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ASSEMBLY-ORIENTED PRODUCT STRUCTURE BASED ON PRELIMINARY ASSEMBLY PROCESS ENGINEERING

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ABSTRACT

Currently, product design is mainly influenced by customer requirements, i.e. designers are more and more focused to have a well-balanced product between function and form. However, other requirements from corporate processes such as assembly process engineering should be taken into account during the product development process to avoid iterations problems and therefore a lack of efficiency and productivity. Based on intensive research over the past several years through assembly process planning and Design for Assembly issues, an emergent research topic is bound to integrate product design and assembly sequence planning in the broader context of Systems Engineering and Product Lifecycle Management. Thus, a top-down approach called "Assembly-Oriented Design" is considered to design product integrating assembly process engineering information in a right first time approach. This paper presents an assembly-oriented product structure methodology based on assembly rules using the System Modeling Language paradigm to model product views relationships for assembly in the early stages of the design process. The proposed approach is based on the multiple domains and multiple views model. The presented industrial automotive case belongs to an exhaust system: a Catalytic Converter & Diesel Particulate Filter system.

Keywords: Assembly-Oriented Design, Systems Engineering, Assembly Sequence, Product structure.

1 INTRODUCTION

Currently, products are more and more customer-centric to the point that designers are more and more concentrated to have a well-balanced product between function and form instead of involving corporate process like assembly process engineering that can deeply impact the product development process. To design a product by considering assembly issues, such as assembly process planning (APP), will impact on design choices, product structure, product modeling and therefore on the product development process. The important issue of APP has been a subject of intensive research over the past several years with a variety of computer-aided assembly planning (CAAP) tools [1] [2]. Since then, much research related to Design for Assembly (DFA) has been developed [3] [4] [5]. This research has introduced assembly issues in the detailed design phases leading to a redesign and consequently to inefficiency during the design process. An emergent research topic is bound to integrate assembly issues into preliminary design stages to improve the design productivity and efficiency. This proactive approach is considered as a top-down approach called "Assembly-Oriented Design (AOD)" [6]. AOD is a promising way to bring out a contextual way for product structuring and modeling by taking into account the resulting preliminary assembly sequence in the early design stages. Keeping in mind this main issue, this paper describes an initial effort towards an assembly-oriented product structure methodology based on a product model integrating stakeholders' views in product and assembly process domains. The System Modeling Language (SysML) [7] paradigm is introduced to describe our model supporting our assembly-oriented product structure approach in the broader context of Systems Engineering (SE) and Product Lifecycle Management (PLM). Considering information and knowledge from the multiple views/viewpoints identified according to the stakeholders' concerns through product life cycle is a key element to design a product in an integrated and collaborative way. Our paper starts with an overview of the industrial issues and research approaches. The current challenges associated to our previous and related work [8] has led to the development of a proactive and interactive DFA methodology [9] in the framework of AOD approaches. Our methodology considers assembly process engineering in preliminary design stages for product structuring and promotes a top-down approach based on the Multiple Domains and Multiple Views model (MD-MV) [10] [11] integrating an emergent Contextual View to support the product structure (Structural View), the product modeling (Geometric View) and others. Finally, our proposed approach is illustrated by an industrial automotive case belonging to an exhaust system namely Catalytic Converters & Diesel Particulate Filter system.

2 INDUSTRIAL AND RESEARCH BACKGROUNDS

2.1 Industrial issues

The current industrial context in terms of Quality-Cost-Time leads automotive industry towards several issues regarding engineering design and manufacturing planning. Indeed, approaches such as collaborative [12] and systems engineering [13] must be set up to facilitate co-operation and coordination in large scale projects involving many different disciplines. This need for improvement in terms of effectiveness and efficiency of existing engineering design processes is highlighted in [14]. Companies are facing their own corporate configuration context integrating geographically scattered teams and networks of expertise through each actor [15]. For most automotive industries, the product-process integration issues are still a great challenge. Product design and assembly process planning domains have received more attention in each community for the past decades. However, a gap between both cannot be denied. The main reasons are the combinatorial complexity of assembly sequences mainly due mainly to the part number, and the difficulty to have an explicit assembly sequence in coherence with product-process director parameters. Therefore designers often neglect assemblability analysis during the product development process and assembly planners generate assembly sequence manually, starting from a complete product definition with their own interpretation and without the support of any appropriate tool [16]. This context is reinforced with a traditional oriented-part approach called Bottom-up, considering part design before assembly design. Therefore, the current challenge in automotive industry points to the integration of assembly engineering information into the product development process, and more particularly in preliminary design stages in order to bring a contextual support for product structuring and product modeling (Top-down approach).

