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Thank you for your assistance.
Product relationships management enabler for concurrent engineering and product lifecycle management

Frédéric Demoly a, Olivier Dutartre a, Xiu-Tian Yan b, Benoît Eynard a, Dimitris Kiritsis c, Samuel Gomes a

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- Application of a product relationships management approach in PLM.
- Approach enabling the concurrent product design and assembly sequence planning.
- Implementation of integrated product-process data management techniques in a PLM hub application.
Product relationships management enabler for concurrent engineering and product lifecycle management

Frédéric Demoly, Olivier Dutartre, Xiu-Tian Yan, Benoît Eynard, Dimitris Kiritsis

ABSTRACT

The current competitive industrial context requires more flexible, intelligent and compact product lifecycles, especially in the product development process where several lifecycle issues have to be considered, so as to deliver lifecycle oriented products. This paper describes the application of a novel product relationships management approach, in the context of product lifecycle management (PLM), enabling concurrent product design and assembly sequence planning. Previous work has provided a foundation through a theoretical framework, enhanced by the paradigm of product relational design and management. This statement therefore highlights the concurrent and proactive aspect of assembly oriented design vision. Central to this approach is the establishment and implementation of a complex and multiple viewpoints of product development addressing various stakeholders design and assembly planning points of view. By establishing such comprehensive relationships and identifying related relationships among several lifecycle phases, it is then possible to undertake the product design and assembly phases concurrently. Specifically, the proposed work and its application enable the management of product relationship information at the interface of product-process data management techniques. Based on the theory, models and techniques such as described in previous work, the implementation of a new hub application called PEGASUS is then described. Also based on web service technology, PEGASUS can be considered as a mediator application and/or an enabler for PLM that externalises product relationships and enables the control of information flow with internal regulation procedures. The feasibility of the approach is justified and the associated benefits are reported with a mechanical assembly as a case study.

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1. Introduction

The current academic and industrial product lifecycle management (PLM) vision—that consists in setting up a comprehensive set of models, methodologies, processes and information systems covering the entire product lifecycle [1–3]—has not yet fulfilled all life phases’ requirements [5,6]. This is particularly right at the beginning-of-life (BOL) phase where product designers, process engineers, and assembly planners are still working separately without any recovery, overlap or feedback loop facilities/features in their tasks. Past research efforts have led to successful design for X (DFX) and knowledge-based techniques in product design in order to integrate all constraints of each life phases (i.e. manufacturing, assembly, disassembly and recycling) [7,8], but some gaps still exist in the management of the various technical entities and the control of information/decision/rationale flow through the product lifecycle [11]. This becomes a barrier for applying an efficient concurrent engineering philosophy in BOL and remains a huge challenge to be tackled [9,10].

Previous work argued that companies required efficient concurrent engineering (CE) [12] and PLM strategies [11] in order to maintain their business competitive edge. One particular industrial requirement is the need for concurrent considerations of lifecycle issues for different life aspects into the early product design process [13–15]. It is clear that current product geometry—based on traditional part and feature oriented modelling approaches—only

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Nomenclature

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tr>
<td>PLM</td>
<td>product lifecycle management</td>
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<tr>
<td>PDM</td>
<td>Product Data Management</td>
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<td>MPM</td>
<td>Manufacturing Process Management</td>
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<td>CAD</td>
<td>Computer-Aided Design</td>
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<td>CAPP</td>
<td>computer-aided assembly process planning</td>
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<td>BOL</td>
<td>beginning-of-life</td>
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<td>DFX</td>
<td>design for X</td>
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<td>CE</td>
<td>concurrent engineering</td>
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<td>ASP</td>
<td>assembly sequence planning</td>
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<td>AOD</td>
<td>assembly oriented design</td>
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<td>PROMA</td>
<td>product relationships management approach</td>
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<td>PASODE</td>
<td>proactive assembly oriented design</td>
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<td>MUVOA</td>
<td>Multi Views Oriented Assembly</td>
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<td>ASDA</td>
<td>Assembly Sequence Definition Algorithm</td>
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<td>ERP</td>
<td>Enterprise Resource Planning</td>
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<tr>
<td>SCM</td>
<td>Supply Chain Management</td>
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<tr>
<td>BOM</td>
<td>bill of material</td>
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<tr>
<td>eBOM</td>
<td>engineering bill of material</td>
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<td>mBOM</td>
<td>manufacturing bill of material</td>
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<td>BOR</td>
<td>bill of relation</td>
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<tr>
<td>UML</td>
<td>Unified Modeling Language</td>
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<td>XML</td>
<td>eXtensive Markup Language</td>
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represent a limited view of product lifecycle information, and have limited benefits for CE and PLM strategies [16,17]. To overcome these difficulties, this paper proposed a Product design Engineering based on Generative Assembly SeqUence planning (PEGASUS) application and it is aimed to bring the potential benefits of CE into this integrated and concurrent product design and assembly sequence planning (ASP) stages.

