A methodology for production system design driven by product modelling and analysis – application in the automotive industry

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ABSTRACT
This article synthesises the return of experience of performing a product variety analysis for a (supplier in the automotive sector) that haven't had yet a product variety management strategy. This paper is part of a multi-year research project on the design of reconfigurable production systems. The contribution is (i) to present at a glance the developed strategy of product similarity assessment and (ii) to underline the industrial benefits of this similarity assessment obtained as a result of the industrial case studies. First, the article reminds, in the context of product variety, a developed methodology to assess product similarities by four indices. These consider the functions, product structures and the way to assemble them. Second, the focus is put on the benefits of their application through three industrial use cases: during the design of a new product identifying its impact on the manufacturing system, identifying the fittest production line for a new product to assemble and generating a new adapted production line by gathering products belonging to the same product family. All benefits are illustrated through the results of the industrial case studies. These are anonymised due to confidentiality issues.

KEYWORDS
Manufacturing system design; design for assembly; variety management; product analysis; methodology

1. Introduction

Since the 1980s, companies have to face strong challenges due to the changing market environment (Koren 2010): mass customisation and reduction of time to market, leading to the reduction of time allowed to design both: products and their manufacturing systems. This new market configuration leads to a change in manufacturing strategies and in their design in the same way. Indeed, the market evolves from few product references produced in large lot sizes – performed by Dedicated Manufacturing Systems (DMS) often with short production times – to an increasing product variety having small lot sizes, which are incompatible with the cost and investments of this kind of manufacturing systems (Koren 2010). Facing these challenges, companies need tools and key parameters helping them on one hand to decide what kind of manufacturing systems (dedicated, flexible or reconfigurable) fits the best the product configuration and supporting on the other hand the design and development of this production system.

To support industrial companies in this evolving environment, the 'industrial chair on safe, reconfigurable and performing production systems' has been founded at Arts et Métiers Metz ('Industrial Chair' n.d.). The methodology and applications presented in this article are part of a multi-year research project in the context of the industrial chair. The research project and the part covered by this article are illustrated in Figure 1.

The methodology and its applications presented in this article are imbricated into the research project and related publications as indicated in Figure 1. Previous publications have detailed the aspects of product modelling (Stief et al. 2018; 2019), a new way to assess product similarity (Stief et al. 2020), and one application oriented to product design improvement in product families (ibid.). This article focuses on the applications of similarity assessment for production system design. To clarify all aspects, it is structured in the following way: Section 2 reminds related literature. A first glance is given to the interest of product variety assessment and management. Then the focus is put on similarity analysis methods and their applications for production system design. Then, Section 3 presents the developed methodology at first in a general way and then by reminding the proposed models and tools (modelling and analysis part of Figure 1). Section 4 focuses on the core of this paper which is the applications of similarity analysis for the design of production systems, detailing the product variety manage-

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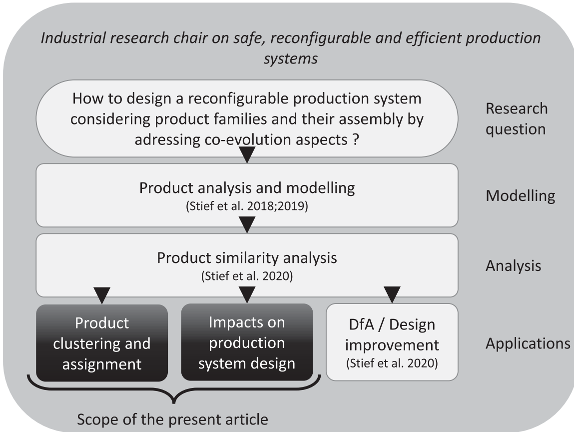

Figure 1. Scope of the article in the context of the research project.

ment part and the implications on the production system itself: (i) the identification and generation of a set of products that can be assembled in the same manufacturing system (a manufacturing-oriented product family) and (ii) the allocation of a product being under development on available production resources (dedicated or reconfigurable). Conclusion and perspectives close the paper.

2. Related literature

As mentioned in the introduction, industrial companies are faced to a still ongoing trend towards more product variety. How does it impact the production system? Products, production processes and production systems are three strongly linked elements. Therefore, increasing product variety means implicitly increasing complexity as product architecture is widely recognised as a crucial complexity driver (Hvam et al. 2019). This effects production processes and the production system. In addition, not only differences in architecture but also the part diversity has a direct effect on complexity by increasing the diversity of the production equipment (Samy and ElMaraghy 2012). In this sense Hu et al. (2008) identify production process complexity, linked to product variety, as an entropy function of the system complexity. Finally, according to (Roy et al. 2011), complexity through variety impacts not only production system but induces also supplementary costs. Figure 2, proposed by (Schuh et al. 2009), sums up the impact of architectural and part complexity on the production system configuration space (grey shaded zone).

At the same time, Figure 2 indicates the two levers which industrial companies can use to cope with the increasing complexity: (i) working on product variety (product variety management) and (ii) working on commonality/similarity (similarity assessment using similarity indices). Complementarily, these challenges are highlighted by (Tolio et al. 2010) and (ElMaraghy et al. 2013). As mentioned by the latter, the co-development of product variety and their adapted manufacturing systems is the key factor to ensure economic sustainability. In this context, the product variety management is driven by the co-evolution and the co-assessment of products, processes and production systems (Tolio et al. 2010). Last, to underline these statements, the literature review by (Bortolini, Galizia, and Mora 2018) highlights the importance of product variety management in the context of reconfigurable production systems.

2.1. Product variety management through product family identification

The previous section underlines the interest for industrial companies to deploy product variety management methods and, in this context, to use similarity assessment to manage increasing complexity in production. Before detailing the aspects of product variety management, it is necessary to define shortly the used terms.

Product variety in general is defined as 'the diversity of products that a production system provides' (Ulrich 1995). The link between product variety and a product family can then be qualified as the product family defines the parameters which are common and which may vary. It means that an individual product is an instance of the product variety defined in terms of the parameters of its product family (McKay, Erens, and Bloor 1996). Last, a product family can be defined as 'a set of similar products that share common technology platforms but have specific functionality/features to address a set of market segmentations and meet particular customer requirements' (Zhang et al. 2019).

In this context, several challenges exist in the domain of product variety management. Figure 3 illustrates the aspects addressed in this paper which are related to product design and production system design and their interactions. An exhaustive overview of challenges can be found in (ElMaraghy et al. 2013).