2.2 Research approach

In the ultra-competitive context previously described, knock-down traditional organizational silos with manual process, such as the assembly sequence generation, - already exist. These problems have caught attention over the past decades with various methods and tools to support APP. A significant amount of research has been made on the automatic generation of assembly sequence in CAAP (Computer Aided Assembly Planning) system [1] [2]. However, experience on complex products has shown that the assembly sequence generation approach must be realized in a semi-automatic way because of the several assembly parameters at various abstraction levels of the product. This issue pointed to the importance of decisions taken during the design process so that the DFA concept could emerge [3] [4] [5]. This approach gathers a multi-disciplinary team to evaluate and validate product design and to allow its suitability for the APP stage. The DFA approach, considered as a reactive tool, lays out formal analysis procedures starting from detailed geometry and leading to redesign rather than advice or assistance during the design process. These efforts have been directed towards each engineering community. An emergent research topic called "Assembly-oriented design" is meant to integrate APP into the earlier preliminary design. This proactive approach promotes a top-down design approach, and focuses on the product creation process related to systems supporting assembly aspects. Emerging solutions have been developed to break down the traditional barriers which block free flow of information among product design and manufacturing process. Indeed, Digital Manufacturing integrates functionalities from Manufacturing Process Management (MPM) and Computer-Aided Process Planning (CAPP) systems as described in [17]. This current strategy tends to be integrated into the PLM environment in order to give a better understanding of product-process relationships for companies [18]. Digital Manufacturing enables the product-related process definition in a concurrent way. Therefore, the main industrial manufacturing company objective is compliant with a PLM strategy. Subsequently, the current challenge is the product/process integration into the broader context of PLM and SE in order to cover product design and APP stages.

3 ASSEMBLY-ORIENTED PRODUCT MODEL

3.1 Product modeling

Our proposed model [11] is based on the strengths of existing product models in literature and integrates current needs in terms of PLM: Systems Engineering from preliminary design stages and the system decomposition according to involved stakeholders' views in product and assembly process domains. Product models such as FBS (Function-Behavior-Structure) [19] [20], Multiple Views [21], MD-MV (Multiple Domains-Multiple views) [10], PPO (Product-Process-Organization) [22], CPM (Core Product Model) [23] and OAM (Open Assembly Model) [24] present a way to decompose the product according to its lifecycle and related views, thus separating the different stakeholders' concerns. Our model is based on MD-MV model and IEEE Standard 1471 viewpoints [25] integrating the AOD context where:

- Each domain is a representation of a whole system or sub-system from the perspective of product lifecycle phase (design, assembly, etc.),
- Each view is a representation of a whole system or sub-system from the perspective of a single viewpoint (functional, structural, geometric, etc.),
- Each viewpoint is a specification of the conventions and rules to build and use a view for the purpose of bringing out a set of stakeholder concerns.

3.2 Identification of stakeholders and related views

To define each view throughout design and assembly process lifecycle phases, we have focused on general DFA rules and five involved stakeholders: product manager, designer, process engineer, assembly planner and ergonomist in Table 1. These rules tend to simplify assembly sequence generation by minimizing the product complexity.

Table 1. DFA rules and stakeholders involved

No.	DFA Rules	Product manager	Designer	Process engineer	Assembly planner	Ergonomist
	Minimize product complexity					
1	Reduce part count with multifunctional part [26]		■			
2	Eliminate fasteners [26]		■	■		
	Structure the product					
3	Integral vs. modular architecture [27] [28]	■			■	
4	Allow functional sub-assemblies to be tested independently	■			■	
5	Minimize part/sub-assembly weight [29]	■	■		■	■
6	Use stable sub-assembly [30]	■	■		■	■
7	Ensure that the product has a suitable base part on which the assembly is built [31]	■	■		■	
	Simplify assembly operations					
8	Facilitate handling [29]		■			■
9	Facilitate insertion (design		■			■

	parts to be self-aligning and self-locating) [26] [32] [33]		■			■
10	Minimize assembly directions (orientation) [32]	■			■	■
11	Use symmetric parts (avoid slight symmetry) [26] [34]		■			■
12	Provide orientation features [26] [32]		■			■
13	Insert parts from above (use gravity) [32]		■			■
14	Ensure accessibility/vision for insertion and fixturing tools or fingers [32] [29]		■	■		■
15	Minimize use of flexible, small and sharp parts		■			■
16	Check materials compatibility		■	■		
17	Eliminate adjustments (through tolerancing)		■	■	■	
18	Use kinematics design principles	■	■			
19	Choose the correct joining method (avoid joins, separate joining elements,	■	■	■	■	