Using previous research results related to assembly oriented design (AOD) and PLM issues [18], the paper presents the implementation of an approach, which aims to reveal the relationships among product parts and operations as well, and maximize the usage of these relationships whilst maintaining information consistency [19] and seamless flow between product design and ASP phases [11].

In Demoly et al. [20–22] a research background and framework entitled Proactive Assembly-Oriented DESign (PASODE) as well as a multiple views model called MultiView Assembly Oriented (MUVOA) [23] and the Product Relationships Management Approach (PROMA) to manage product relationships have been described in detail [11]. Here, the implementation of PROMA into a new PLM hub application called PEGASUS is detailed and it is carried out by using framework and models described in [22]. This approach implementation also uses web service technology to provide wider and easier access and distributed design and working, which is part of latest implementation efforts in PLM systems [25]. The whole approach is intended to extend the traditional PLM systems capabilities to be a new lifecycle oriented application with new theoretical model.

Section 2 presents a survey on current PLM systems implementations status in industry. This survey is followed in Section 3 by the description of the research background in terms of model, framework and approaches. Section 4 introduces the description of the PROMA application in PEGASUS, which is based on web service technology and used C# as programming language. The implementation aims to enable the reasoning and control of information flow between PDM (Product Data Management) and MPM (Manufacturing Process Management) systems, and CAD (Computer-Aided Design) applications. Last, considering the implementation as a prototype, an industrial case study has been undertaken and is detailed in Section 5, so as to demonstrate the applicability and the benefits of PROMA and PEGASUS.

2. Survey on application status of PLM systems in industry

Introduced at the beginning of the 2000s, the PLM strategy consists of the management of the whole product data-information-knowledge for its entire lifecycle [16,17]. This research topic has since also received much attention from industry where current practices are more focused on the management of product technical data and associated workflows through various engineering systems [24]. As such, many industrial engineering departments have tackled PLM issues, essentially in BOL and Middle-Of-Life (MOL) of the product, by implementing methodologies into various systems such as PDM, PLM, MPM, Supply Chain Management (SCM) systems in a single and global digital environment, where all enterprise departments have a role to play [20].

In the above defined context of CE, several research issues have to be investigated and tackled on current industrial practices in PLM systems, especially on PDM and MPM systems [26,27]. Specifically, a PLM system is intended to ensure that the right information is available for the right person at the right time and in the right format by introducing various functionalities such as versioning, bill of material (BOM) management, workflow management, check-in-check-out procedures, and engineering change and configuration management to name a few [28,29]. Regarding engineering design data that consists of parts, sub-assemblies, BOMs, specifications, analysis results, configurations and so on, PDM systems can be considered as product model storage systems and still be centred on product information usually embedded and sometimes hidden in files and documents [11].

In addition to the above concerns, a lack of associativity in PLM systems has also been highlighted [30], where only “parent–child” (i.e. “is part of” class) relationship exists. For a large scale company, the management of relative positions of parts using positioning matrices is implemented in PDM systems in order to be more closely related to geometric models defined in CAD systems, and to facilitate change management and part positioning [32]. Furthermore, other authors [33,34] have proposed an advanced PDM system based on a property-driven development/design (PDD) approach by introducing the handling of predicted engineering characteristics (i.e. structure, shape and material) and properties (i.e. product’s behaviour) of the product with their interdependencies in a separate manner. However, information related to product relationships and assembly process engineering is not effectively treated in their proposal. PLM systems have moved towards web-based and web service technologies, in order to facilitate information exchange and access in distributed and extended enterprises [7,25]. An additional effort towards ontology and semantic web can also be found [35–38]. Recently, Cantamessa et al. [39] in their PLM implementation survey have stressed a similar need about the future role of PLM in supporting and coordinating knowledge by allowing easier access to product data and embedded tacit knowledge.