From a design point of view, modularity is a product design method outset to separate the fulfilment of functions into distinct design parameters (Suh 2001; Pimmler and Eppinger 1995; Eppinger and Browning 2012). This means, that each module is dedicated to one distinct function. A more morphology-oriented definition is proposed by (Salvador 2007), who defines modularity possibility to combine separable components or modules. As a result, modularity allows to design different products adapted to variable functions by using different module combinations (Fixson 2007; Bi et al. 2008; ElMaraghy et al. 2013; Krause et al. 2014). An

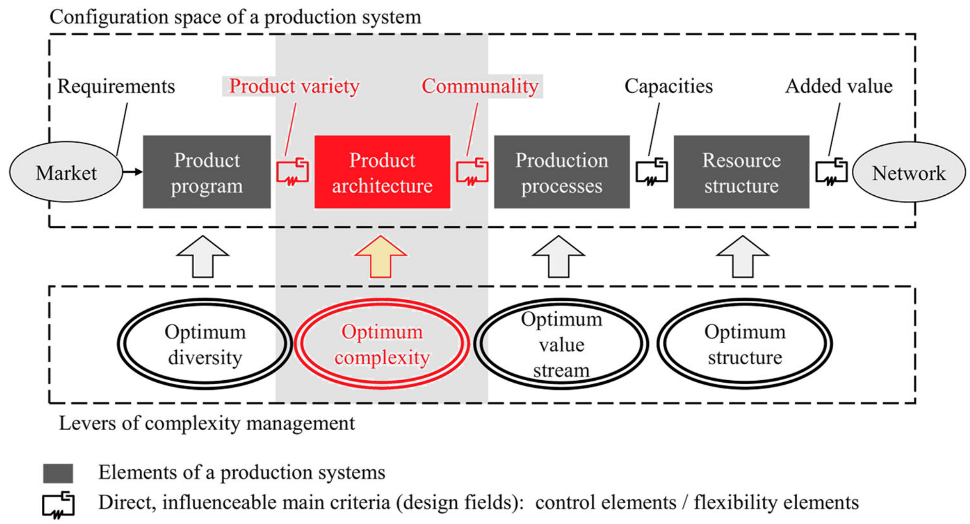

Figure 2. Complexity levers of a production system and their main influencers.

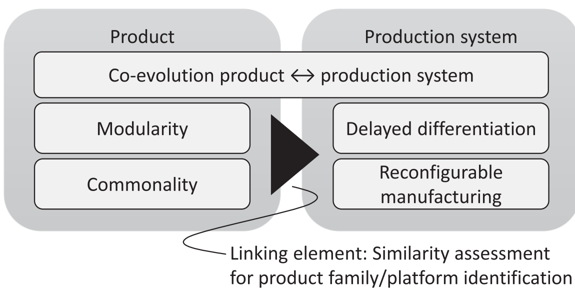

Figure 3. Variety challenges in the product and production system domain.

overview of economic impacts of modularity is given in (Hackl et al. 2020).

In complement to modularity, commonality concerns the mutualisation of components and modules towards a usability in a multitude of products. Consequently, it is defined as the number of components that are used by more than one product and is determined for the subset of a product variety (Ashayeri and Selen 2005). An exhaustive overview of literature concerning the use of commonality analysis in product family design is proposed by (Simpson et al. 2014), in particular the contribution (Pirmoradi, Wang, and Simpson 2014). An analysis of similarity indices and a set of four new ones are proposed in (Stief et al. 2020).

These two complementary elements, commonality and modularity, are related to product design. In the context of variety management, they can be used for the design of reconfigurable manufacturing systems which are designed for a part or product family (Koren et al. 1999; Mehrabi et al. 2002; Koren and Shpitalni 2010). The second possibility is to use them for delayed product differentiation production systems which are outset for product platforms (AlGeddawy and ElMaraghy 2010; Galizia et al. 2019; ElMaraghy and Moussa 2019). Differentiation is defined as the set of dedicated features of a product variety which should be postponed as long as possible in the production system (He, Kusiak, and Tseng 1998). Recent developments consist of combining reconfiguration with delayed product differentiation (Huang, Wang, and Yan 2018; Huang and Yan 2019). Finally, the co-evolution of products and production systems concerns the continuous adaptation of both of them to the ongoing market environment changes (Bryan et al. 2007; Tolio et al. 2010; AlGeddawy and ElMaraghy 2011; ElMaraghy and AlGeddawy 2012).

To conclude, the importance of product variety management to handle the complexity of both products and their production system has been proved in the previous section. However, though the approaches are well known now, their application to industry seems to be still an important issue. Two shortcomings have been identified throughout the literature review: Either the approaches are well established in the industrial application as for example Group Technology (Burbidge 1991; Waghodekar and Sahu 1984; Kusiak 1987), but are lacking capacity of considering variety induced by different degrees of component and technology similarities. Or the approaches try to propose more complex similarity analyses focusing principally on cost evaluation but do some facilitating hypotheses about technical similarity (e.g. Kumar, Chen, and Simpson 2009; Johnson and Kirchain 2014). On the side of the industrial applications, during the research project, it has been stated that even experienced production companies have an interest and potential in applying product variety management. One of its key elements is the identification of product families and product platforms, by identifying common and dedicated modules/components of the

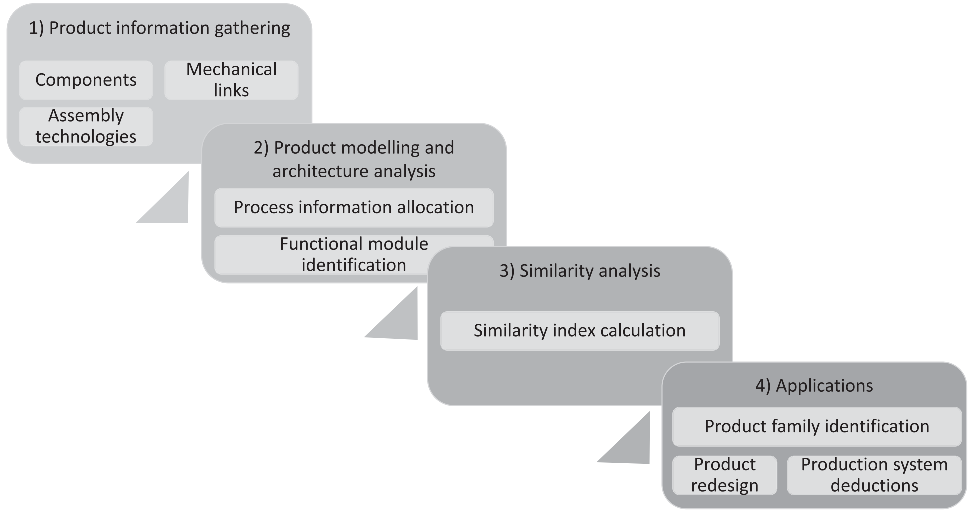

Figure 4. Methodology framework.

products. These are enablers for reconfigurable and/or delayed differentiation production systems. On the side of scientific research, throughout the literature review, it has been stated that older approaches have difficulties to deal with today's product variety. On the other hand, complex recent approaches propose cost-oriented analyses, but still lack methodological examination of variety and similarity on the technical level. In this context, to close this research gap, a new methodology framework is proposed, focusing on technical similarity. It has been applied on real-life industrial case studies. The methodology framework is presented in the next section focusing on the manufacturing system-oriented product variety identification and management.

3. Proposed methodology

The generic methodology framework is based on four steps which are described in Figure 4: (i) product information gathering, (ii) product modelling and analysis, (iii) similarity analysis and (iv) industrial application. The contribution of this article focuses on the application cases of similarity analysis for product family identification and production system deductions. To remind, the first three steps and the product redesign application are the object of previous publications as detailed in Figure 1. In the following, the main content of the steps needed for similarity analysis is briefly summed up. The aim is to ease the understanding of the complete methodology.

At the beginning, the aims of product variety identification have been defined with a causality analysis concerning the co-evolution of products, processes and manufacturing systems. These aims are mapped to the product models and their use for manufacturing system design as synthesised in Table 1. Needed information can be extracted out of product documentation (first line). For products under development, the preliminary CAD files are available; for other products being already under production, the whole product documentation including process plans can be analysed. A physical product structure representation is generated out of the gathered product information (second line of Table 1).

On this level, the commonality of assembly technologies can be analysed, considering that the assembly technology solution impacts directly the requirements for assembly cells in the production system and influences therefore the selection of a technical solution. In complement, on a more macroscopic level, the product architecture influences the manufacturing system architecture. In the context of high product variety, analysing the functional product architecture enables a macroscopic view of the product structure independent from the number of parts (line three of Table 1). On this level, modularity is addressed by identifying common and differing modules for a product variety. The identified product modularity impacts the needed modularity of the production system.