Standard design						
20	Standardize parts (to reduce part type) [32]		■			
21	Use standard materials		■	■		
22	Use standard joining processes		■	■		

We consider that these 22 rules will impact on design choices, product structuring, product modeling but also assembly operations/activities. Three assumptions are to be analyzed to build our model:

1. The product is the result of a top-down design approach integrating activities conducted by various departments and disciplines involved (Design For X approaches),
2. The product is the result of various assembly operations starting from a high abstraction level,
3. The assembly sequence and DFA rules as a contextual support to AOD.

Thus, we have identified 3 domains and 5 different views in the context of AOD:

- Design Domain:
  - *Structural view* (or *ontological view*) considers the structure of the system,
  - *Functional view* considers the functions of the system,
  - *Behavioral view* considers the system behavior,
  - *Geometric view* considers the form and position of the system,
  - *Contextual view* considers the system in the design context.
- Assembly Process Domain:
  - *Structural view* considers the structure of assembly operations*,*
  - *Functional view* considers the functions of assembly process*,*
  - *Behavioral view* considers assembly sequence planning*,*
  - *Geometric view* considers the interface between two components*,*
  - *Contextual view* considers the system in the assembly process context*.*
- Use Domain:
  - *Functional view* considers the used functions in the assembly process*,*
  - *Structural view* considers the structure of operator activities*,*

Contextual view considers the system in its handling during the assembly process.

3.3 A multiple views model for AOD

The proposed model is represented with SysML Package in order to organize the views and domains identified previously (*Figure 1*). SysML has extended the concept of view and viewpoint from UML to be consistent with the IEEE 1471 standard. This enables stakeholders to specify the product model aspects which are important to them, and to represent such aspects of the system in a specific view integrating its own set of features [35] [36].

