed around common components in the product family. These parts need to be exactly the same and induce therefore strong constraints to product design.

The general objective of DfA methods is to provide a feedback to the designer concerning the impact of design decisions on product assembly. It aims at reducing assembly time and cost (Formentini, Boix Rodríguez, and Favi 2022). Since the well-known presentation of the DFA approach by Boothroyd, Dewhurst, and Knight (2011), a plenty of different applications and derivations of the method have been developed: a DfA approach based on sticky notes is introduced by Moultrie and Maier (2014) in order to ease its application in industry. Other work has been carried out to integrate DfA to product design in order to improve ergonomics of the assembly line based on workers' feedback (Bader et al. 2018) or based on a simultaneous analysis of ergonomic and assembly criteria (Bouissiere et al. 2019; Favi et al. 2020). An analysis of DfA method applications to product CAD files during early design stages has been published by Francia et al. (2020) using as case study a bolted assembly. Complementary work concerns DfA in large assemblies for the design improvement of solar panels (Remirez et al. 2019). For DfA in the aircraft industry, Halfmann, Elstner, and Krause 2011a; (2011b) have developed a method of assembly modularisation based on product structures and Datum Flow Chain. In addition to the single product applications, Nielsen and Yu (2022) present an application of DfA extended to a product family. Setti, Canciglieri Junior, and Estorilio (2021) propose an integrated design method combining DfA and value engineering. Finally, DfA can also be applied to disassembly analyses as shown by Soh, Ong, and Nee (2016).

The literature analysis shows that DfA approaches are today well-known and well-understood. A lot of work has been carried out since the 90's to extend the methods and to ease their application. However, the DfA methods are very often focused on the product and the assembly system is mainly considered by assembly processes with help of measures and indices provided by catalogues. There is no application of DfA known by the authors which can support the identification of assembly system architectures for product variants from the assembly system viewpoint.

Design Structure Matrices (DSM) are a tool for exploring dependencies in a visual manner. They have been applied to different domains, for example to model interactions between components, organisational tasks and communications (Eppinger and Browning 2012). Farid and McFarlane (2006) use DSM for modular system design in a distributed, reconfigurable manufacturing system. A dependency analysis of generic components of a product family of unmanned ground freeride vehicles, displayed with the help of DSM, is proposed in Otto et al. (2016). The use of DSM to gather components into subassemblies using the example of heavy vehicle suspensions is illustrated in Forti, Ramos, and Muniz (2023). Sinha, Han, and Suh (2020) extend the DSM method by adding constraints to component clustering by defining components that must be in different modules. Modularity similarity of product assemblies are evaluated based on DSM by Qiao et al. (2017) who use a metric which is calculating a theoretical 'cost' of dissimilar clusters by counting the number of elements which are not allocated to the same cluster. Recent work couples DSM with axiomatic design by clustering design parameters (DP) in DSM matrices in order to improve the design matrix containing the relations between functional requirements (FR) and DP (Mollajan and Iranmanesh 2021; Park et al. 2022; Tamayo et al. 2019). A less-used application of DSM is its application to assembly system layout design as presented by Gong, Liu, and Jiao (2017) who use weighted assembly process plans in order to determine assembly

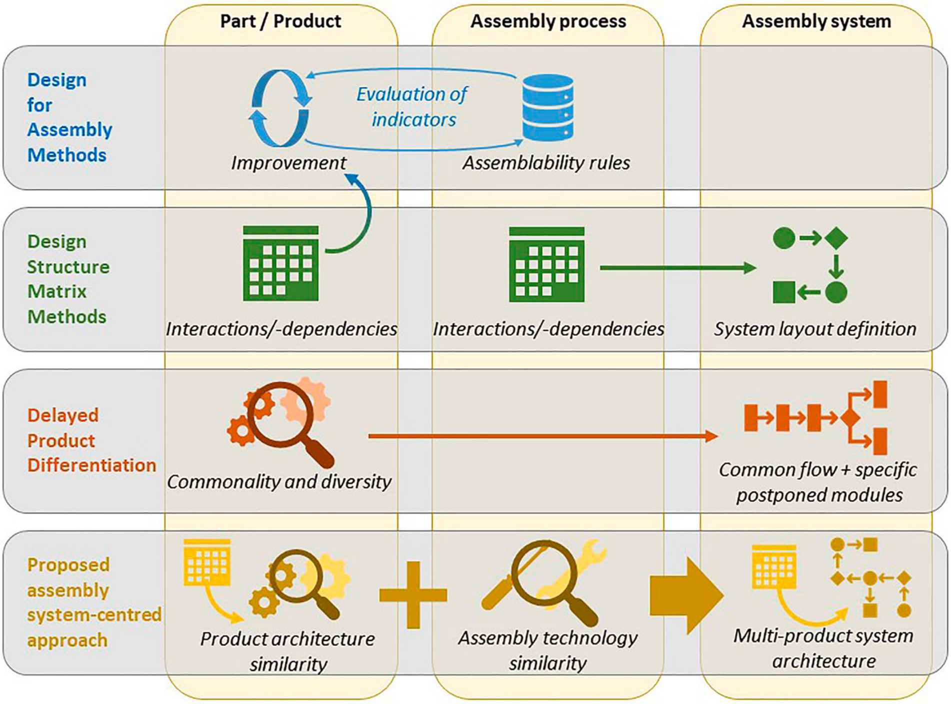

Figure 2. Position of DfA, DSM, DPD and the proposed method.

system clusters in the plant layout. In the here presented case study, DSM-related tools are used at two stages: intrinsically during the product modelling step for similarity analysis by mapping the relations between functional groups, and during the assembly system architecture design by grouping assembly tasks.

Figure 2 synthesises the literature review on methods dealing with variety in assembly. DfA methods offer the possibility to analyse and improve products but they remain very often on the product level and no application is known to the authors where DfA is used for assembly system layout design. DPD allows the definition of multi-product assembly system architectures by commonality and diversity analysis of the product family: All common subassemblies are assembled on a shared assembly line and variety is achieved with the last assembly steps on product-specific assembly system modules.

The shortcoming of the DPD methods is the lack of consideration of partial similarity in a product family instead of 'commonality'. The latter is more restrictive as it looks for exact coincidence with a binary conclusion (yes/no), whereas partial similarity evaluates particular similar features depending on its application. DSM methods are widely used to analyse dependencies between elements which can be on the product level, the process level or the assembly system level. However, there is no transition between the matrices of the different levels. In the proposed methods, DSM applications occur at two stages: the product analysis and the final production system architecture identification. The here presented method aims at bridging the gap from product analysis to assembly system architecture determination for product families with product variants by using the mirroring hypothesis (Colfer and Baldwin 2016) that similarity on the product and assembly process level induces similarity on the assembly system architecture and vice versa.

The question remains how to treat a product family having variant components which are similar but not exactly the same. To determine similarity between the variant products, similarity metrics have to be used. A wide range of commonality and similarity metrics have been developed during the past 30 years. Table 1 synthesises several similarity and commonality measurement approaches presented in literature.

However, similarly to DPD approaches, very often the metrics concern commonality (i.e. searching for the exact same components or manufacturing features in variant products). They do not include the possibility of having components of similar shape (not exactly the same references) and/or using the same production process. In this case, even if the components or manufacturing features are not exactly the same, the different products may be assembled on the same assembly system. This gap is addressed by the presented application. Instead of using the very discriminant constraint that the components must be the same, the similarity analysis is based on three levels: the similarity of the physical and functional product architecture, the similarity of used assembly processes and the similarity of components used for positioning during the assembly operations themselves. To enable the identification of those similar components, a set of four similarity indices, indicated in the last line of Table 1, has been developed in a previous research project ('Industrial Chair,' n.d.). In continuity of this research work, those four indices have been applied to the novel case study in the context of the new method. Section 3 will give further information about the application.