Therefore, in the proposed methodology, the similarity analysis is performed at two modelling levels: (i) at the level of elementary assembly information (assembly technologies), looking for mutual use (commonality) of assembly technologies. And (ii) at the functional architecture level describing the product structure by the mean of functional modules (modularity). At this level, the aim of the similarity assessment is to analyse the product complexity and the product capability to be modular. In the following subsections, the tools and methods developed in the context of the multi-year research project are introduced to help the reader to understand the application section. Those are used to fulfil the different working steps of the methodology in the context of the industrial case study.

Table 1. Description of models, content and causality.

Model	Use	Aims	Content
CAD, drawings and process plans	Information gathering for product modelling	Extract detailed production information: components, mechanical links and assembly technologies	Product representation by displaying its real shape, detailed component and production information
Physical product structure representation	Assembly similarity	Link between functional architecture and detailed product representation; Gather elementary assembly information for production system operation selection	Product representation by displaying its components, mechanical links, used production technologies
Functional product architecture	Architecture and complexity similarity	Analyse macro product structure analysis for assembly system architecture determination	Product representation by displaying functional modules and their relations

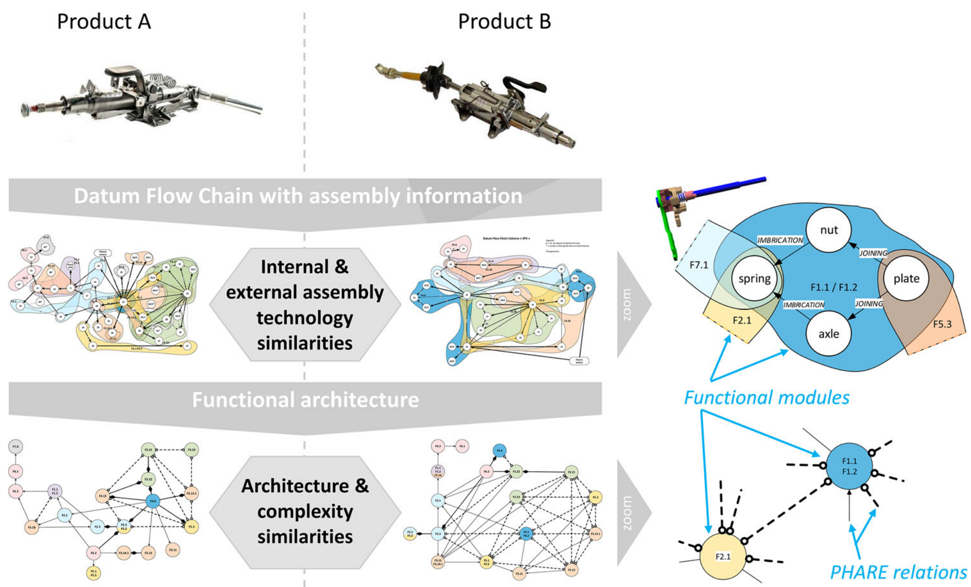

Figure 5. Product representation framework.

3.1. Product information gathering and product modelling

Using basic product information (part lists, assembly drawings, CAD, and -if possible-assembly process plans), the products models are generated. An overview of these models is given in Figure 5. Concerning the physical product structure, a graphical representation of existing products (Figure 5) is generated using a new model developed out of Datum Flow Chain (DFC) models. It represents the product as an oriented graph where components are nodes and mechanical links are arcs. The standard DFC model itself is an evolution of the liaison graph (Bourjault 1984) by adding information about positioning and eliminated degrees of freedom on the arcs (Mathieu and Marguet 2001; Whitney 2004). To adapt this model to the presented methodology, additional information is added. The functional allocation of each component based on a single functional decomposition of products and the assembly technology is indicated by coloured zones in the graph. And assembly information is added for each mechanical link. A detailed excerpt of an adapted DFC is illustrated in Figure 5, on the middle right-hand side.

The functional allocation of each part enables the identification of functional modules. These are here defined as a set of parts which perform a technical function. One part can contribute to several technical functions. At this stage, no assumption is made about the fact that the product is uncoupled or not.

Concerning the functional architecture, represented by a graph called PHARE, is generated from the adapted DFC. A detailed methodology is available in the related previous communications. The acronym PHARE stands for physical and functional architecture. In this representation, each node represents a functional module (coloured zone in the adapted DFC). The example in Figure 5 shows the link between the DFC and the PHARE representation by considering the functional modules. In the PHARE representation, the nodes are linked with arrows detailing the four possible relations between the functional modules: identity, inclusion, partition or contact. For example, if two functional modules are performed by several common parts, their interaction is then considered as partition (as illustrated in Figure 5, considering the functional modules F1.1/1.2 and F2.1). By extension, if all the parts allocated to two functional modules are strictly the same, their link is identity (as illustrated by the functional modules F1.1/1.2 in the same figures). The whole possibilities have been described in detail in the mentioned previous publications.

The main property of the PHARE is that all products are represented with the same number of nodes because they are based on the same single functional decomposition. The component number, their references and the component types are no longer influencing the product representation and then its analysis.

As detailed in Figure 5, the two product models allow to analyse the impact of the product on the production system on two detail levels: The PHARE model which represents the product architecture and its complexity related to the production system architecture. And the more detailed extended DFC model, as it contains assembly information, is related to the production cell. The linking element between the product and the production system is then the similarity analysis. The advantages of the similarity assessment with the adapted DFC and PHARE at several granularity levels have been highlighted in the related publications. The next section sums up the proposed set of similarity indices, synthesising the proposed similarity evaluation method.

3.2. Product-similarity-evaluations based on their structure and assembly technologies

As detailed at the end of the literature review section, the aim of the similarity analysis is to provide a detailed variety-sensitive analysis of differences on the technological level, i.e. the product architecture and used assembly technologies. Thus, at the functional architecture level, the aim of the similarity assessment is to analyse the product complexity and the product capability to be modular. So, the first index S_1 represents the capability of the same functional module of two products to be modular for a product variety (1).

It evaluates for each functional module the ratio of common PHARE relations compared to all of them. A high value indicates a design similarity for the same functional module in different products. It should be noted that for the four indices, 'common' means that the same element, PHARE relation or assembly technology, occurs for the same functional module in different products.

$$S_1 = \frac{\text{Common present PHARE relations}}{\text{Present common and unique PHARE relations}}\,\% \tag{1}$$

The second index S_2 displays the complexity similarity of interactions of the same functional module of two products (2). It measures the difference in the number of PHARE relations for each functional module. A high value means that the same functional module in different products has the same number of relations to the other functional modules.

$$S_2 = \frac{\text{Common present} + \text{ common absent PHARE relations}}{\text{Number of possible PHARE relations}}\,\% \tag{2}$$

To give an example: Imagine a product family having five functional modules. Each of them is represented in the PHARE by a node. The overall number of possible PHARE relations which one node can have is therefore four (i.e. one relation to each other node). It is calculated by the 'number of functional modules – 1'. For product one, the functional module 1 is linked to modules 2 and 3, and has no link to modules 4 and 5. For product two, the same functional module is linked to module 2 and has no link to modules 3, 4 and 5. Therefore, S_1 is calculated 1:2 = 50%. And S_2 is calculated 3:4 = 75%.