According to the above applications and approaches, a lack of support of associativity among product models using product relationships still exist and is a barrier for effective and integrated lifecycle oriented design [16,30,17].

At the interface of Computer Aided Assembly Process Planning (CAAPP) and ERP systems, MPM systems enable the management of
3. Research background: model, framework and approaches

Over the past five years, the authors have addressed particular attention to the development of model, methods and tools, which cover the assembly-oriented design field, by considering concurrently product design and assembly sequence planning [18]. In the following subsections, a brief description of the research background is introduced.

3.1. MUVOA as a multiple views model

As part of an initial effort, the MUVOA model has been defined for describing product-process concepts, their related associations and structures so as to be used in an integrated and proactive manner. This model has been organised into several view models (functional, structural, behavioral, contextual, geometric and technological), which are consistent with viewpoint, concern, and purpose associated to each stakeholder (i.e. product architect, designer, assembly planner and process engineer) involved in product design and ASP phases (Fig. 2) [42,43]. A detailed description of this model can be found in [23] on which a proposed information flow in PROMA facilitating information propagation [11] is considered in the PEGASUS application, especially on concepts relationships (i.e. both in contextual view in product domain and assembly domains).

Fig. 1. PLM systems and CAX tools at the BOL phase [11].

Fig. 2. UML class diagram describing the MUVOA model [23].

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3.2. PASODE as a comprehensive framework and related approaches

Based on this multiple views model which covers product design and ASP concerns, a general and comprehensive framework called PASODE has been proposed in order to promote a proactive AOD vision in the early product development process before defining product geometry (Fig. 3). This framework incorporates two mathematical algorithms related to two approaches:

- called Assembly Sequence Definition Algorithm (ASDA) based on DFA and ASP heuristics rules, associated to a tolerance analysis, which defines an optimal assembly sequence by considering as input the definition product relationships at various abstraction levels [20,22,21];
- called SKLeleton-based Assembly Context Definition (SKL-ACD) based on kinematic and technological pairs, which describes design intents from a top-down manner and therefore supports product modelling activity in CAD application through skeleton entities and structure [32].

As such, the act of defining an assembly sequence using part-to-part relationships information enables the definition of assembly skeleton (i.e. geometric entities) related to lifecycle engineering issues for geometric product modelling in CAD applications [15,32]. Fulfilling current stakes in AOD issue, the PASODE framework consists of various steps, in which four stakeholders, such as considered within MUVOA, are involved. At this stage the product architect can be considered as a highly skilled and experienced system designer who has an overall vision of the product or system definition and functionality. His major role is to define the product overall functionality and lifecycle requirements and generate a product architecture which fulfils functional and technical requirements related the product lifecycle stages. At lower abstraction levels, the designer is more concerned with the sub-assembly and parts definitions by taking into account the product architect’s definitions for each of these parts or sub-assemblies. The assembly planner is concerned with planning task of putting parts together once they are completed and manufactured through the process engineer’s inputs (i.e. technological information). So this framework presented in Fig. 3 can be deployed as follows:

Step 1. Based on functional requirements, geometric requirements such as Performance Key Characteristics (PKC) are deployed into the PDM system through the engineering BOM (eBOM).

Step 2. The part-to-part relationships definition phase is carried out by the product architect at various abstraction levels such as functional, behavioural, technological and geometric. Each layer of relationships information is computed to optimise part number and generate admissible assembly sequences.

Step 3. For each admissible assembly sequence, a consistency checking procedure related to constrained degrees of freedom is processed to highlight specific requirements namely Assembly Key Characteristics (AKC).

Step 4. All admissible assembly sequences and related AKC are introduced in a tolerance analysis tool in order to find which assembly sequence fulfils all geometric requirements of the product.

Step 5. So the selection of the well-balanced assembly sequence can be carried out by introducing AKC interval values.

Step 6. Once the assembly sequence is defined, several information embedded PLM systems views can be generated, including manufacturing BOM (mBOM) in MPM system, product...
structure and skeletons-based assembly context in PDM/CAD systems.