To synthesise, the research literature review emphasises that existing methods of co-evolution and delayed product differentiation are difficult to apply to the problem of the partner company. For this reason, a new and comprehensive approach has been proposed, based on similarity analysis (Stief et al. 2019; 2018) and the use of similar components for common component positioning in the assembly system (Stief et al. 2023). The aim of the method is to support the determination of assembly system architectures which can be shared by similar but variant products of a product family. The architectures need therefore to be adapted to a product mix independent of the component and process commonality. It is achieved by analysing the similarity of product architectures and assembly processes despite their variety.

The next section describes the approach which has been applied during the industrial application and it details in a step-by-step manner the tools and methods which have been used. To remind, a description of the industrial problems is given in the introduction.

3. Method, tools and activities used for industrial application

An overview of the applied method is given in Figure 3. It is composed of four steps: (A1) product modelling, (A2) product analyses, (A3) identification of common positioning and (A4) final identification of the multi-product assembly system architecture.

In the following subsections, the different activities are briefly explained and the used models and tools are presented. For each activity, its aims, prerequisites, needed input items and generated output items are detailed.

3.1. Product modelling (A1)

The product modelling activity ensures an objective comparison of the product mix in order to identify a consistent product family. As mentioned before, a similarity analysis with four

Table 1. Overview of similarity and commonality metrics, extended from (Stief et al. 2020).

Ref.		Title	Concern	Short summary
(Collier 1981)	DCI	Degree of commonality index	Product family	Comparison on component level; average number of common component items per average distinct component part. Improvement of system performance
a. (Wacker and Treleven 1986) b. (Baylis, Zhang, and McAdams 2018)	TCCI	Total Constant Commonality Index	Product family	Comparison on component level; modification of DCI to be relative with an absolute boundary. Component standardisation (a). Example of an application to product platform selection in (b).
(Martin and Ishii 1997; 1996)	CI	Commonality Index	Product family	Comparison on component level; Extension to DCI considering the number of varieties offered; design for a minimum variety cost
(Siddique, Rosen, and Wang 1998)	%C	Percent Commonality Index	Product family & system	Simple comparison (common divided by common + unique); Analysis of product platforms
a. (Kota, Sethuraman, and Miller 2000) b. (Jung and Simpson 2016) c. (Lima and Kubota 2022)	PCI	Product line Commonality Index	Product family	Comparison on component level. Benchmarking product families (a). More recent applications in combination with DSM for platform architecture identification (b) and to explore commonality of specific components in modular design (c).
(Jiao and Tseng 2000)	CI(c)	Component Part Commonality	Product family	Comparison on component level; Evolution of DCI considering component cost to favour sharing high price parts
(McAdams and Wood 2002)	–	Similarity projection	Product family	Analysis based on functional modules, normalised similarity matrix is represented by vector projection.
(Blecker and Abdelkafi 2007)	TCI	Total Commonality Index	Product family	Evaluation based on generic BOM. Considers the probability of part variations to be chosen. Evaluates common, variable and optional components.
a. (Thevenot and Simpson 2007) b. (Jung et al. 2021)	CMC	Comprehensive Metric for Commonality	Product family	Comparison on the component level; trade-off between diversity and commonality and product redesign (a). Recent identification of CMC for Design for Non-Assembly. (b)
(Lai and Gershenson 2008)	–	Similarity Matrix	Product family	Pairwise comparison of similarity and dependency of components of one product; assembly processes included
(Alizon, Shooter, and Simpson 2009)	CDI	Commonality versus Diversity index	Product family	Comparison on component level; Determining ideal trade-off between diversity and commonality
(Goyal, Jain, and Jain 2013)	BMIM	Bypassing Moves and Idle Machines	Production line	Similarity value based on Shortest Common Super-sequence, total number of operations and number of idle machines and by-pass moves
(Wang et al. 2016)	S_{ij}	Similarity coefficient	Component Production line	Similarity analysis based on processing sequence of parts. Similarity is calculated by the number of common steps, idle machines and by-passing moves
(Stief et al. 2019; 2018)	**S_1-S_4**	**Similarity coefficient**	**Product family, Process**	**Analysis based on the physical and functional product architecture. Assembly processes are considered. Four indices: S_1 and S_2 for design and complexity; S_3 and S_4 for assembly technologies**

Note: In case of multiple references, the original research is always indicated in a.

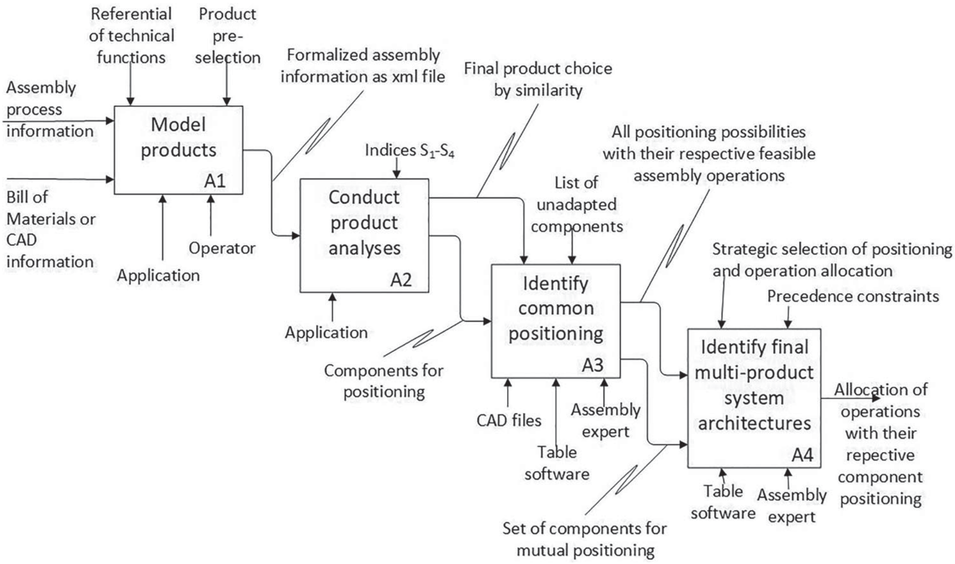

Figure 3. IDEF0 representation of the activities composing the method applied in industry.

Table 2. Synthesis of activity A1.

Aim	For each concerned product, its physical and functional structure has to be modelled in order to enable an objective similarity analysis
Prerequisites	Product documentation (component list, assembly information, CAD files), referential of technical functions for the product type
Input items	Manual input of components, their mechanical links and their allocation to a technical function
Output items	Product models as xml save file containing the input items

indices on the product design level and assembly process level has been chosen in continuity with a previous research project. This similarity analysis is based on the *PHARE* models (Stief et al. 2018). It uses an oriented-graph assembly model similar to Datum Flow Chain (DFC). DFC represent the product as directed graphs where the vertices represent components and the arcs with their directions indicate an assembly relation: the component with the outgoing arc is referencing partially or completely the position of the component with the ingoing arc (Mantripragada and Whitney 1998; Whitney 2004). This model has frequently been used for tolerance propagation analysis. In the here used 'enriched DFC' representation, each directed arc represents a mechanical link between two components. The component having an ingoing arc is assembled to the one at the origin of the arc. The model is extended by information about technical function allocation and used assembly processes. In this way, an assembly logic can be established and the relation between the functional subassemblies can be displayed and analysed. The activity is synthesised in Table 2:

To ease the generation of the assembly models, a software prototype has been developed and provided to the industrial partner. The used models have been published previously (see references (Stief et al. 2019; 2018)) and are therefore not detailed again.