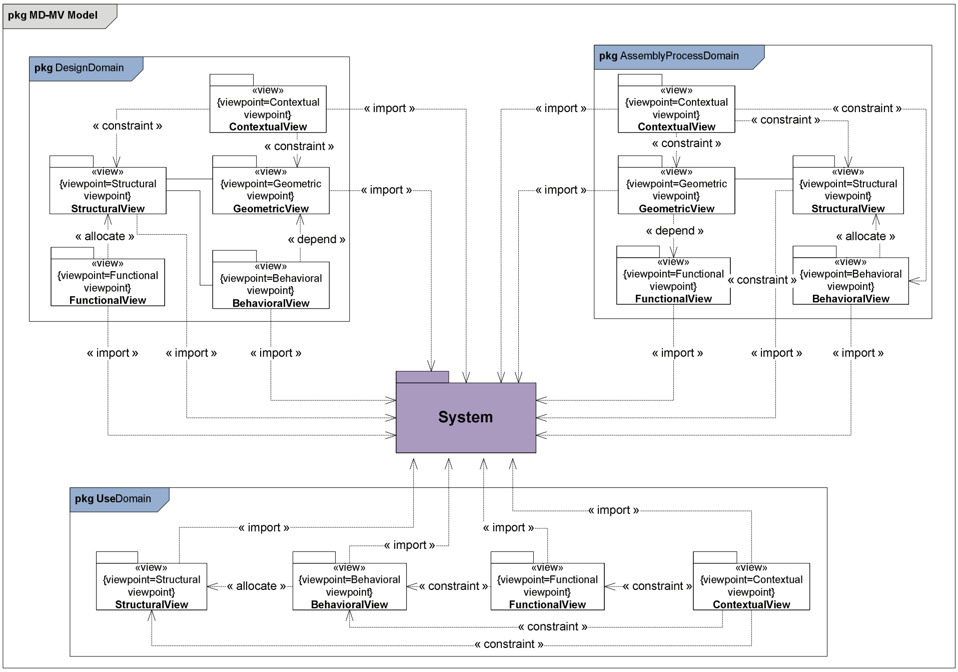

Figure 1. MD-MV Model adapted to the AOD context

The lack of specific assembly process engineering data in preliminary design phases can be found. The use of higher-level features model should solve most of these problems. As described in this section, most of the product models used in the product design is not able to provide the information needed for APP directly, and vice versa. The promising results in APP using product models containing assembly features have not had much influence in this domain yet. However, information generated during APP should be stored in the product model. Thus, the assembly process data integration in the early design stage will allow the product design and the assembly sequence generation to work in a simultaneous and collaborative way. In this case, we have integrated stakeholders' views into the product model and a specific contextual view in each life cycle phase to highlight the nature of knowledge related to decision making. The notion of context presents too complex and dynamical characteristics to give a unique and common definition. We need to consider three kinds of context: external context, internal context (knowledge context) and procedural context to provide information in a proactive way [40]. From an engineering point of view, a context can be defined as the collection of relevant conditions and surrounding influences which make a situation unique and comprehensible. For the proposed approach, the design context will be defined by the assembly sequence master.

4 PROPOSAL OF ASSEMBLY-ORIENTED PRODUCT STRUCTURE

Based on the proposed model, the authors describe an assemblyAOD approach throughout the product structure which is considered as a core discipline in PLM system [37]. Product structure is a way to organize the product and the design process in the context of multi-disciplinary team and extended enterprise [38]. Besides, the product structure behavior can be observed through the lifecycle with various abstraction levels like E-BOM (Engineering Bill of Materials) and M-BOM (Manufacturing Bill Of materials) and various product configurations [39]. E-BOM depends on the functional aspect of the product and M-BOM depends on manufacturing operations. However, there is a need to reinforce the relation between these structures. Our proactive DFA approach lays out the integration of assembly process engineering constraints in the preliminary design stages in order to design the product based on preliminary resulting assembly sequence. Our previous works have focused on assembly sequence generation starting in preliminary design [8]. Therefore, our challenge is to define the setup product structure based on preliminary assembly sequence master in order to bring out a contextual support for AOD. Thus, the approach can be described according to the following steps:

1. To define product lifecycle phase contexts (contextual view):
2. To identify the product composition (systems, sub-systems and parts, etc.) in higher abstraction level through the functional view integrating the independance degree (integral vs. modular architecture) (Figure 2a);
3. To insert specific assembly information (contact and dummy connections) with a directed graph associated to matrix-based modeling throughout the functional view of assembly process domain (Figure 2b);
4. To identify the nature of feasible sub-assemblies and assembly layers by specific algorithms [8] integrating serial and parallel assembly filters monitored by the contextual view;
5. To generate the assembly sequence master in the dynamical view from assembly process domain as a contextual support to the design process (Figure 3a);
6. To generate and manage the setup product structure integrating items, such as contextual support (skeleton), sub-assembly and part, in the structural view from the design domain (Figure 3b).

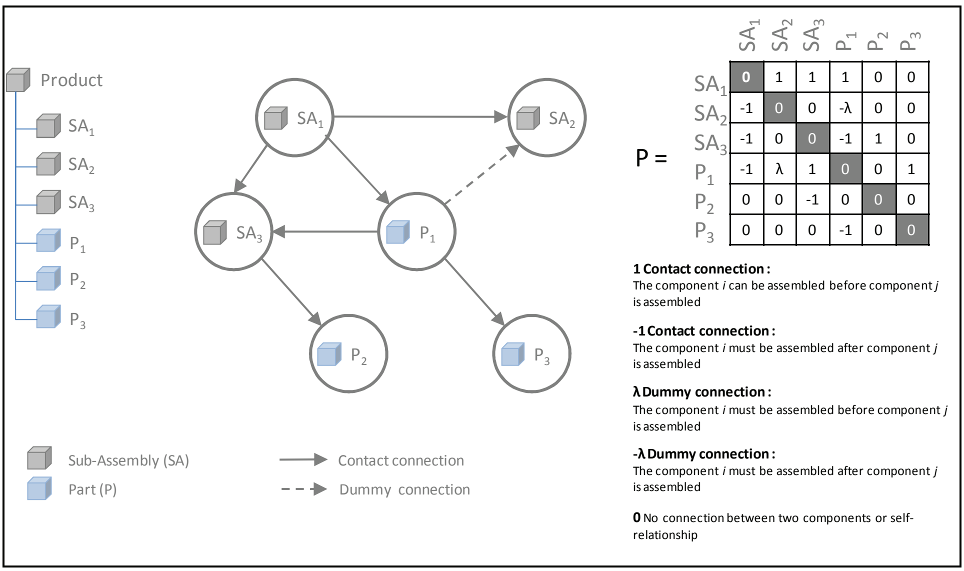

Figure 2. Product decomposition and directed graph associated to a matrix-based modeling approach