The index couple S_1 and S_2 is the link from product analysis to production system deductions through the hypothesis that the similarity of the product design, architecture and complexity allows to estimate the production system architecture: Similar products can be produced on similar architectures whereas dissimilar products need more complex production system structures to handle the dissimilarities.

At the assembly information level, the adapted DFC is used for the similarity assessment (Figure 6). It has to be distinguished between two cases: the analysis of assembly technologies used inside the scope of one functional module (S_3). And the analysis of assembly technology used to link two functional modules (S_4).

$$S_3 = \frac{\text{Common internal assembly technologies}}{\text{Common and unique internal assembly technologies}}\,\% \tag{3}$$

$$S_4 = \frac{\text{Common external assembly technologies}}{\text{Common and unique external assembly technologies}}\,\% \tag{4}$$

In consequence, S_3 evaluates the similarity of assembly technologies used to assemble the parts contained by considered functional module (3), i.e. technologies used to assemble components belonging to the same functional module; S_4 evaluates the similarity of assembly technologies used to assemble the considered functional module with others, i.e. technologies used to assemble components belonging to different functional modules (4).

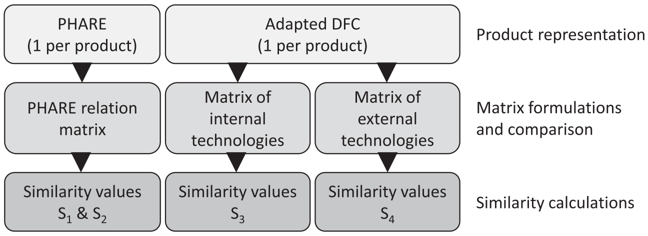

Figure 6. Similarity assessment process based on the product models.

Related to the production system, it means that the third index S_3 represents the capability of the same functional module of two products to be assembled with the same production cells (using an identical assembly technology). The fourth index S_4 represents the capability to assemble the considered module with the others with the same production cells. It has to be noted that the definition of assembly technologies determines the analysis granularity level (e.g. a category 'welding' is less detailed than 'electric arc welding'). The following section provides a more detailed description of the similarity indices impact on the production system.

4. Using methodology framework with the developed tools and methods: benefits for companies

This section illustrates how the functional architecture similarity indices presented in the previous section are helpful during the design of both the product and its manufacturing system in an industrial environment. These use cases were all tested and validated in real industrial products provided by our partner. The functional decomposition has resulted in a maximum of 22 technical functions, which implies that a product may have maximum of 22 functional modules. The characteristics of the product variety are summarised in the upper part of Figure 8.

At the moment of the case studies, no particular strategy for product variety management had been in use in the partner company. As well, no standardisation or modularisation policy had been used for product design. Every new product is designed from scratch following the customer requirements and therefore highly dedicated to single customers.

Figure 7 details the methodology followed to obtain the product analysis results used in the application cases presented in this section. Note that the methodology is one possible use of the methodology framework (see Figure 4) using the previously presented tools. In this representation, the main inputs, outputs, resources and constraints are named (arcs between the activities). It shows how the proposed tools can be used to apply the generic methodology on an industrial problem. During the industrial case study, all four indices are evaluated for all functional modules of each of the ten products. For manual application, it means that 20 product representations have to be generated and analysed (10 adapted DFC and 10 PHARE). The complexity of each DFC graph can

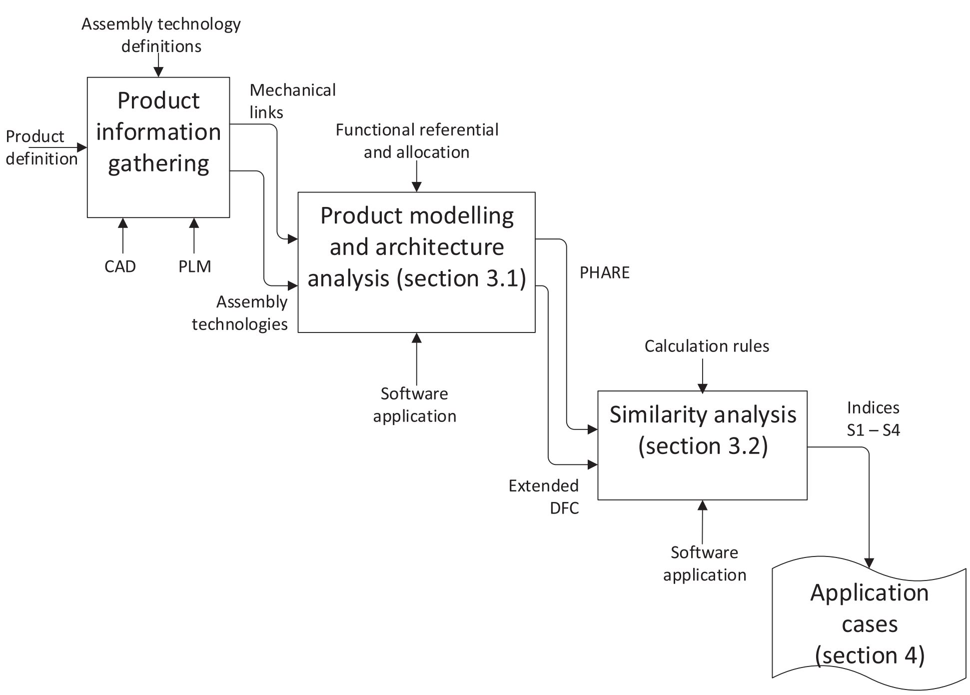

Figure 7. Methodology used for product modelling and analysis.

Product variety handled by the software application during the case studies

Product variant	Component count	Mechanical link count	Product type	Functional modules (max 22)
Product 1	56	73	Mechanical	20
Product 2	19	28	Mechanical	15
Product 3	46	72	Mechanical	18
Product 4	38	57	Mechanical	19
Product 5	84	130	Electrical	19
Product 6	41	56	Mechanical	19
Product 7	75	121	Eletrical	20
Product 8	33	47	Mechanical	20
Product 9	44	57	Mechanical	19
Product 10	36	48	Mechanical	20

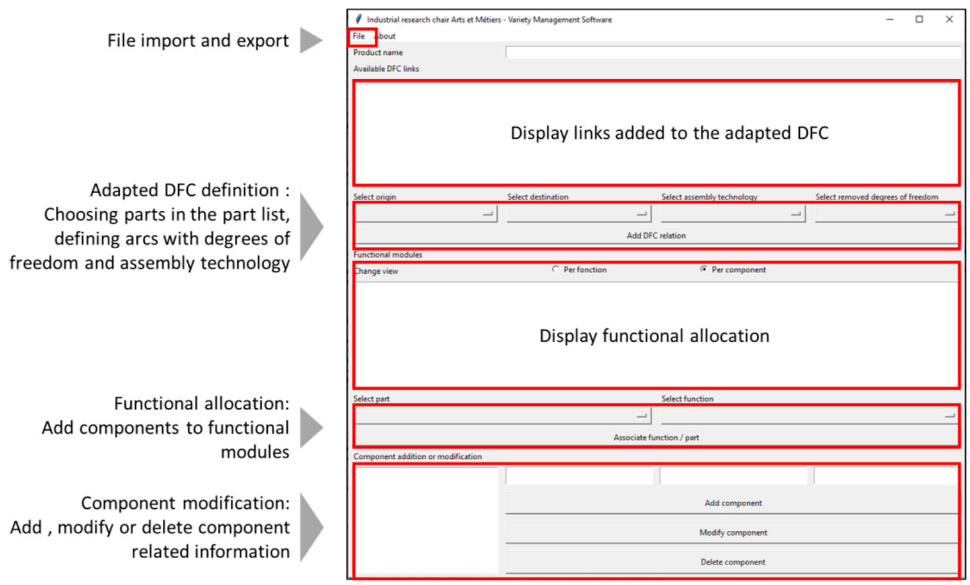

Figure 8. Product variety description and software application (user interface).

be deduced from the table in the upper part of Figure 8, as it displays each component and each mechanical link. For similarity analysis, 45 binary comparisons have to be made to cover the product range. Face to those inconveniencies, to speed-up their calculation time and to ease their use by a company, a software application coded in Python has been developed. Its main features are the following:

- Component list import from the PLM system;
- Definition of the adapted DFC by defining its nodes and arcs;
- Generation of the PHARE representation;
- Evaluation of the four similarity indices S_1-S_4.