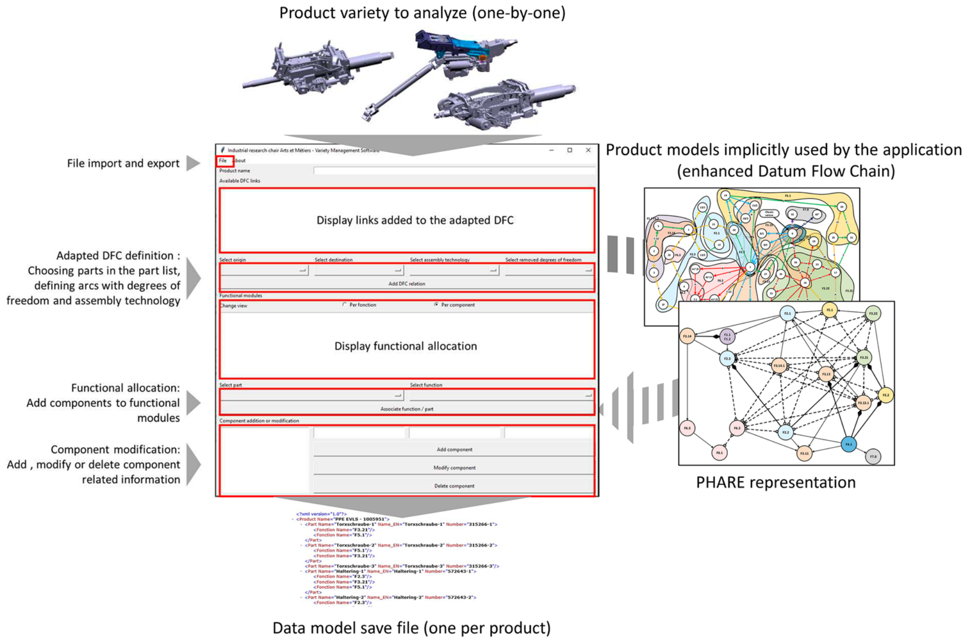

Figure 4. Illustration of the product modelling step.

Figure 4 illustrates the product modelling step. The products are modelled step-by-step into the application: First, the components are imported from the bill of materials if existing products are analysed. If the application concerns products under development, information can be retrieved from the latest CAD models. Then, their mechanical links and assembly operations (joining, screwing, …) are defined. And finally, the components are allocated to a technical function. The technical functions are predefined and chosen out of a referential which is unique for a product family. The product models which have been developed in previous research work and which are implicitly used by the application are detailed at the right-hand side of Figure 4. Their elements are saved in an XML file but the graphical representations are not generated. These XML sheets, illustrated at the bottom, are used in the next activity.

3.2. Product analysis (A2)

The product analysis activity is divided into two independent parts: (i) the use of similarity indices to decide if the analysed product portfolio can be assembled on a shared assembly system, and (ii) the identification of components which can potentially be used for positioning during the assembly processes (which are 'platforms' to conduct the assembly operations needed to form a subassembly). This information is the key element for the identification of a multi-product assembly system architecture. **The hypothesis is: similar positioning and assembly operation = common system work cell,** similar to the mirroring hypothesis explained in (Colfer and Baldwin 2016). The activity is synthesised in Table 3:

The first part of the product analysis aims at determining the product mix which can potentially be produced on the shared multi-product assembly system. As output item, a

Table 3. Synthesis of activity A2.

Aim	(i) Identify similar products (either for product family generation, or for consistency check of an existing portfolio) (ii) Identify all components (product by product) which could be used for positioning during the assembly process
Prerequisites	Product documentation (component list, assembly information, CAD model), referential of technical functions for the product type
Input items	Product models as xml save file containing the input items
Output items	Similarity indices (aim (i)) and list of components which could be used for positioning (aim (ii))

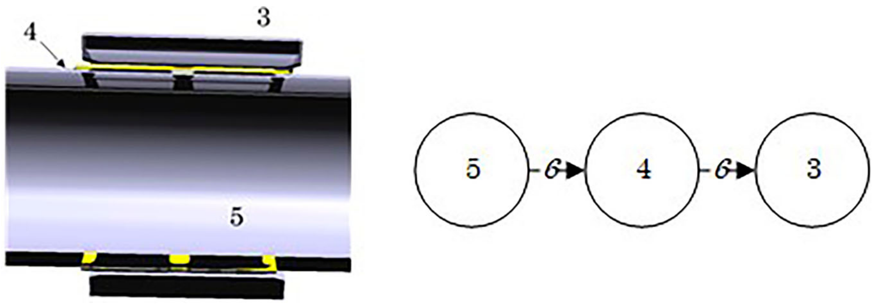

Figure 5. Example of a simple assembly (components left, sequence in the product model right) for the identification of components which can potentially be used for positioning.

consistent product family is determined and only the selected products are submitted to the next activity. The second output is one component list per product, containing for each product and its components which can be used for positioning. This list is an essential input for the next activity (identification of common positioning). Components which can be used for positioning are identified based on the product model (see subsection 3.1). An example is given in Figure 5. **The hypothesis is: Any component at the beginning or the end of an assembly sequence can be used for positioning.**

An assembly sequence is determined out of the product model: it is a sub-sequence of the oriented assembly graph from a vertex without incoming arcs to a vertex without outgoing arcs. Figure 5 illustrates a simple assembly sequence: component (3) is assembled to the tubular component (5) by indirect press fit with a tolerance ring (4). The assembly sequence is therefore: (5) $\rightarrow$ (4) $\rightarrow$ (3). Component (5) is at the beginning of the assembly sequence and component (3) is at the end of the sequence. Both are possible components for positioning which can be used to assemble the subassembly {3;4;5}. If component (3) is selected, it has to be positioned, and then the components (4) and (5) are inserted. If component (5) is chosen for positioning, the tube is put into position, then the components (4) and (3) are mounted.

To refine this first identification of components for positioning, a list of undesirable components (e.g. screws and fasteners) can be defined. These components are deleted from the output list by etymological correspondence.

3.3. Identification of common positioning for a product family (A3)

The identification of a common positioning for the product family is the core activity of the proposed method. All steps of this activity are complex as it concerns the analysis of product

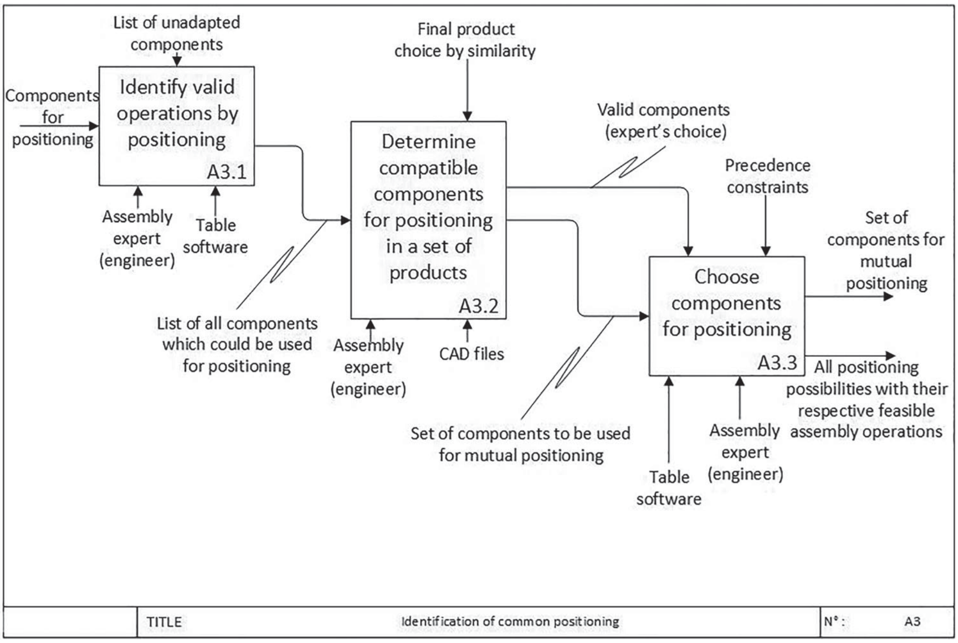

Figure 6. Detail of activity A3.