Fig. 3 illustrates various mechanisms (grey boxes) and related input/output information (white boxes) to show the aforementioned steps. The relevance of part-to-part relationships as well as product relationships in these above-mentioned approaches requires emerging needs in their management so as to capture an original state of the product-process, propagate information from PDM system and CAD application and check information consistency with assembly technologies in MPM system.

3.3. PROMA as an internal regulation approach

Key to the concurrent development of product solution as well as assembly planning, a novel approach entitled PROMA has been developed as a critical technology in PEGASUS to improve the capabilities of current PLM systems (i.e. CAD, PDM and MPM systems) by introducing procedures of managing product relationships at various abstraction levels of information for a better information control and flow. It is the core mechanism to support the use and management of relationships extracted from product and assembly process domains in PLM systems. In such a way, a proactive and interactive concurrent product and assembly plan development using assembly process information, as a representative of lifecycle process, is enabled. More specifically, in such a design session, assembly process and information are used to externalise and highlight any potential negative issues and impacts caused by a product design decision.

For example, relying on the use of too many bolts and nuts for assembling two or more parts together results in much long assembly operations, hence higher assembly complexity and cost. Through revealing such design decisions and its associated consequences, it is possible and feasible to externalise these decisions and their negative impact on the design. At the same time, designers, assembly process planners and process engineers are encouraged to explore alternative method- ods, technologies or means to fulfil the assembly process requirements.

In order to support this new and concurrent vision, the PROMA approach has been initially developed in [11] and can be illustrated in Fig. 5 where it deals with various traditional PLM modules, establishes important links among lifecycle models and bridges the gap between lifecycle models, especially at the BOL stage. These relationship types existing in product lifecycle include those between product structure and its function and design rationale; product structure and overall assembly sequences; part features and assembly operations; product structure and CAD models; eBOM (engineering bill of material) and mBOM (manufacturing Bill of Material); component material and suitable manufacturing processes including disposing processes and so on. Further details can be seen in Fig. 5, where the centralization of parts, assembly operations and assembly skeletons relationships is described. As such and according to the aforementioned PASODE steps, PROMA will manage the information propagation through design and manufacturing data structures (i.e. eBOM, CADBOM and mBOM) by using the Bill Of Relations (BOR) concept [11]. In order to facilitate understanding, this paper only describes and focuses on the relationships identified between product design and assembly sequence planning phases as an example of lifecycle activity to illustrate the PROMA philosophy. Similar approach can be extended and applied to other lifecycle phases such as maintenance, disassembly and so forth.

4. Implementation of PROMA in a PLM hub application

Based on this additional description of PROMA approach [11], its relevance and feasibility need to be demonstrated. As such, a PLM hub application (PEGASUS) as prototype application is introduced to manage information flows and provide internal regulation procedures between design and assembly planning stages.

4.1. Overview of PEGASUS introduction in current PLM systems

The PLM hub application has to fulfill current ICT requirements in design and manufacturing fields, especially at their interfaces. As addressed in Section 2, some common issues in PLM systems such as PDM and MPM systems are the lack of associativity, understanding and reasoning based on knowledge in order to promote reactivity and agility in engineering design. This explains in part the traditional barrier between design and manufacturing phases as well as between manufacturing and production phases. In Fig. 1, an existing gap has also been highlighted between PDM, MPM and CAD systems, and therefore Fig. 6 illustrates an
Fig. 5. Centralization of parts, assembly operations and assembly skeletons relationships.

Fig. 6. Introduction of the PEGASUS application in connection with PDM, MPM, and CAD systems.
introduction of PEGASUS as a hub application which orchestrates information flows between above-mentioned systems.

Currently PDM systems enable the management of engineering technical data such as eBOMs, subassemblies, parts, product structures, documents, configurations, and provide comfortable support for designers and product architects. At the manufacturing side, MPM systems enable the management of manufacturing/assembly data such as mBOMs, operations, documents and so on, and provide assistance in assembly planning and assembly line balancing phases. At a lower abstraction level, CAD applications consist in modeling product geometry including its parts, subassemblies, forms, parameters, constraints to name a few. The current information exchanges between these systems are represented with dotted arrows, and can be understood as follows:

- a one-way eBOM-mBOM synchronization/reconciliation associated to product configuration capturing between PDM and MPM systems;
- bidirectional procedures of check-in/check-out and versioning between PDM and CAD systems;
- a one-way assembly features recognition between CAD and MPM systems.