This software application represents an additional result of the case study as it has been created in strong cooperation with the partner company and is now used by them for the modelling and similarity evaluation of a set of newly arriving products.

Figure 8 illustrates in its lower part one part of the software, illustrating the user interface dedicated to the product description, and more specially the data supported by the DFC graph. The benefit of using this software is that instead of the numerous models and comparisons, only the 10 adapted DFC have to be defined. All the next steps of the assessment process are automatically supported: from automatic PHARE generation, similarity index calculation to product comparisons or product family identification. The next sections detail these use cases.

4.1. Support to design for assembly and manufacturing system redesign

As explained in the previous sections, the developed similarity indices take into consideration both: the functional architecture and manufacturing viewpoints of a product to assemble. By using these indices, it is possible to identify early in the design phase of a product if

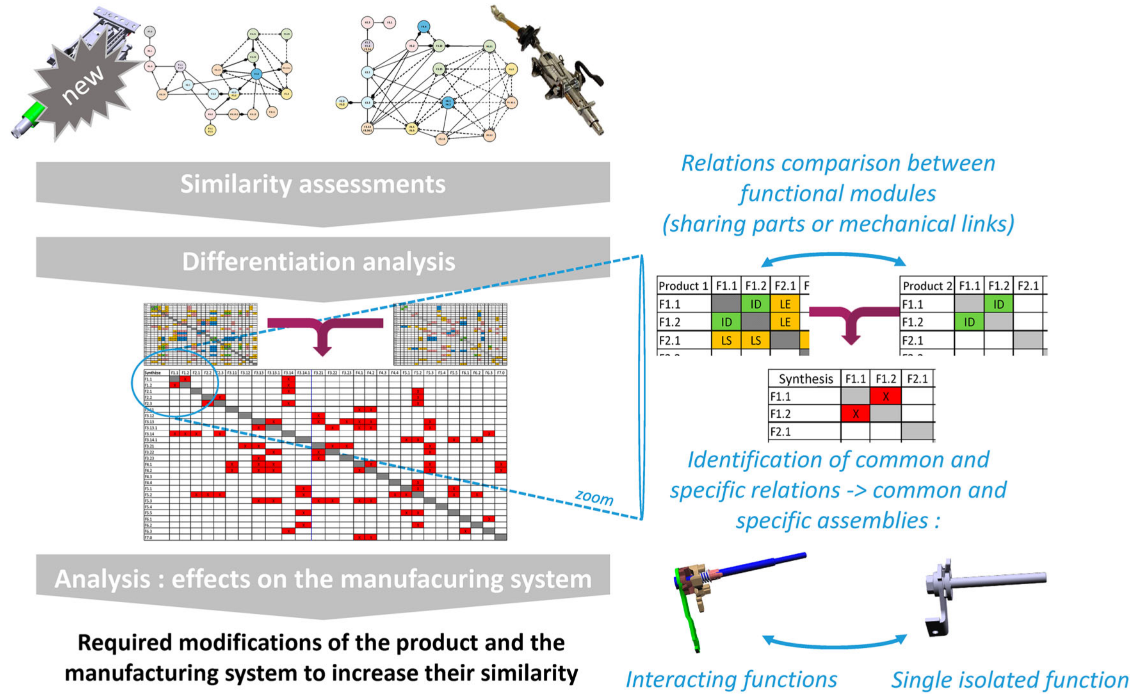

Figure 9. Comparison process between a product under design (new) and another one already manufactured.

product design choices (for instance architectural and/or assembly solutions) are far from or close to the ones previously designed in the company and currently under production. This analysis can be used in two ways:

(i) Either it can be used for the product redesign in order to identify variations in product design and to increase product architecture similarity for product family members; application detailed in (Stief et al. 2020).
(ii) Or it can be used to analyse product variations oriented to the manufacturing system to identify where differences due to product variety may cause difficulties in the manufacturing system design.

The second strategy can be applied to two different use cases: either a new product can be treated which has to be adapted to an existing family or a set of new products under development can be treated in order to increase the similarity between them. The approach is then based on the following working hypothesis: the more the design choices are close and similar, the more the manufacturing system will be easy to reconfigure or to adapt to this new product. For instance, the working hypothesis has been validated empirically during the case studies with the industrial partner.

As widely known today, the impact of the choices made during the design phase of a product is by far more important than the cost influence of the production department. 70% of the overall costs are determined by the design compared to 5% which are determined by production. At the same time, changes during the design phase are far less costly than changes during production, as the design department is only responsible of 5–10% of the real costs (Asiedu and Gu 1998; Laperrière and Reinhart 2014; Padfield 2018). Therefore, the benefits of the use case presented in this section help industrial companies to avoid costly changes because incompatibility problems have been detected to late, at the beginning of the production cycles (Rossi et al. 2019).

Figure 9 illustrates the process followed to identify the differences between two product designs and their possible effects on the manufacturing system. In the illustrated case, one of the products is under development which means that similarity analysis is based on its preliminary design documentation.

After the similarity assessment, two comparison matrices displaying disparities for each functional module are calculated. One compares the PHARE matrices (for product architecture comparison) and the other one compares the assembly technology matrices (for assembly comparison). Note that one of the two matrices is displayed in Figure 9.

All non-highlighted empty cells of this comparison matrix refer to a difference in the functional allocation or part assembly. For each of these cells, the effects of these design differences on the manufacturing system need to be analysed. Concerning the example shown in the figure,

Table 2. Manufacturing design decisions based on similarity assessment.

S1	S2	S3	S4	System choice
high	high	high	high	dedicated (multi-product)
high	intermediate	intermediate – high	intermediate – high	reconfigurable
high	intermediate	low	low	dedicated (to single product)
high	low	intermediate – high	intermediate – high	Flexible
high	low	low	low	dedicated (to single product)
low	low	—	—	NoGo decision

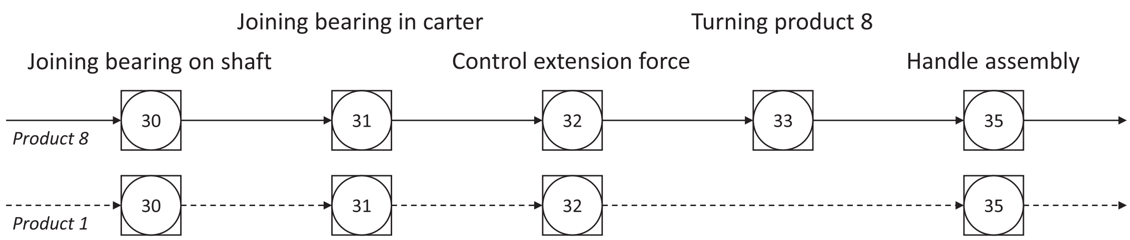

Figure 10. Excerpt of the process plan needing a supplementary module.

the difference is relied to two different technical solutions: the right example is a simple single-function solution whereas the left example represents a more complex solution which realises more than one function. In opposite to the previous tasks, this comparison cannot be performed automatically and needs an expert guided by the defined indices. Thanks to the approach, and to limit manufacturing system modifications which are costly and time-consuming, the manufacturing system designer should be able to propose changes to product design which are outset to ease the integration of the new product to the production line of the existing product (family). In a second step, after modification, the comparison matrices can be updated and the analysis process restarts in an iterative way.