Table 4. Synthesis of activity A3.

Aim		(A3.1) For each product, and for each component useable for positioning, identify all possible assembly operations which could be carried (A3.2) For the chosen product family, identify which components allow a compatible positioning (A3.3) For each product, apply per product assembly strategies driven by the choice of certain components for positioning
Prerequi-sites		(A3.1) Table software tool and knowledge about product assembly (A3.2) CAD files and knowledge about product assembly (A3.3) Table software tool, knowledge about product assembly, precedence constraints
Input items		(A3.1) List of components which can be used for positioning (A3.2) Output of step (A3.1) (A3.3) Output of step (A3.2)
Output items		(A3.1) All combinations of positioning possibilities with their respective feasible assembly operations (A3.2) Set of all possible combinations of components for positioning with their assembly operations valid for a mutual use in the entire product family (A3.3) Strategic selection of positioning and operation allocation for each product to generate the common multi-product assembly system architecture

assemblies and requires knowledge about how the product is built and how it works. Thus, the intervention of an engineering expert is needed. A detailed view of activity A3 including its three sub-activities is provided in Figure 6. The activity is synthesised in Table 4:

The input of the first step (A3.1) are the files containing for each individual product all components which can possibly be used for positioning. The intervention of an assembly expert is then needed to validate this input for further consideration in the next activities: first, the component list has to be validated. This means that undesired components have to be unselected so that they are no longer considered during the next activities, for example, because of their material or because they have functional surfaces which cannot be used for

Table 5. Synthesis of activity A4.

	Aim	For each product, define which positioning has to be used in the main assembly flow, then decide for secondary assembly flows
	Prerequisites	Table software tool and knowledge about product assembly
	Input items	Output of 3.3
	Output items	Macro-architecture of the assembly system by identifying main and secondary work flows

clamping. And second, for each valid component, a valid assembly scenario has to be identified. This includes that for each valid component three items have to be determined: (i) the set of all other components which can technically be assembled on it, (ii) the needed assembly technologies and (iii) the orientations (i.e. accessibility constraints) of each assembly operation in the product coordinate system. This activity has to be carried out individually for every single product being part of the product mix which has been selected based on the similarity analysis at the end of activity A2. The set of undesirable components can be stored in a taboo-list and reused during further analyses to create a small data base of components which cannot be used for positioning. This may reduce the number of components to treat and decrease the time needed for this activity, as components which are figured on the taboo-list are not submitted to the validation by the assembly expert.

Once the components which can be used for positioning are validated separately for each product, activity A3.2 aims at identifying those ones in the product family which can be used to enable mutual assembly. To do so, the geometry, size and shape of the components have to be compared by an assembly expert (either the real components if products are already industrialised, or the CAD files if products are still in the design phase). In addition to the geometrical criteria, it must also be checked if assembly orientations and operations are compatible. Due to the complexity of this comparison, an assembly expert is needed.

The last sub-activity (A3.3) consists of making a final decision. For each product, the components for positioning have to be chosen. Two criteria must be satisfied: (i) all assembly operations of a product must be covered, and (ii) components should be preferably selected which are compatible for the whole product family.

3.4. Final identification of multi-product assembly system architecture (A4)

This last activity of the proposed method aims at exploiting the results of the previous ones in order to determine a global multi-product assembly system architecture adapted to the product family. The **hypothesis is that the main flow is composed of components for positioning which are shared and which gather a maximum of assembly operations.** All other components for positioning are arranged around the main flow and constitute secondary assembly flows. The activity is synthesised in Table 5:

During this activity, an assembly expert has to compare the outputs of activity A3 for the whole product family in order to identify the global assembly system architecture according to the criteria mentioned above. The next section illustrates the industrial application with the help of the case study excerpts.

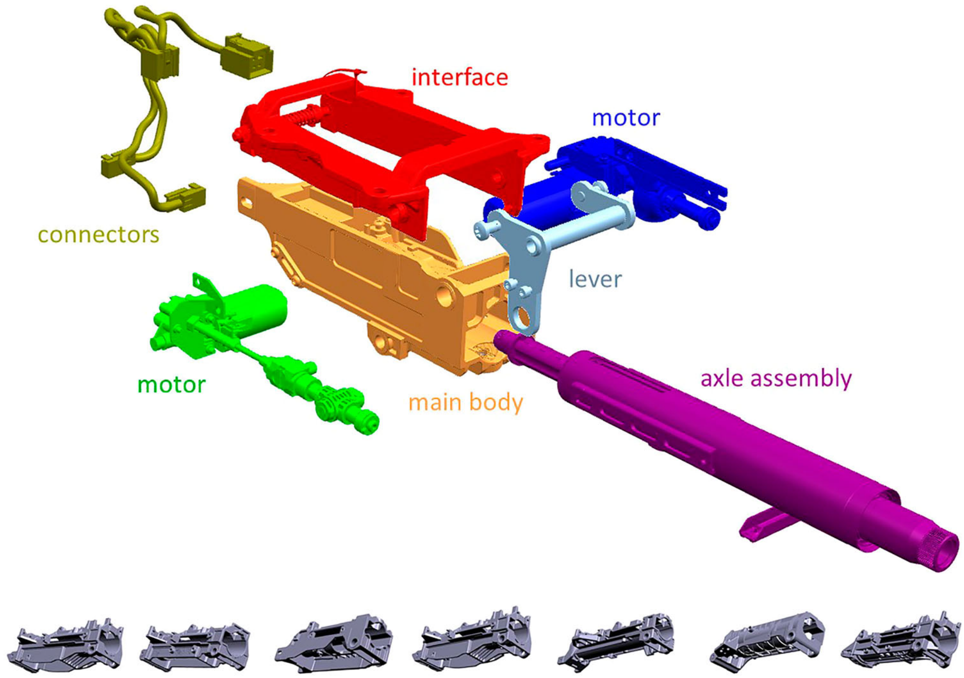

Figure 7. Main subassemblies of a steering column and an example of variant components below.

4. Industrial case study

The industrial case study has been carried out in strong cooperation with the industrial partner. The important issues identified by the industrials have been described at the end of section 1. In the following subsections, the developed method is applied to the industrial case study and for each activity, an overview of the application, the outcomes, and a critical discussion is provided.

The study case concerns the assembly of the upper part of a set of eight electric steering columns, numerated P1 to P8. Figure 7 provides a schematic illustration of the main subassemblies of these products.

An electric steering column is a complex mechanical assembly, gathering in average about 50 components, using about five to six different assembly technologies and having up to 120 mechanical links and contacts between the components.

4.1. Product modelling (A1)

As described in section 3, product modelling has been done using a software interface to ease the input of product assembly information. The bill of materials of each product, extracted as Excel file out of the PLM system of the industrial partner, can be inserted directly into the application. A set of components is then already available for product modelling. The output of this step are the XML save-files, which store all components, their mechanical links, the used assembly technology and the allocated technical functions. Linking the application to Microsoft Visio allows to display the enriched Datum Flow Chains if

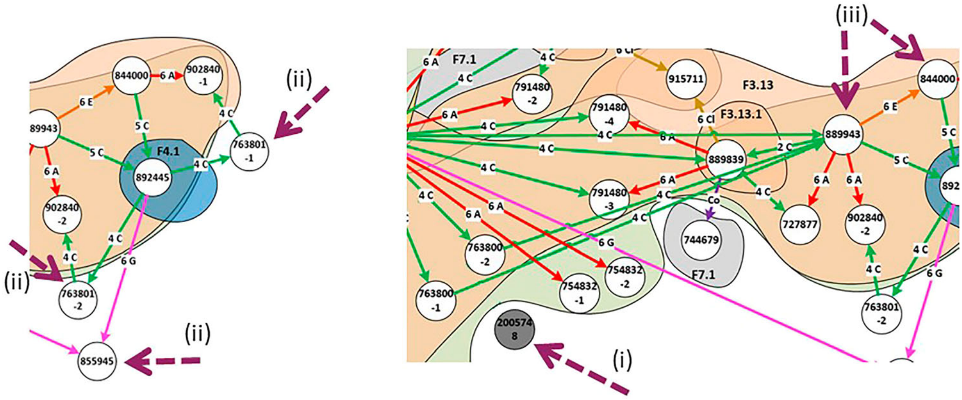

Figure 8. Most recurrent errors in product modelling: (i) isolated components, (ii) no functional allocation, (iii) redundant components.

desired. For check-up, the component list and functional allocation can be extracted from the application.