To overcome current PLM limitations and increase its capabilities in information propagation and data consistency, a hub application is introduced as a central application which supports the orchestration and maintains associations between design and assembly technical data/information. As such, new technical entities, such as relations, bill of relations (BOR), assembly skeletons and so on, are introduced in order to provide an additional state of product-process information (i.e. a new picture of product-process engineering efforts), therefore enabling the understanding for both sides [11]. Thus this novel application integrates procedures associated to the PASODE framework in order to impact existing views in PDM, MPM and CAD systems [22,21]. Based on these explicit representations of relationships, PEGASUS reasons and highlights the relevant relationships to enable concurrent product and assembly process development. Moreover, the aforementioned exchange procedures are reviewed in order to be used and triggered in a central manner. These new exchange procedures will be described in detail in the implementation section.

### 4.2. Functional specification of PEGASUS

PEGASUS, the so-called hub application, has to support four types of stakeholders of a product development process, namely, the product architect, assembly planner, designer and process engineer. Within PEGASUS, the tasks which are normally performed in a sequential fashion by the product architect and the assembly planner have been identified and represented as a generic set of integrated product development tasks. The potential inherent relationships between these two groups of tasks are also shown in Fig. 7 and they are vital for the concurrent design solution and assembly sequence generation. For example, when the product structure is defined, all key part-to-part relationships are then finalised. Using this information, it is possible to concurrently generate all admissible assembly sequences. Similarly, using the product or component material information in conjunction with product geometry information, it is possible to define the manufacturing context as well partial manufacturing process and assembly operations. This concurrent model can then be used to validate the design solution in terms of meeting product manufacturability, such as successfully tackled with assembly issues [21].

The development of the proposed application first requires functional specifications in consistency with expected PASODE mechanisms and future PEGASUS functionalities before full implementation. Basically, the interlinked and concurrent tasks for stakeholders such as the product architect and the assembly planner have to be identified and represented first and in this research; they have been represented in a UML (Unified Modeling Language) use case diagram as shown in Fig. 7. It is important to emphasise that this representation introduces new integrated

![Fig. 7. UML use case diagram of PEGASUS application.](http://dx.doi.org/10.1016/j.compind.2013.05.004)
management functionalities to address the identified needs for the PEGASUS application underlined in Section 3. At this stage, PROMA is considered as an additional enabler for facilitating information propagation through product and process views. This UML diagram also provides further engineering tasks derived from current PLM systems. In addition, the MUVOA model presented in Fig. 2, as proposed in [23], has been implemented as a data model on which PROMA approach is based, and PEGASUS consequently.

Once UML use case and class diagrams have been completed, a new UML diagram—considered as a macroscopic sequence diagram—is introduced in Fig. 8 to show expected scenarios in the PEGASUS application. This UML sequence diagram is intended to provide an example of the chronology of concurrent tasks and automated operations embedded in PEGASUS and enabling the definition of the product and the assembly process models in a concurrent manner.

This UML sequence diagram (Fig. 8) illustrates information flows through tasks in the PEGASUS application in greater details and is an expansion of the PASODE theoretical framework [21]. It is now important to allocate views based on the MUVOA model illustrated in Fig. 2, which is considered as the data model of the PEGASUS application. Table 1 presents such a proposed allocation that highlights the implementation of the main view that is product contextual view into PEGASUS, in which part-to-part relationships are captured and managed. Once this view is defined, product design stakeholders can then focus on developing in-depth relationships, based on which integrate product design and assembly sequence planning can be achieved.

### 4.3. PEGASUS architecture and implementation

As a result, the PEGASUS application has been developed as a research demonstrator and Fig. 9 shows the proposed architecture of the system. Amongst the required functional modules, the PEGASUS architecture is composed of:

- a product relationships definition module, which captures the required input (i.e., relationships) at various abstraction levels for processing and reasoning in design and assembly planning phases;

<table>
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<th>Table 1 Allocation of MUVOA views to PLM systems</th>
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<td>Domain</td>
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<tr>
<td>Product</td>
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<td></td>
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<td>Assembly process</td>
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![Fig. 8. UML sequence diagram related to PEGASUS interactions.](image)

![Fig. 9. Resulted PEGASUS architecture.](image)
• an assembly sequence definition module, which uses algorithms for assembly process planning (e.g., including generation/assessment of admissible assembly sequences) based on previously-defined part-to-part relationships;
• a product structuring module, which manages the product structure based on the resulting assembly sequence, product relationships and part number optimization;
• a control of information flow and exchange module, which maintains data consistency and ensures the propagation of information between PDM, MPM and CAD systems;
• a web service module, which enables interoperability over web with PDM, MPM and CAD systems.