The designer's choices can be guided by the analysis of the similarity indices: both couples of indices support the product design phases by limiting undesirable effects of design choices. Nevertheless, the indices S_1 and S_2 may be more interesting for the product designer emphasising product design improvement potentials. Whereas the indices S_3 and S_4 may be more interesting for the manufacturing system designer by emphasising differences in the used technologies. Indeed, S_1 index highlights that a functional module is differently designed on two compared products, S_2 index underlines the difference in the design complexity (number of parts and/or links needed to perform a common function). By analysing the values of both S_3 and S_4 indices, the designer can identify respectively the differences between the technical solutions used to perform a link between the functional modules or between the parts belonging to a functional module. This approach has been applied to an industrial case study which was linked to the production problems which the industrial partner company met during the industrialisation of product 8 (numbers refer to the ones of Table 2). This product has been introduced without a complete and methodological similarity analysis on the production line of product 1, which had at a first glance similar design and functionalities. During the integration, difficulties have been brought to the light which lead to costly changes of the production line (e.g. process differences and differences in the joining orientations needing supplementary modules turning around the subassemblies, see Figure 10).

Due to these difficulties, the similarity analysis following the presented method has been carried out later on. The new common production has already been built but the aim was to identify if there would have been another, more adapted solution. It revealed that the integration of product 8 to another production line, the one of product 10, would have been more adapted. This finding has been validated by the industrial partner who, after an internal evaluation, confirmed that a mutual production system for these products (1 and 10) would have been more pertinent. And applying the differentiation analysis as presented previously, the differences between the products could have been highlighted probably causing changes in the production system. Therefore, the case study has confirmed the empirical statements of the partner company and underlined the interest in using those analysis methods to provide an objective judgement for product integration to production lines. It highlights that the proposed method is a tool which can be used for design and the evaluation of design choices in regard to the production system.

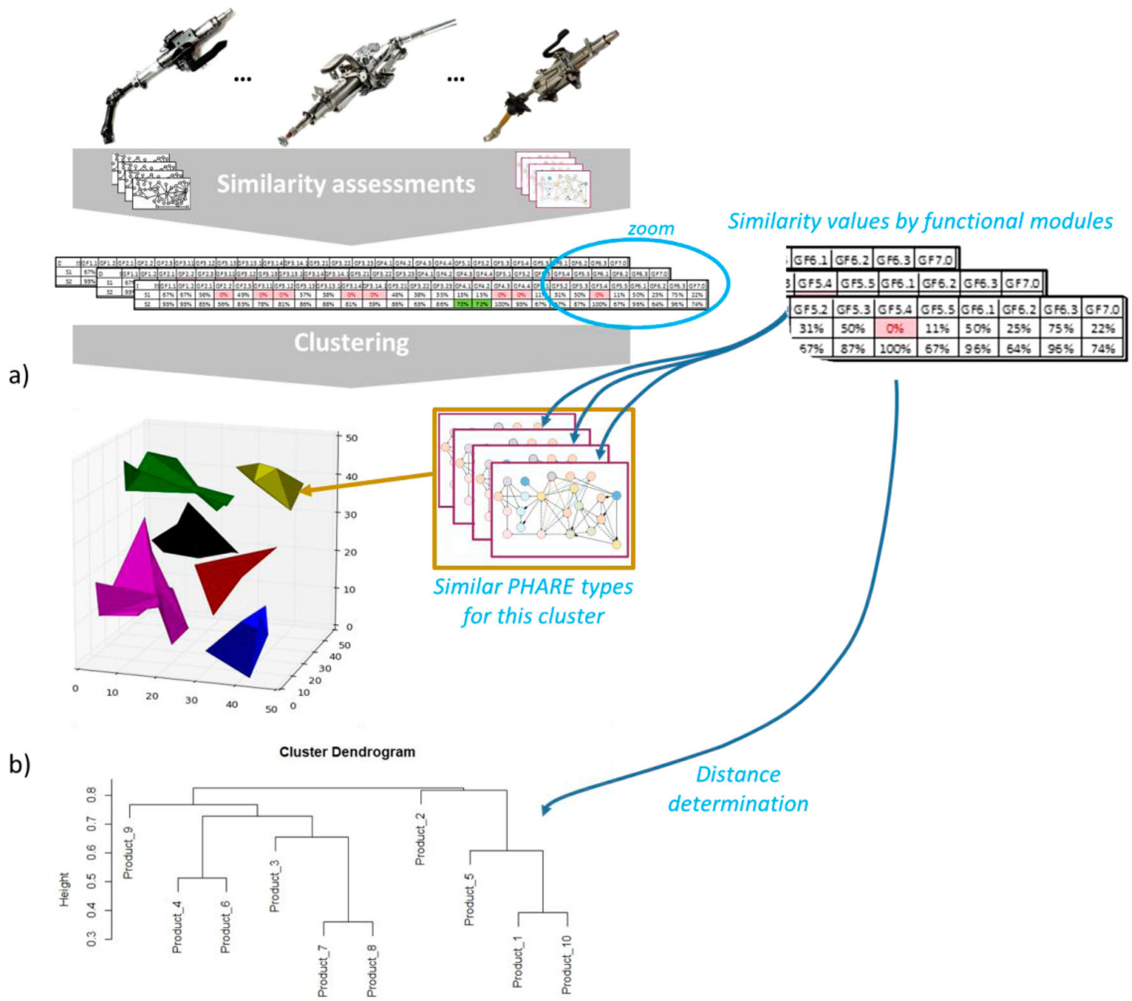

Figure 11. Use case 1: clustering of 50 virtual products into six product families (a) and dendrogram of the 10 use case products (b).

4.2. Support to the identification of product families

As explained in the literature review section, an important lever to help companies to handle complexity is the identification of product sets that can be considered similar (supporting product family identification). Using the similarity indices defined in Section 3, calculated on each functional module, it is possible to define similarity as a distance between two compared products. This distance is used for the identification of product clusters, and therefore product families. Here as well, two different use cases exist: Either, the approach can be applied to an existing product portfolio, an application interesting for a company having not yet developed a product variety management. In this case, the aim on the level of the production system should be to design one production system adapted for one product family of similar products. Or the approach can be used to decide on which product family a newly arriving product should be integrated. When there is an existing production system for this product family, it means in consequence that the newly arriving product is meant to be produced in the same production line type.

The top of Figure 11 illustrates the process performing the gathering of products to families according to the first use case. After modelling all products to analyse and gather, the similarity indices are calculated and their relative distances in multiple dimensions are assessed. The number of dimensions depends on the designer's choice and the granularity of his analysis. Indeed, it is either possible to aggregate the similarity indices into only one criterion to have a global glance to compare and group products, or to have a more precise view by considering each similarity indices (from S_1 to S_4) on each functional module. The latter offers a more precise analysis but complicates the interpretations due to the combinatorial multiplication of similarity values.