Return of experience: The product modelling step is the entrance to the method. Even if the activity itself is a repetitive and time-consuming task, all the following activities rely on the correct and consistent execution of this task. Three recurrent errors have been detected linked to the complexity of the product architecture: (i) components or subassemblies which are not connected by mechanical links in the model, (ii) components or subassemblies without a functional allocation in the model (which would signify that those components have no reason to be) and (iii) redundant components appearing in the model.

Those errors are illustrated in Figure 8, using the enriched Datum Flow Chain representation to display the entered product modelling information. The nodes represent the components. The arcs indicate a positioning logic and carry information about used assembly technologies and eliminated degrees of freedom. The coloured areas represent technical functions with allocated components. On the left-hand side, three components (nodes in the graph) have no functional allocation. On the right-hand side, the grey component – without functional allocation – has in addition no mechanical link to the assembly. Finally, the components 844000 and 889943 are redundant as they indicate the same component on different levels in the bill of materials (BoM) which is extracted out of the PLM system. In consequence, for an optimal product modelling, some supplementary actions should be conducted: the preliminary check of the BoM to eliminate inconsistencies before product modelling starts, enhanced training of the operators who are in charge of the product modelling, and a final check of the product models using the enriched DFC representation.

4.2. Product analysis (A2)

After their final check, the product models have been validated by discussions with the industrial partner. The items which have been validated are the functional allocation, the consistency of relations between the components (placement and directions of the arcs in the graph) and the used assembly technologies. Based on those verified and validated product models, the product analysis has been carried out. At first, the eight products have

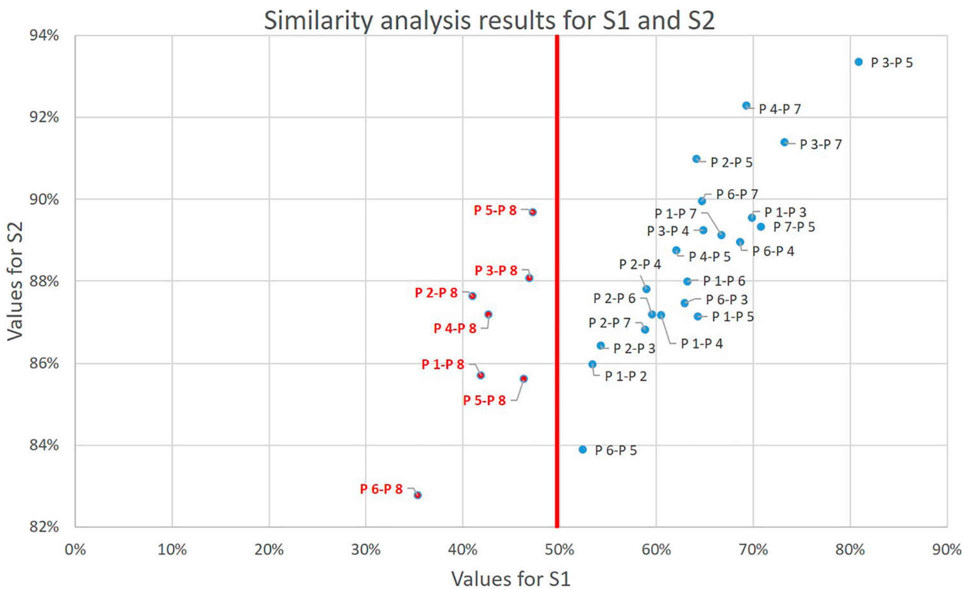

Figure 9. Similarity results for S1 and S2 (binary analysis of two products, results for all combinations of the examined products).

been submitted to the similarity analysis in order to check if the selection is suited for the shared multi-product assembly system. Figure 9 illustrates the results of the analysis with the product architecture similarity indices S_1 and S_2. S_1 describes the similarity of the product architecture and S_2 gives an indication about the similarity of the complexity of the product architecture (complexity means in this case the number of imbrications of technical functions). It can be seen that product P8 has very poor similarity values, especially for design similarity S_1. They are under the threshold of 50% for all binary comparisons and therefore not eligible for a common production line (see threshold explanations for S_1 in (Stief et al. 2019)). This means that product P8 is eliminated from the product mix and only the products P1 to P7 are submitted to the identification of possible components for positioning during assembly. The low similarity values are linked to a different design of the steering column as the architecture is completely different (placement of the electric motors, kinematics). It means that P8 does not fit to the initially proposed product mix. There are two possibilities: either there are other products which are similar to P8 or it is an isolated case. In the first case, another multi-product assembly line can be designed for the product family around P8. In the second case, a dedicated assembly system has to be used for P8 and it should be checked by the design department if product design changes are feasible to increase the similarity of P8 with an existing product family.

For the identification of possible components for positioning, a subgraph of the enriched Datum Flow Chain is analysed for each functional subassembly. It is checked which components are at the beginning or at the end of a sequence in the subgraph (see Figure 10). Those components are considered as candidates for positioning. In the first time, this step was realised manually with Microsoft Excel but has then been automated based on the XML files generated in activity A1.

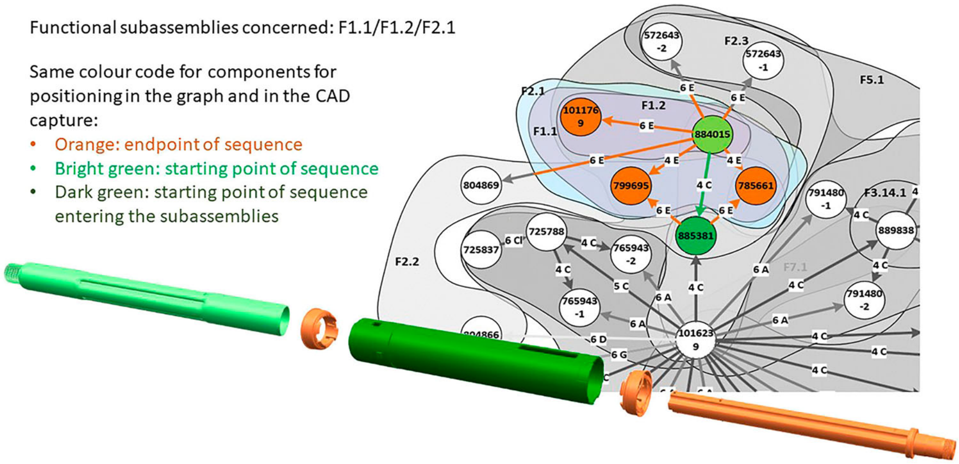

Figure 10. Components for positioning – excerpt of P6.

To extend the solution space, two additional criteria have been added: (i) a component is also saved as candidate if it is linked to a starting point or an ending point having all six degrees of freedom eliminated by this mechanical link. And (ii) a candidate can also be an important component, i.e. a component which is under the top 25% having the most mechanical links in the product and which is not at the beginning or at the end of a sequence. Therefore, four criteria exist: (a) components being starting point of a sequence, (b) components being end point, (c) components having a solid link to the components of (a) and (b), and (d) components being in the top 25% of the ones having the most mechanical links in the product. For example, 32 components which can possibly be used for positioning have been identified for product P7. This number is similar for each of the seven products.