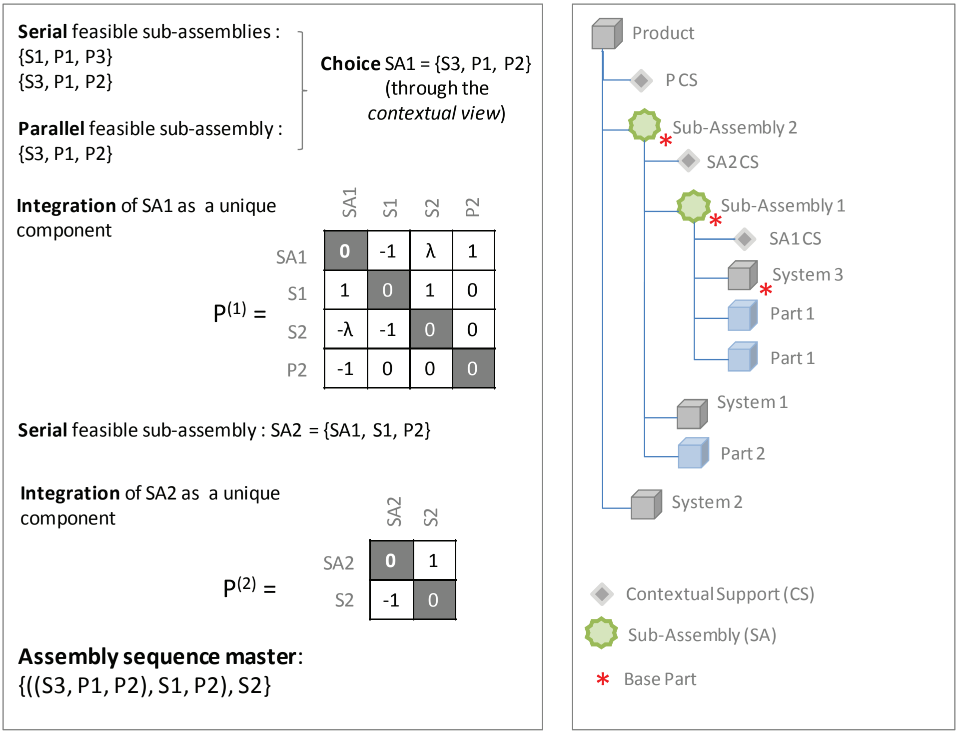

Figure 3. Assembly-oriented product structure approach based on preliminary assembly sequence master generation

5 EXPERIMENTATION

5.1 Technical description

An industrial automotive case belonging to an exhaust system will be chosen in order to illustrate the proposals: a Catalytic Converters & Diesel Particulate Filter system (CAT Converters & DPF). The example is depicted as a sub-assembly of the exhaust system and satisfies two main functions: minimizing gas emissions by redox and eliminating particulates by filtration and combustion. We have chosen to execute our assembly-oriented product structure approach throughout various tools: a PLM prototype called ACSP (in French: Atelier Coopératif de Suivi de Projet), a mathematical tool (MATLAB) and a CAD system (CATIA V5) using XML exchange format for each step (*Figure 5*).
Starting with the product decomposition from the functional structure in ACSP PLM prototype, the authors add specific assembly process information such as precedence and contact constraints based on an assembly process feasibility context (*Figure 6*). The authors have chosen to represent the precedence knowledge of the product in a directed graph form where each node represents a system or a part and where each bond between nodes indicates the presence of a connection between two elements. Among the connections, this graph identifies two types: contact connection (in solid line) and dummy connection (in dashed line), thus bringing an assembly order constraint if there is no contact between two components. This first assembly engineering information integration is exported in XML format in MATLAB where three filters (2 serial sub-assembly matrices and a parallel sub-assembly matrix) have been defined previously according to the assembly process context (*Figure 7*).
An algorithm taking into account these filters has been developed for assembly sequence generation in [8]. Starting from the defined connections matrix, the algorithm allows the following steps:

- The detection of serial and parallel sub-assemblies and assembly layers for various dimensions,
- The interference analysis between each sub-assemblies detected and other individual components in order to validate detected sub-assemblies,

- The management of sub-assemblies layers integrating base parts and contextual supports (Skeleton models)
- The assembly sequence master generation,
- The setup product structure generation in XML format.