The clustering algorithm is based on the k-medoids partitioning approach and has been developed as part of the research project (Brunstein 2019). This approach aims at finding an allocation of product on families where all products belonging to the same family are very close to each other and where two families are far enough to be considered different. Since this iterative algorithm is very sensitive to its initialisation, it is coupled with a

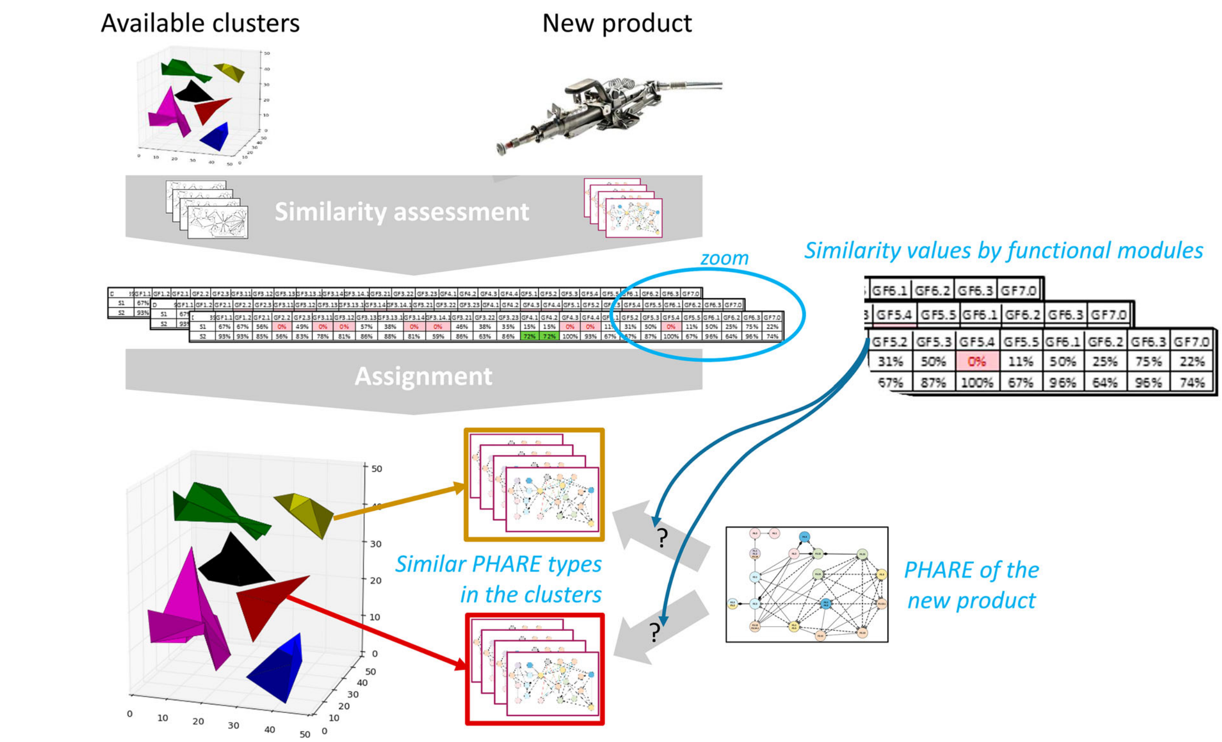

Figure 12. Use case 2: Assignment of a product to an existing product family.

genetic algorithm to find the best generation of product families. An example is given in Figure 11(a) where 50 virtual products have been analysed and gathered into six product families. To do so, an aggregation of the four similarity indices calculated on 22 functional modules has been realised. Each of the clusters represents a distinct PHARE pattern gathering a set of similar PHARE representations. For illustration reasons, this figure only displays a 3D projection of the 22 dimensions available, i.e. each axis represents the aggregated similarity value of a functional module (in %). Beside the clustering in a 22-dimensional space, a more classical hierarchical clustering approach can be applied to the results of the similarity analysis. As well either for each functional subassembly or for the entire products (through aggregation of the indices).

The outcome of a second application, hierarchical clustering, is illustrated in Figure 11(b): a dendrogram classifying the ten products of the industrial partner. The similarity values have been aggregated with the mean calculation and the similarities have been transformed into distances. The dendrogram has been realised with the open-source software R using the 'hclust' operation having the distance matrix as input ('distmat').

It can be seen that the clustering result of the dendrogram is consistent to the results of the disparity analysis presented in the previous subsection and supports through its statements: product 1 and product 10 have much higher similarity values than product 1 and product 8 and are even grouped together on the first level of the hierarchical approach (lower right-hand side of the dendrogram). This shows that the analysis of the product portfolio allows to identify product mixes minimising changes in the production line. The second use case (product assignment to existing families) is illustrated in Figure 12. In this case, the newly arriving product is compared to all the other products in order to determine the appropriate product family.

This second use case can be seen as the logical development of the first use case. It is prerequisite that all existing products have been modelled, their similarity has been assessed and they have been gathered into product families. It is therefore adapted to companies having already a product variety management strategy. The previously generated knowledge (use case 1) can be used during this application. The main effort by applying the two presented use cases is the modelling of the existing products. Once all products are modelled, their similarity information can be reused infinitely and only the newly arriving products have to be modelled. It is compared with the products already clustered in order to assign it to the cluster with the highest similarity. If no similar cluster exists, a new one may be generated.

Through several industrial case studies on ten different products of the partner company, the signification and pertinence of the similarity values have been verified. The cooperation led to the project of the introduction of a product variety management approach according