Return of experience: The similarity analysis application has been proved its importance to ensure the consistency of the product mix before starting the detailed analysis. It avoids wasting time on products which are not suitable for a shared multi-product assembly system. An aggregated view (as shown in Figure 7) is necessary to ease the evaluation of the similarity indices. Initially, the identification of all possible components for positioning was a fastidious task and was submitted to human errors due to the duration and repetitiveness of the information collection phase. This problem has been solved with informatic treatment as the component list can now be generated automatically in the software prototype.

For all products, the distribution of components in the four criteria (a) to (d) is almost the same: around 5% for (a), 60% for (b), 20% for (c) and 15% for (d). This means that components which are at the end of a sequence represent one-third of the components which can potentially be used for positioning. A closer verification of the components in category (b) has shown that it contains many fasteners (e.g. screws, bolts, nuts) and bearings as illustrated in Figure 10. They are often at the end of an assembly sequence. However, those components are not desirable for positioning. A taboo-list has been established to eliminate these ones and to facilitate the work of selecting valid components for positioning in the following activity A3. The taboo-list is dressed by enumerating all undesirable components (e.g. thread pin, distance sleeve, plate nut, …) and used as sorting criteria for the next

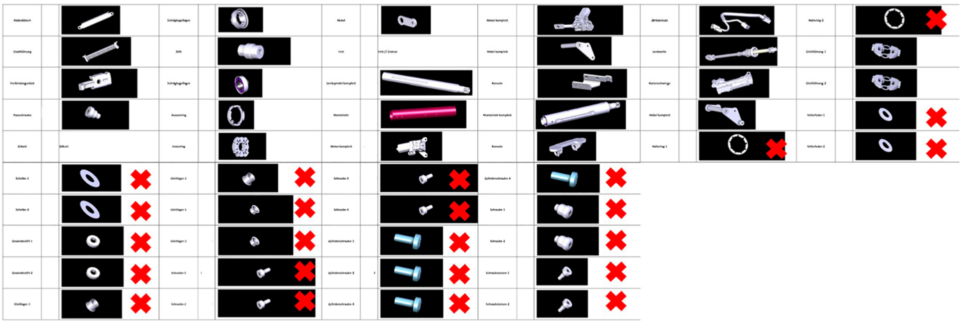

Figure 11. Example of components eliminated by the taboo-list (marked with a cross).

activity. As activity A2 is entirely based on the enriched Datum Flow Chain with functional allocation, it underlines the importance of an accurate product modelling.

This activity of the proposed method gives an objective view of components which can be used as platform for assembly in the system. It helps the assembly system designer to consider components for positioning which are not of common use in existing systems. In this way, it provides a basis to support thinking 'out of the box' and to identify innovative solutions for the assembly system architecture later.

4.3. Identification of common positioning for a product family (A3)

The third activity starts with the identification of all possible assembly operations for each component which can be used for positioning (activity A3.1), after filtering them with the taboo-list. Throughout the case study, a list of 40 words representing undesirable components has been generated, valid for the entire product mix. With this taboo-list, the number of possible components for positioning for each product has been reduced from around 80 components to around 20 components. This reduction eases a lot the step of operation allocation for each of the components for positioning. Figure 11 gives an example of the components which have been filtered with the taboo-list. After this automated elimination, an assembly expert has to validate the about 20 remaining components.

For each validated component, the expert allocates all assembly operations which are feasible if this component would be used for positioning. The results of this allocation are gathered in a table.

The next sub-activity (A3.2) consists of identifying components which can be used for positioning across the product family. To do so, the results of step 3.1, i.e. the tables with all validated components, have to be compared across the product mix. The assembly expert has to determine an inventory of compatible components based on their geometrical similarity. The criterion for the selection is that the positioning and fixturing of the selected components do not need a tool change if the product reference changes. The appropriate product family has been determined by the results of activity A2, the product analysis step.

The last step of activity A3 is the final choice of components for positioning (A3.3) which will be used for the identification of the multi-product assembly system architecture. For this step, two different strategies can be applied. As a general rule, it can be defined that components for positioning which are compatible for the entire product family must have

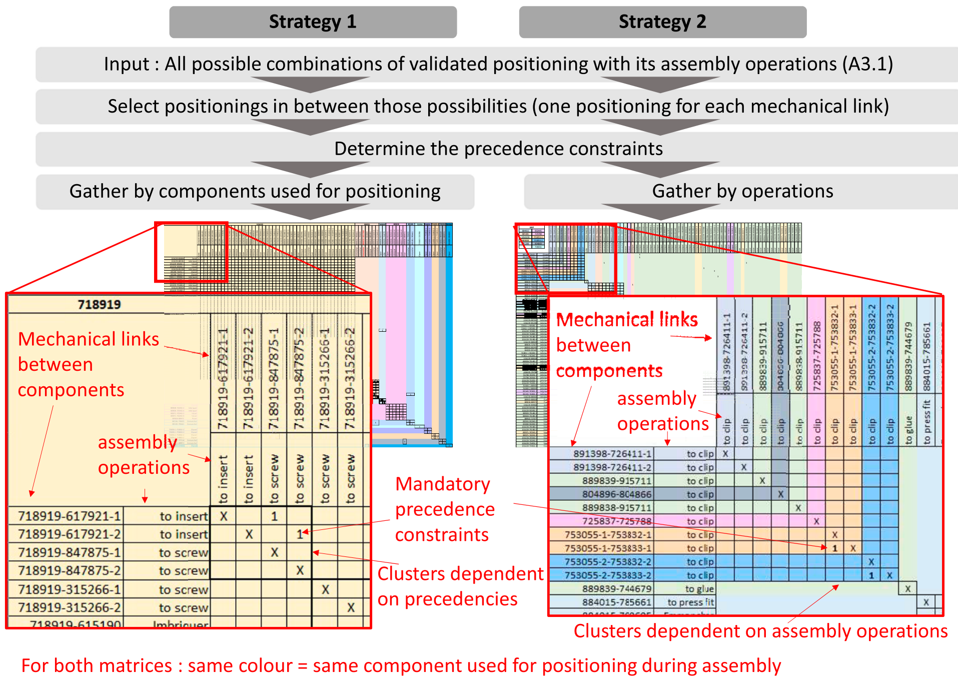

Figure 12. Strategies for the final determination of positioning in the assembly system.

priority over components which are special to a single product. The two strategies are described in Figure 12.

The first step of both strategies consists of the final selection of components for positioning in between all validated possible ones. One, and only one, component must be allocated to each of the assembly operations, i.e. the realisation of a mechanical link using a distinct assembly technology. This allocation can be done by using the assembly expert's knowledge only or by adding some additional criteria as for example minimising the use of highly personalised components, or eliminating positionings with flexible components (as for example cables) or components having mobilities (remaining degrees of freedom). Those additional criteria depend on the industrial use case. The allocation of mechanical links with their assembly operations to a component used for positioning is illustrated by the colour code in the matrices of Figure 12.

In the second step, the precedence constraints have to be added. No particular recommendation is given in this paper concerning the question of how to determine the precedence constraints. For the industrial application, a matrix representation has been chosen, similar to Design Structure Matrix applications: The matrices represent the precedence constraints for one same product. Mechanical links with the used assembly technologies are indicated in the lines and columns of the matrices. '1' in the matrix indicates that the mechanical link in the line must be realised before the mechanical link in the column. To simplify the representation, the transitivity rule is used (if A before B and B before C, then A before C).