The PEGASUS application has been developed in order to implement the PROMA approach. This PLM-based application actually uses the Model View ViewModel (MVVM) design pattern to support the development and is also mainly part of the technical specifications (Fig. 10). This emergent pattern includes three information layers such as the Model, View and ViewModel. The Model, as the first element, represents the content of actual state. The View, considered as the presentation layer, describes references to all elements, which are displayed by the graphical user interface (GUI). Last, the ViewModel represents the link between the Model and the View, so as to process the data through the context and therefore bind the model object properties to the View fields. This latter level also allows the control and propagation of changes made by the user to the Model. From that point of view, the ViewModel contains therefore the business logic aspect. Here the bindings enable the two-way data binding interactions between the View and the ViewModel. The related command allows the View to request a method related to the ViewModel.

Towards this end, Fig. 10 presents an overview on the MVVM architecture to AOD vision (i.e. including framework, approach, model and involved actors). An allocation is proposed for each layer of the MVVM architecture, as follows:

• MUVOA model will be considered as Model layer (a formal ontology integration called PRONOIA is also planned in order to reason on semantic and logic aspects [45]);
• PROMA approach will be implemented as ViewModel;
• PASODE framework will be instantiated as View layer;
• involved actors will mainly use the View layer (i.e. the PASODE framework).

Furthermore, since PEGASUS will be used simultaneously in different geographic areas, its model needs to be considered in a distributed way. A web service has therefore been specifically developed in order to share concepts between different users in an immediate manner. This module is actually based on open standards and protocols. The XML-based syntax is used to encode the data and information independent of computing platforms. In addition, the Simple Object Access Protocol (SOAP) is considered as a communication protocol that enables the transmission of messages among computer entities [46]. However, this protocol does not define yet what messages can be exchanged to get a successfully interaction. The Web Service Description Language (WSDL) is also used in order to describe operations offered by the service, inputs and the outputs [47]. With such WSDL language, it is then possible to define the service location and communication protocol to be used.

On another level, the implementation of the PASODE framework sounds more complicated. It can be considered as a set of interaction rules, on which the user carries out an action via the View. Afterwards the ViewModel executes the related action and updates the Model. As such, the implementation of the framework is made at the ViewModel layer, therefore considering the interaction rules and the conditions to be executed. Since

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computer infrastructure is quite specific to each company, it is
assumed that all business applications are accessed by using web
services. With such a technology, the PEGASUS application will
be able to evolve in a heterogeneous business applications environ-
ment.

5. Case study

The above described implementation has been applied to a
well-known mechanical assembly as a case study in order to
demonstrate the potential benefits and relevance of such an
integrated and proactive engineering relationship management
paradigm, especially at the interface of product design and
assembly sequence planning phases. The chosen part is a
PLAYMOBIL® toy. A number of tools and facilities developed for
PEGASUS have been used to demonstrate the working principles
and processes how this PROMA approach tackles the research
issue.

5.1. PLAYMOBIL® and its design problem formulation

Built on the PASODE framework, and deploying the MUVOA
model, this research derives a novel management approach called
PROMA to tackling product relationships management. In order to
achieve a successful product development, it is necessary to
emphasise the importance and capture the relationships between
parts and sub-assemblies of a product. This provides the basis to
promote and control information sharing and flow in a proactive
and intelligent manner.

From a lifecycle engineering point of view, this case study
requires information consistency procedures between product
design and assembly process specifications. Currently, all product
parts are manufactured and assembled by the same company. The
closer integration of assembly process and the product develop-
ment process is crucial to meet success and avoid much rework.
This whole thing is to apply PROMA approach within PEGASUS as
easily as possible in product design stage.

The proposed case study is illustrated in Table 2 and Fig. 11,
where a parts list, and a previously developed isometric and
exploded views of the final solution are presented. This description
enables the understanding and contrast of traditional product
development process versus the concurrent product design and
assembly process planning. Currently, this product includes nine
parts as listed in Table 2.