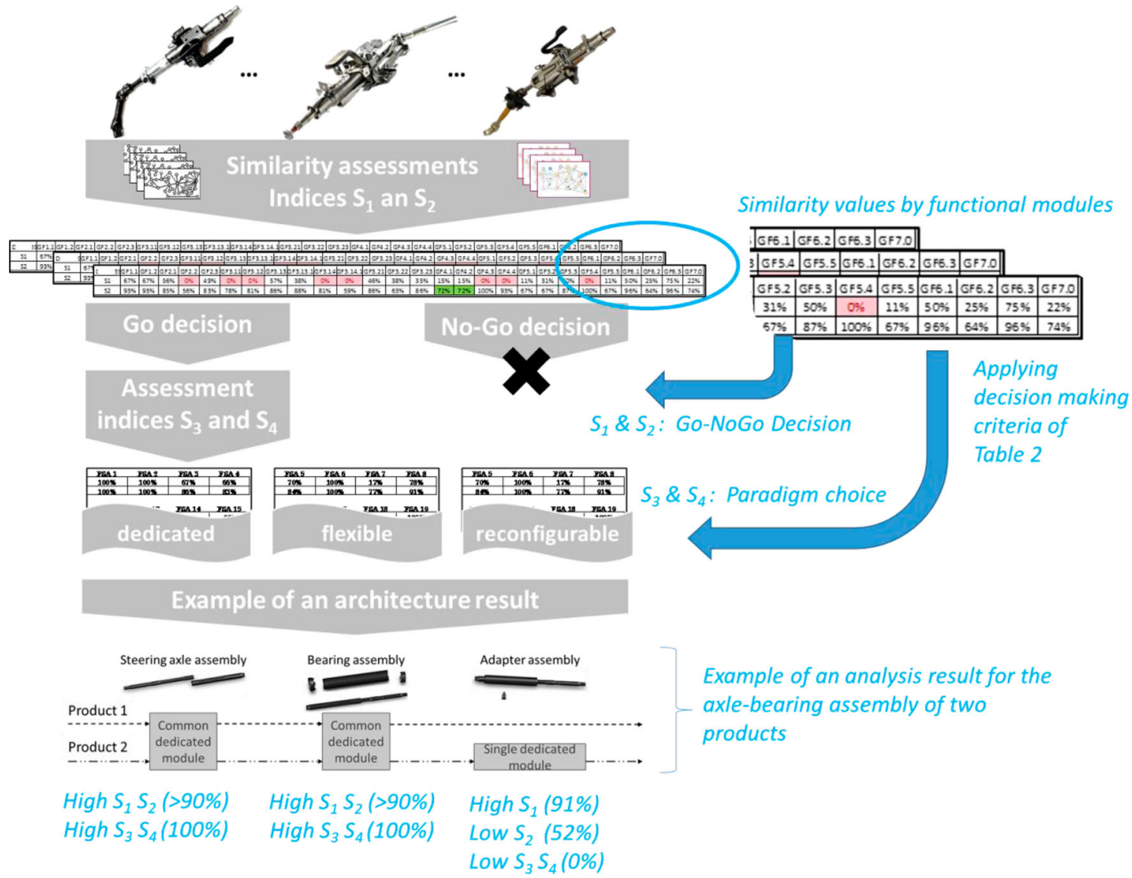

Figure 13. Similarity assessment for production paradigm choice and its impact on the system architecture.

to the two use cases in this company. Furthermore, the knowledge obtained during the modelling and similarity analysis steps can be reused for the product variety analysis method presented in Section 4.1.

4.3. Support for the design of dedicated or reconfigurable manufacturing systems

The hypothesis behind this application of the PHARE and its similarity evaluation is the following: A product can be characterised by its PHARE representation (i.e. the product 'fingerprint'). Then, a product family can be defined as a set of products having similar fingerprints. Overlaid with different standardised production system architectures, the potential of reconfigurable assembly is situated on the intersection of families with appropriate production system architectures.

To support this approach, by extension, the presented product comparison methodology allows to identify which existing manufacturing technology can be used to assemble it or which type of manufacturing system (reconfigurable, dedicated, flexible) is needed (Figure 13).

An overview of the similarity value combinations and their interpretation to guide the manufacturing system design is given in Table 2. This analysis can be carried out during the design stages of a new product.

The indices S_1 and S_2 are here used to identify the product families as detailed in the previous section. In a second step, the detailed analysis of their values may guide the decision towards a distinct manufacturing system type: at first, the indices S_1 and S_2 are used to identify if products are similar enough to be sent on the same manufacturing system (called Go/No-Go decision in Figure 13). Then, the indices S_3 and S_4 are added to quantify the changeability needs. Strong similarities S_1 to S_4 guide the choice towards a dedicated system for the entire product family. A strong S_1 index in combination with intermediate S_2 values guides the choice to reconfigurable systems as product architecture is similar and complexity differences are intermediate. Low S_2 values guides the choice towards flexible systems as high complexity differences need to be addressed.

Considering more in detail the technology-oriented indices, a low S_3 index involves a differentiation of manufacturing cells of the considered functional module, and a high S_3 index suggests a mutual use; a strong S_4 index implies the pooling of the manufacturing cell of the considered module with others and a low S_4 indicates difficulties for mutual use (indicated by dedicated to single product). The results of this analysis have been validated theoretically by industrial experts of the partner company throughout the case studies. An excerpt of one of these case studies is illustrated at the bottom of Figure 13, representing a part of the real industrial assembly. Based on the product analysis, it could be identified that for two similar products the axle and bearing assembly is almost identical (despite slight press fit effort differences) which lead to dedicated multi-product modules. However, one product has a supplementary adapter assembly (participating to a common function but being additional content for product 2) which needs a dedicated single product module.

5. Conclusions and perspectives

Proposing a support to product and assembly system designers, by identifying product similarities and their effects on the manufacturing systems, this article describes the results of applying a methodology to assess product similarities in industry. Taking into account the functional architecture provides the definition of referential to compare product designs in the context of high product variety which is independent from detailed product description (component number and references). The purpose of this article is to underline the benefits of this similarity evaluation in both, the product design (product family identification) and the manufacturing system design (by limiting the modifications to an existing manufacturing process or by designing a manufacturing system associated with a product family) as the return of experience from the industrial case studies.

The industrial deployment has been performed on ten different product variants from our industrial partner (22 technical functions are considered, the products have between 19 and 84 components, and their architectural complexities are low to high). It highlights that the product variety identification is the first step of the product variety management.

5.1. Conclusions out of the industrial case study

On the side of the industrial partner company, the case studies have led to a beginning change in considering product variety. This development is pronounced around three axes:

- First, to limit investment and reduce costs, currently, the methodology described in Section 4.1 is applied to avoid designing products too far from the ones already produced or to increase products commonality or modularity;
- Second, the industrial partner is going to deploy the framework and PHARE approach presented in Section 4.2 to all product references available in the company to analyse their product variety;
- And third, the hypothesis and use of similarity indices for production paradigm deduction have (4.3) led to a new research project having as objective to deploy the approach on a new product family.

The last result of the product variety identification is the development of complex products based upon platforms. In fact, the methodological analysis has resulted in the identification of two sets of functional modules with strong similarity indices. These can be considered as the common platforms and the other modules as differentiating elements. Highlighting commonality potentials and possible modularity in product design has triggered the development of targeted standardisation strategies between the production and the design department. Therefore, the product variety identification is the first step of the product variety management process and of the platform-based design.

5.2. Perspectives for further research

Concerning scientific research topics, there is still work needed to be done in applied research, continuing the industrial cooperation during ongoing and future research projects. The industrial application of the models showed the fact that the maturity of the functional decomposition influences the relevance of the similarity analysis and the product variety identification. Differences in the interpretation of product design can lead to different definitions of functional modules and may therefore impact the similarity analysis. Also, it has been revealed that the approach of functional decomposition and the generation of the adapted DFC product models may be difficult to understand for beginners. Further work should examine how the robustness of the modelling part can be improved.

Concerning the similarity indices, their relevance has been proved through industrial case studies. Future work will consist in doing a larger experimentation based on the presented case study perimeter in order to compare them to already existing indices, underlining their complementarity.

Concerning the product redesign part (Section 4.1), it may potentially be coupled to design for assembly or manufacturing (DfA/DfM) in a large sense as mentioned in (Halfmann, Elstner, and Krause 2011; Demoly et al. 2012). It is to examine how the presented use cases can be beneficially integrated into these methods.

Last, the product family identification is still ongoing. Future work has to be carried out in cooperation with the industrial partner and monitoring the use of the proposed models and tools in order to adapt and refine them whenever necessary. The aim should be to accompany the approach from its development until its complete implementation in the industry.

Acknowledgements

The authors gratefully acknowledge the support from the members of the research chair entitled 'reconfigurable, safe, and efficient production systems', co-founded by Thyssenkrupp, the European Regional Development Fund 'Programme opérationnel FEDER-FSE Lorraine et Massif des Vosges 2014–2020'. The authors acknowledge also Mr. Victor BRUNSTEIN, Master student of Arts et Métiers engineering school for his work in the implementation of the clustering algorithm.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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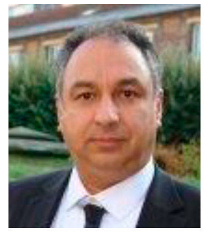

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Funding

This work was supported by the European Regional Development Fund [Fonds Européen de Développement Régional (FEDER)]. The funding is part of the program 'Programme opérationnel FEDER-FSE Lorraine et Massif de Vosges 2014–2020'. There is no grant number but only the reference to this funding program.

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