At the last step, which is distinguishing the two strategies, the mechanical links with their assembly technologies are gathered into clusters which will later on determine the assembly system modules: for strategy 1, they are gathered by components used for positioning, for strategy 2 by used assembly technologies. Strategy 1 is a positioning-oriented approach. It will lead to an assembly system having a work flow from one positioning to another one, but the use of different assembly technologies during one same positioning is possible. Strategy 2 is an assembly technology-oriented approach. It will conduct towards an assembly system where the assembly system modules are dedicated to one assembly technology but different positionings are used inside the module. These differences are highlighted at the bottom of Figure 12. The most important information is linked to the colour code: the colours indicate the used positioning (same colour = same component for positioning). Clustering is done either by positioning and precedence constraints on the left-hand side, or by assembly operation on the right-hand side. Two conclusions become evident:

(1) If a gathering by components used for positioning is chosen (left side of Figure 12), it can be seen that one positioning covers almost two-thirds of the mechanical links and the other nine positionings are needed for the one-third left.
(2) If a gathering by assembly technologies is chosen (right side of Figure 12), the positioning has to be diversified. Four assembly technologies are dominating as they cover the majority of the mechanical links.

The implications of both strategies for the identification of a multi-product assembly system architecture are detailed in the next subsection.

Return of experience: The step of identifying a set of validated components for positioning has enriched the system design process of the industrial partner by highlighting different possibilities for positioning the product subassemblies. The gain is a deeper insight on possibilities to design the assembly system. The commonalities, similarities and differences in product design have been highlighted throughout the identification of components for common positioning. These results can also be used to give an objective, rationally reasoned feedback to the design department, to implement design for assembly (DfA) activities in order to improve the product family similarity in regard of the assembly system. The application of strategy 1 allowed to identify that one principal component for positioning could be used to assemble the majority of the product, especially as this component is usable across the entire product family. In former single-product assembly systems, another set of highly varying components is usually used for positioning in the main assembly flow. The gain is therefore a new solution space for the designer to build the assembly system architecture for a multi-product system.

Beside this value added by activity A3, a risk concerning its application has been identified. Due to the complexity of the information and the knowledge needed for the identification of valid components for positioning, their comparison across the product family, and the allocation of all feasible operations, this step cannot be automated and needs an assembly expert. As it relies on this person, the repeatability of the activity is not granted if the assembly expert changes. To master this risk, the formalisation of the expert's knowledge and the implementation of an information system should be studied.

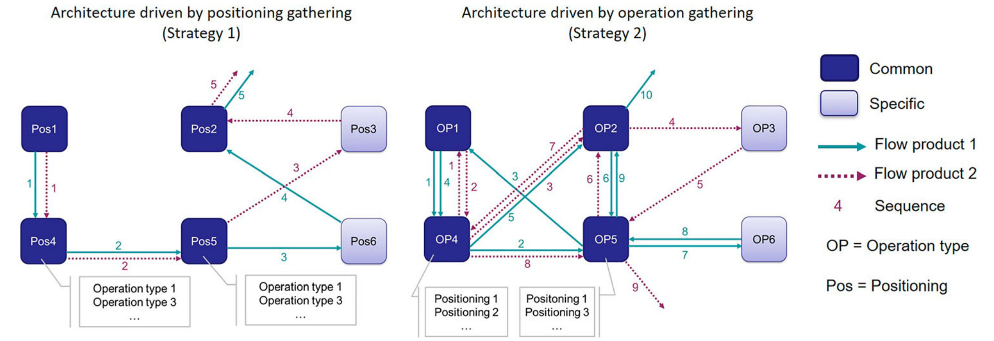

Figure 13. Example of the impact of strategy choices on the assembly system architecture.

4.4. Final identification of multi-product assembly system architecture (A4)

The final identification of the multi-product assembly system architecture aims at determining the main modules of the assembly system as well as the main assembly flow and the secondary assembly flow(s). The input is the result of the applied assembly strategy in activity A3.3. The global assembly system architecture can now be defined based on the tables shown at the bottom of Figure 12. The clusters in the matrices define the macro-modules of the assembly system and the flow between those macro-modules is defined by the precedence constraints. A system macro-module is here defined by the content of the matrices: it contains the knowledge about the components to assemble, the used assembly technology, the component which is used to position the subassembly during the assembly operations, and the precedencies of all assembly operations inside the module. In reality, a macro-module can correspond to one workstation or a group of workstations. Based on the two strategies, a set of possible system macro-architectures can be determined. An example is illustrated in Figure 13, the macro-modules are in blue, the assembly flow between the modules is indicated by the arcs. The assembly sequence is indicated with numbers. On the left-hand side, the modules are organised by components used for positioning, on the right-hand side by assembly operations.

The assembly flows are based on the precedence constraints. It can easily be identified that a strategy of assembly modules dedicated to assembly technologies (strategy 2, right-hand side) leads to complex work flows with several round trips to cells already used. In opposite, the positioning-based strategy 1 has a single directed work flow (left-hand side). By the identification of compatible positionings, it can be determined which module is dedicated to a particular product and which modules can be used for multi-product assembly.

In the first time, the principal positioning is defined, and used for the main assembly flow. The component used for this positioning should be similar and compatible across the product family. For the secondary workflows, an analysis of the content across the product family has been realised and different strategies have been compared. Figure 14 gives an overview of all determined positionings, their occurrence and compatibility in the product family from P1 to P7. The black line represents the principal positioning. If a component is mentioned in the table, it means that it can be used for positioning. The columns

	P1	P2	P3	P4	P5	P6	P7
Principal positioning	**Body 1** *variant 1*	Body 1 *variant 2*	Body 1 *variant 3*	Body 1 *variant 4*	Body 1 *variant 4*	Body 1 *variant 5*	Body 1 *variant 6*
Positioning 1	**Spring** *variant 1*		**Spring** *variant 2*	**Spring** *variant 2*	**Spring** *variant 2*	**Spring** *variant 2*	
Positioning 2	**Lever** *variant 1*	**Lever** *variant 2*	**Lever** *variant 3*	**Lever** *variant 4*	**Lever** *variant 5*	**Lever** *variant 6*	
Positioning 3		**Coverplate** *variant 1*	**Coverplate** *variant 2*	**Coverplate** *variant 1*	**Coverplate** *variant 1*	**Coverplate** *variant 3*	**Coverplate** *variant 1*
Positioning 4		**Body 2** *variant 1*	**Body 2** *variant 2*	**Body 2** *variant 3*	**Body 2** *variant 4*	**Body 2** *variant 5*	
Positioning 5		**Fixture** *variant 1*	**Fixture** *variant 2*	**Fixture** *variant 3*	**Fixture** *variant 3*	**Fixture** *variant 4*	**Fixture** *variant 5*
Positioning 6			**Interface 1** *variant 1*	**Interface 1** *variant 2*	**Interface 1** *variant 3*		**Interface 1** *variant 4*
Positioning 7		**Interface 2** *variant 1*	**Interface 2** *variant 2*				**Interface 2** *variant 3*
Positioning 8			**Cover** *variant 1*			**Cover** *variant 1*	
Positioning 9				**Motor 1** *variant 1*	**Motor 1** *variant 1*		
Positioning 10				**Motor 2** *variant 1*			**Motor 2** *variant 2*

Green: common positioning
Orange / **blue**: specific positioning

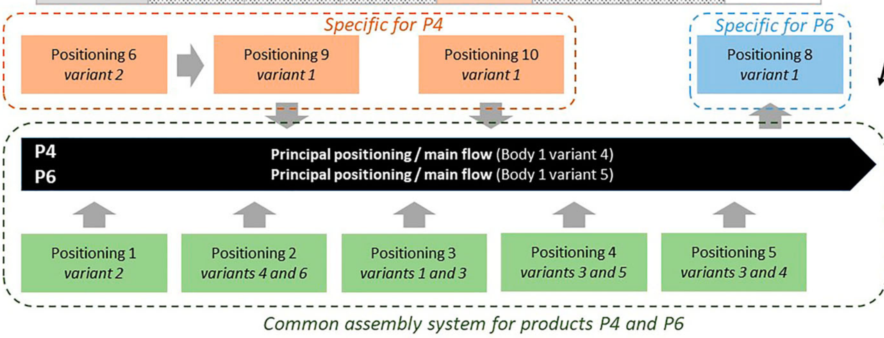

Figure 14. Positioning analysis for principal and secondary assembly flows with example of a multi-product assembly system for P4 and P6.

indicate the concerned product and the lines regroup a common positioning. The intersection of column and line indicates the component variant which is used for each product. Concerning the assembly system architecture identification, three possibilities have been analysed:

- N°1: Mono-positioning/multi-technology (one cell for each positioning),
- N°2: Multi-positioning/mono-technology (one cell for each assembly technology used),
- N°3: Multi-positioning/multi-technology (gathering by consecutive subassemblies).