Moreover, three systems have been introduced in order to be
connected with PEGASUS (i.e. PLM hub application enabling
the definition and management of product relationships and
the control of product-process information flows), namely as
follows:

- ACS (in French: Atelier Coopératif de Suivi de Projet) which is a
  legacy web-based PLM system and here used as a PDM (Product
  Data Management) system for the experimentation.
- NOTIXIA which is a commercial platform enabling the manage-
  ment of assembly process information and here considered as a
  MPM (Manufacturing Process Management) system.
- CATIA v5 which is used to define and visualise assembly
  skeletons of the product and here used as a CAD (Computer Aided
  Design) application.

By introducing this prototype and the aforementioned commer-
cial systems, it would be possible to evaluate the effectiveness
of the approach, and at the same time, the practical difficulties one
would face in implementing the PROMA approach.

5.2. System execution

Based on the above described technical implementation and
case study, the proposed PEGASUS implemented within PLM
systems is illustrated in Fig. 12, in which each step (steps 1–7)
are presented consistently with the PASODE framework mechanisms.
All information exchange procedures are supported by eXtensive
Markup Language (XML) language format, i.e. X-oriented BOR (Bill
Of Relations) [18]. So PEGASUS is considered as a hub application
at the interfaces of PDM (ACSP), MPM (NOTIXIA) and CAD (CATIA v5)
systems, which enables the centralisation, processing, and
orchestration of information and knowledge of product-process,
as described in the following steps:

Step 1. PEGASUS captures the initial eBOM which has been defined
by the product architect in the PDM system (ACSP), by
using the PDM-oriented BOR. At this stage, the product
structure and part-to-part relationships are not yet defined.

Step 2. Based on the definition of part-to-part relationships within
PEGASUS, the embedded ASDA algorithm enables the
generation of admissible assembly sequences, and so the
selection of the well-balanced one to be exported to MPM
system (NOTIXIA). As such, the resulting assembly sequence is sent to MPM via the MPM-oriented BOR in
order to build the assembly operations structure.

Step 3. Once the assembly processes structure is defined, the
assembly planner and process engineer incorporate technol-
ogical information for each assembly operation. This
information is sent to PEGASUS via the MPM-oriented BOR
and enables the definition of a technological layer of the
product.

Step 4. Within PEGASUS, these relationships enable the product
structuring based on the early-defined assembly sequence. This
is done via the PDM-oriented BOR to PDM system

Table 2

<table>
<thead>
<tr>
<th>No.</th>
<th>Part name</th>
<th>No.</th>
<th>Part name</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Body</td>
<td>2</td>
<td>Thorax</td>
</tr>
<tr>
<td>3</td>
<td>Legs</td>
<td>4</td>
<td>Head</td>
</tr>
<tr>
<td>5</td>
<td>Hair</td>
<td>6</td>
<td>Left arm</td>
</tr>
<tr>
<td>7</td>
<td>Left hand</td>
<td>8</td>
<td>Right arm</td>
</tr>
</tbody>
</table>

![Fig. 11. Isometric and exploded views of a previously developed PLAYMOBIL® toy.](https://example.com)
Step 5. At the same time, PEGASUS generates skeleton-based geometry related to kinematic and technological pairs such as defined within PEGASUS. These skeleton entities enable the definition of an assembly context for designers. This can be done by considering the resulted product structure and assembly skeletons structure as captured in the CAD-oriented BOR.

Step 6. Based on this assembly skeleton structure, the product designer can allocate volume, shape, values related to each skeleton. At this stage, he is not allowed to directly change the assembly skeleton but a change request can be sent to PEGASUS via such CAD-oriented BOR.

Step 7. Once designer has defined all product geometric characteristics, the CAD models are stored by using check-in/check-out procedures in PDM system (ACSP).