The generated setup product structure is imported in a CAD System (CATIA V5) throughout the execution of a Visual Basic script in order to be visualized and used. This script takes into account the detected sub-assemblies, the sub-assemblies layers, the base parts and the nature of each sub-assembly.

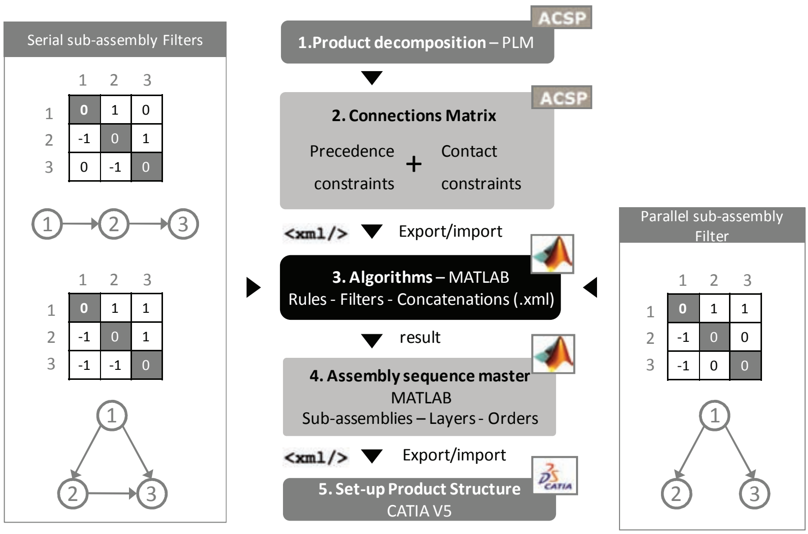

Figure 5. The assembly-oriented product structure approach with associated tools

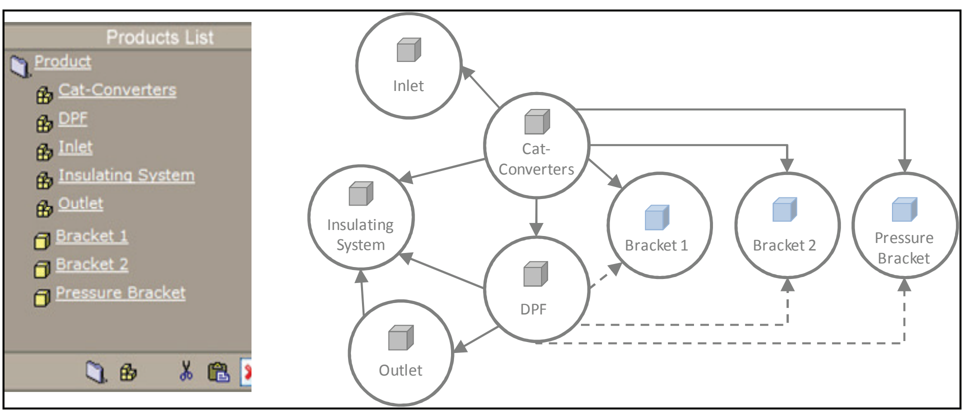

Figure 6. Product decomposition from PLM system (a) and directed graph associated to a matrix-based modeling approach (b)

	Cat-Converter	DPF	Insulting System	Inlet	Outlet	Bracket 1	Bracket 2	Pressure Bracket
Cat-Converter	0	1	1	1	0	1	1	1
DPF	-1	0	1	0	1	λ	λ	λ
Insulting System	-1	-1	0	0	1	0	0	0
Inlet	-1	0	0	0	0	0	0	0
Outlet	0	-1	-1	0	0	0	0	0
Bracket 1	-1	-λ	0	0	0	0	0	0
Bracket 2	-1	-λ	0	0	0	0	0	0
Pressure Bracket	-1	-λ	0	0	0	0	0	0