The result of the analysis is that the possibility n°3 generates a harmonious assembly flow but complexifies strongly the system module design as it has to cope with different components for positioning and different assembly technologies which disqualifies its application. As mentioned previously, gathering by assembly operations (n°2) generates more complex assembly flows. In addition, work cells with one positioning and multiple technologies are considered less costly than cells with one assembly technology needing multiple positionings. In consequence, the possibility n°1 has been chosen for the determination of the modules in the secondary assembly flow. The final result (principal work flow, secondary work flow) is illustrated at the bottom of Figure 14.

The figure illustrates the macro-architecture of a multi-product assembly system. The colour code of the modules is the same as one of the positionings in Figure 14, illustrating a multi-product assembly system architecture for P4 and P6. It should be noted that it is possible to detail each element of the macro architecture as the mechanical links (and therefore the components to assemble), the used assembly technology and the precedence constraints are known for each of the modules. This information has been gathered and formalised during activity A3 and can now be used for the preliminary design and analysis of the proposed multi-product assembly system architecture.

Return of experience: The application of the positioning-oriented method has provided several answers to the industrial partner which is challenged by the product variety. The pertinence of a positioning-based reasoning has been put into evidence. As a benefit, the identification of the main components used for positioning has revealed the potential of a multi-product assembly system. But it has also revealed the need for future DfA actions which should be implemented, focusing on the design of shared and standardised interfaces for the subassemblies across the product family. The subdivision into a common main flow and secondary flows which can be shared, reconfigured, or dedicated allows to handle the variety induced by product variants in the family.

As for the previous activity A3, the weak point of activity A4 is the strong impact of the assembly expert's choices on the final result. The expert's knowledge is needed to handle the complexity of the task but impacts the repeatability and robustness of the activity. In addition, the identification of precedence constraints in complex assemblies with some hundred mechanical links has been revealed fastidious. It underlines again the need to formalise the expert's knowledge and to implement an information system to save and reuse already generated knowledge and information.

5. Discussion

A detailed return of experience on the industrial application has been given at the end of each subsection of the case study. This section aims at providing critical feedback on the research questions presented at the beginning of the article and the two strong hypotheses used during the case study. The three following research questions have been introduced and are discussed point by point:

5.1. How to identify a consistent product family concerning design similarity, process similarity?

This question concerns the statement that product variant analysis needs indicators analysing partial similarity. A set of indicators proposed in (Stief et al. 2019; 2018) is used in this case study. It is the 3rd application of the indicators to the products of the industrial company. The threshold for product gathering, defined during previous research work, has been confirmed. However, their application in the partner company has been confronted to the barrier of modelling and analysing the complex products. The input tasks are, even if partially supported by a software prototype, fastidious and a possible source of errors impacting the output of the method.

5.2. How to determine common positioning and fixturing which is an enabler for a multi-product assembly system?

From the industrial perspective, the positioning-based design method has been applied to a representative product mix in the examined product family. The method has been shown to be able to cope with product and process variability. Throughout the industrial application, the proposed method brought an added value to the reflections of the industrial company: a DfA process has been initiated by highlighting the differences and similarities of components for positioning. Their lack of standardisation represents a barrier for shared multi-product assembly system architectures and a targeted DfA could ease their design. The presented case study relies on existing, industrialised products and the designs are frozen. However, it is possible to apply the method to new design. The product models which are used in activity A1 can be generated based on information provided by CAD models and the assembly operations chosen by the product designer. It means that an application on new design is possible when a product architecture and CAD model have been defined.

5.3. How to determine the global architecture of the final multi-product assembly system?

Two hypotheses are used to answer this question: (i) when similar positioning and assembly operations occur in the subassemblies of two different products, then their assembly can be carried out on a shared system work cell, and (ii) the main flow is determined by components for positioning which are similar in the product family and which gather a maximum of assembly operations. The first hypothesis, based on work presented in (Stief et al. 2023), has been successfully applied. However, the criteria remain on a macroscopic level of assembly technology and component similarity. A more detailed view including the fixture needs and process details can be added. The second hypothesis is applied as the industrial partner wished to keep a linear main flow. A modification of the criteria for the allocation of operations to positionings is possible. With this modification, other layouts as for example a cellular manufacturing system can be generated.

To sum up, the method has been successfully applied for the generation of a solution space which has not been considered yet. The understanding of the method and its activities has been judged easily by the industrial partner. Also, the analysis of components for positioning has revealed opportunities to allocate operations to the main and secondary flows which have not been studied before.

6. Conclusion and perspectives

Increasing product variety and more and more unstable market environments push the manufacturing industries towards the experimentation and implementation of new production paradigms as it becomes difficult to make dedicated manufacturing lines profitable. New paradigms as reconfigurable manufacturing, co-evolution of products and systems, and delayed product differentiation (DPD) have emerged. Compared to those concurrent approaches in literature, a new method has been introduced in this paper, consisting of four activities: (A1) the modelling of a product variety with its physical and functional architecture to enable similarity comparison; (A2) the similarity analysis of a product variety in order to identify a consistent product family based on similarity metrics; (A3) the identification of components which can be used to position subassemblies during the assembly steps and the identification of common ones in a product family; and finally (A4) the identification of a multi-product assembly system architecture for the product family based on the common positioning. The here presented method has shown its potential by supporting the identification of multi-product assembly system architectures even if the product family has not been conceived with DfA methods or for DPD. This advantage makes the method applicable in industrial sectors where the customer's influence on the product design is strong, as it is the case of suppliers in the automotive industry.

The perspectives for further work are oriented on the one hand side towards a better support for its application, and on the other hand towards its integration to linked research issues. Concerning the optimisation of the method, it has been emphasised by the case study that the modelling activity needs more support. In this context, the generation of a rule set should be examined for more robust product modelling. Also, some automatic verifications could be useful to signal the most recurrent modelling errors. In addition, for the activities concerning the identification of components for positioning, the formalisation of knowledge and the generation of a database supporting positioning identification and its compatibility analysis could help to increase the repeatability of the activities. In addition, a software support for positioning selection and positioning strategy application would minimise the impact of the individual experience of the assembly expert.

Concerning the related research issues, further work should consist in linking the approach to reconfigurable manufacturing system design methods. Especially for the secondary assembly flows, it will be interesting to identify the perimeter and potential of reconfigurable assembly cells. The aspect of modular design should also be integrated through links to DfA and modularisation approaches, on both sides: for the assembly system and for the product. For the assembly system, modularity can help to overcome the problem of idle stations and by-passing moves in linear multi-product assembly systems by branching the assembly flow in a cellular layout. Also, plug-and-play modules can be used to ease reconfiguration. For the product, based on the components used for positioning, a modular design can be implemented: needed variety should be achieved by personalised modules around standardised interfaces which ensure the ability of using shared multi-product assembly systems. In the context of DfA, an application of the method the other way around should be investigated: in the current case study, the product family conditions the assembly system. However, the approach could also be used to reuse (entirely or partially) the assembly system by propagating constraints to the product design, especially concerning the interfaces used for positioning.

Last, the proposed assembly system architectures can be optimised by operations research approaches, adding positionings as supplementary parameter. In this way, cost criteria can be combined to the analysis which is until now based on technical criteria.

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