As a consequence, this case implementation has been broken down into seven steps in order to reach objectives of the proposed PROMA approach. First, the process begins with the definition the initial eBOM (product structural view) in the ACSP system which is actually performed by the product architect (Step 1) as illustrated in Fig. 13. Based on this, the product architect has the possibility to define part-to-part relationships at various abstraction levels (product contextual view) in PEGASUS (Fig. 14) using the...
Table 3
Description of part-to-part relationships

<table>
<thead>
<tr>
<th>Relation name</th>
<th>Kinematic pair</th>
<th>Technological pair</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{1,2}$</td>
<td>Rigid</td>
<td>Press fit</td>
</tr>
<tr>
<td>$R_{1,4}$</td>
<td>Revolute</td>
<td>Snap fit</td>
</tr>
<tr>
<td>$R_{1,6}$</td>
<td>Revolute</td>
<td>Snap fit</td>
</tr>
<tr>
<td>$R_{1,8}$</td>
<td>Revolute</td>
<td>Snap fit</td>
</tr>
<tr>
<td>$R_{2,3}$</td>
<td>Revolute</td>
<td>Snap fit</td>
</tr>
<tr>
<td>$R_{4,7}$</td>
<td>Revolute</td>
<td>Snap fit</td>
</tr>
<tr>
<td>$R_{4,9}$</td>
<td>Revolute</td>
<td>Snap fit</td>
</tr>
</tbody>
</table>

Fig. 14. Definition of product relationships in PEGASUS.

Fig. 15. Definition of manufacturing/production context in PEGASUS.
6. Discussion

The authors have argued all along the paper the novelty of such a product relationships management approach in its ability to support proactive assembly oriented design philosophy. This approach therefore bridges the gap between engineering management approaches [48] in product development and assembly process planning by integrating these two important aspects together. The proposed implementation in PEGASUS and experimentation through a well-known case study and PLM systems has highlighted strengths and weaknesses of PROMA. The case study shows the added value of PROMA in two aspects. Firstly, this approach enables better utilisation information and its flow between product engineering and process engineering by extracting the cross-view relationships of product development in a separate way [49]. This leads to the introduction of the concept of bill of relations (BOR) to facilitate information exchange between existing PLM systems at the beginning of the product lifecycle. Secondly, PROMA provides an effective support to apply the proactive framework PASODE in product multi-view relationship management as described in previous work [18]. Although the
Fig. 19. Part description of a CATscript file generating the product structure in CAD.

Fig. 20. From initial eBOM to updated eBOM including assembly skeletons within CATIA v5.
proposed approach and implementation have been applied small assembly, some additional industrial case studies have been tested and proved benefits.

Nevertheless, the introduction of such an effective engineering relationship management paradigm has highlighted the information exchange problems because the various heterogeneous systems involved at the beginning of the product lifecycle do not support seamless information sharing and exchange. This is mainly due to the limitation of the implementation of commercial systems used in this study [2]. If these were implemented as theoretical systems, there would have been no such an issue, which from the research point of view, will not present any problem.

7. Conclusions and future work

Current status and challenges in assembly oriented design and the related support of data-information-knowledge systems such as PLM systems highlight urgent needs for a better interaction, flexibility and information sharing between product and lifecycle oriented models [50]. Based on this need, a product relationship management approach called PROMA is proposed and implemented in a new application called PEGASUS in connection with PDM, MPM and CAD systems. The proposed approach enables the control of internal regulation procedures between product design and assembly sequence phases, so as to provide a proactive and interactive support for lifecycle oriented product development. Specifically, the PROMA approach is based on a PASODE framework which is featured by an assembly sequence definition algorithm (ASDA) [22] and a multiple view model (MUVOA) [23].

Hence, the proposed paper has addressed this urgent need and taken advantages of rich information available from lifecycle phase using assembly as an example, by proposing and investigating in a new product engineering management vision to support the dynamic and proactive aspect of assembly-oriented design. Managing product relationships and their evolution at various abstraction levels is a central issue to PLM strategy [17]. This paper has demonstrated a novel approach to product relationship extraction, sharing and proactive design support using these vital cross-view relationships, especially at lifecycle phase assembly. It is this area that the paper provides contribution beyond the current state of the art in broad concurrent engineering and PLM implementation in industry.

Further research is required to address the compatibility issues and extension of a similar approach into other life phases. The implementation of PROMA in PEGASUS addresses interoperability and compatibility issues related to others PLM systems such as PDM, MPM and CAD and this will be discussed in future work. In addition, more relational information among other life phases will be considered and captured, especially between the BOL and end of product lifecycle phases, such as maintenance, disassembly and recycling, where lifecycle oriented sequences have to be managed in acoherent way [51].

References


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