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- <matrix name="connection_constraints">
  - <matrixCol Part="1" Name="Cat_Converters (Cat_Converters)">
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      <matrixCell Part="3" Name="Insulating_System (Insulating_System)" Justify="0">-1</matrixCell>
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Figure 7.Connections matrix and the related XML format

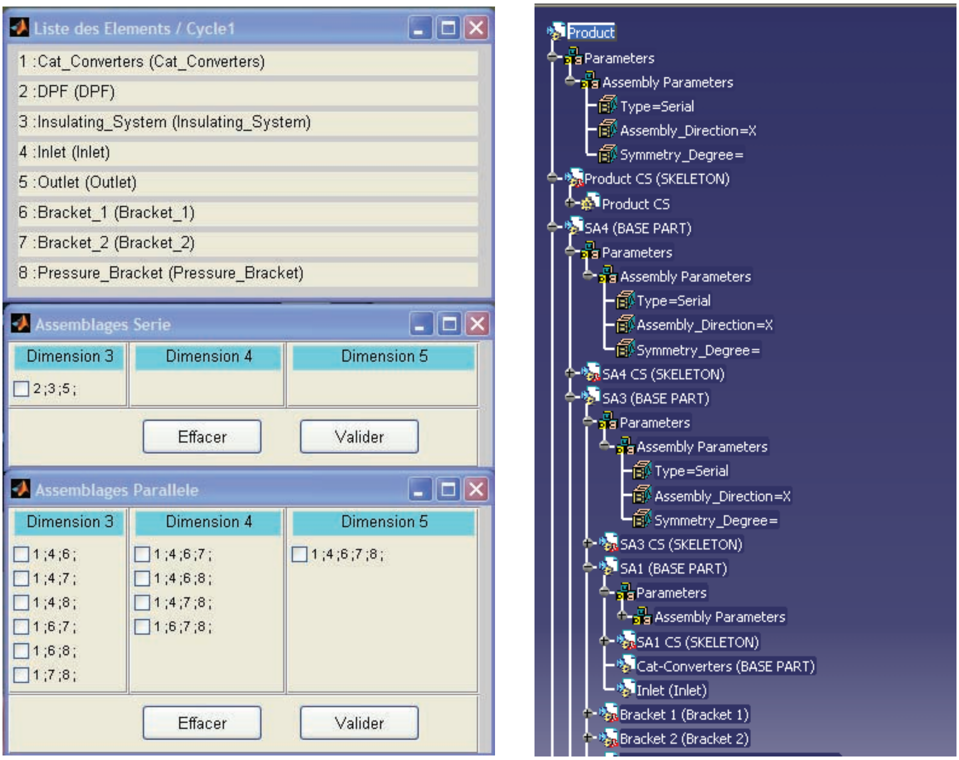

Figure 8. Sub-assemblies choice for assembly sequence master in MATLAB tool and the related setup product structure imported in CATIA V5

5.2 Discussion

The authors have focused on assembly sequence master definition in preliminary design stages in order to define a setup product structure. This proactive approach breaks out the traditional engineering design approaches that define assembly sequence after the detailed design stages. We have compared our assembly sequence master with the existing assembly sequence for our experimentation. Indeed, the existing Process Flow Chart has showed similar results. It will be interesting to integrate other specific assembly process information (i.e. assembly directions and sub-assemblies weight constraints) in order to complete decision support for the assembly sequence generation, and therefore the setup product structure.

6 CONCLUSION AND FUTURE WORKS

Current status and challenges in DFA approaches have been highlighted in this paper. Assembly sequence issue affects various aspects of product design and production and it is relevant to many lifecycle issues of the product. Last but not least, an emergent topic called Assembly-Oriented Design or proactive DFA can integrate assembly process engineering information in preliminary design stages. In this paper, an assembly-oriented product structure approach based on the MD-MV Model has been analyzed. We have taken into account the preliminary assembly sequence master generated in early design stage as a contextual support to provide specific assembly information in a proactive way. A setup product structure supporting contextual elements based on the assembly sequence master, such as the skeleton model, is highlighted. In fact, considering assembly sequence and product design in a simultaneous way focus on so many strategic and tactical aspects of the product that the issue can be used as a natural launch pad for integrative product design. To pave the way for future research and development in this area, the authors will integrate the model and the related AOD approach into a PLM system in order to manage information and knowledge throughout the various identified views.

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