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Framework for Propagating Product Variability to Digital Assembly Instructions

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Abstract

As the amount of product iterations within high variety low volume assembly environments increases, the need for efficient management of variability and engineering changes within assembly instructions rises. This work proposes a methodology and a system architecture that facilitates the interplay between product lifecycle management (PLM) systems and digital assembly instructions, using an ISA-95 based data model. The framework consists of three main components: (1) a product variability model that integrates PLM information, (2) a digital instructions authoring tool, and (3) an assembly instruction variability model that connects to instruction platforms. Finally, the approach is applied to a validation case.

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Keywords: Assembly; Computer aided design (CAD); Knowledge Management; Product variability

1. Introduction

Mixed-model manual assembly systems are characterized by increased complexity due to mass customization. Consequently, there is a high need for supporting shopfloor operators with qualitative assembly instructions. Nevertheless, managing the increasing amount of assembly information becomes very complex due to the increasing number of product variants [1]. Modern manufacturing companies already have integrated Product Lifecycle Management (PLM), and computer-aided technologies (CAx). In this way, an effective product family design and management is achieved. However, given that high complexity and increased variability, product families in modern manufacturing may have thousands of variants, effective management becomes essential [2].

Managing product variability has proven to be necessary, both in terms of easily linking customer requirements to a product variant and in managing the current state of production. Propagating information and changes between variants need to be thus linked to new ways of information delivery. The manufacturing industry is looking for innovative ways to link production operators with digital systems and information and thus may benefit from unifying the process under a digital solution. Digital work instructions (DWIs) are becoming more and more applied in industry as an effective way of delivering information, enhancing traditional text-based manuals with understandable media (photos, videos) and clarifying animations [3]. Connecting current systems of product variability management with these approaches will facilitate their integration in manufacturing, reduce time to create information and the time to update information, while delivering a more perceivable result.

This study proposes a framework that connects product family management with DWIs, enabling effective management and information reuse. The proposed approach focuses on the identification of common product nodes, like

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same parts/ sub-assemblies, to transfer and reuse instructions between different product variants.

2. State of the art

Product family engineering, also known as product line engineering (PLE), is a modern approach to treat conflicting challenges of customization and at-the-same-time cost/time reduction in management and production [4]. Nevertheless, the industrial adoption of PLE with its various stages and concepts, like central variability representation, feature model and integrated software platform varies between different companies and is yet, in general, far from being widespread or fully incorporated [5]. One of the main challenges, a unique source of information, requires integration of many software packages used in various parts of design, management, and production phases, which are company-specific and not always integrated between one another. Therefore no particular architecture solution is predicted to cater to a generic format that can be universally used. At the same time, on the way to highly customized production, many industries encounter similar problems, which may still benefit from a general framework.

Platforms that enable the authoring of digital work instructions have already reach the market. Although they may have some differences, and offer different features and integration options, systems like Manual.to [7], Azumuta [8], Proceedix [9] enable DWI authoring, combined with assistive illustrations. Moreover, other platforms enable the development of illustrations and instructions on a 3D viewer, stemming from the CAD file (e.g. Dassault Systèmes 3DExperience). Other instruction authoring systems focus more on the manual annotation of images of the CAD or the assembly (e.g. eFlex [10]), including pre-determined signs and arrows. These approaches, as well as the traditional paper-based instructions, require a lot of manual effort both from the engineering and the manufacturing department. It requires both a knowledge of the generation tool, as well as a feedback loop from experienced operators, so as to generate the media files and provide feedback. There are also studies towards delivering work instructions that can be catered to the operators' expertise, selecting the appropriate delivery method and filtering information [11]. Tools for automatic sequence extraction are not yet widely available, with some example being available in lower readiness level [12]. Moreover, platforms that enable the creation of Augmented reality instructions have also been introduced, but their acceptance and integration in the common practice is still lacking [13].

Within this article, a methodology and PLE framework to propagate variability of assembly instructions from design phase first towards method engineer with a semi-automatic digital work instruction authoring tool and then, finally, to the assembly operator on the shopfloor is proposed. Real-life industrial phases are modeled, starting from CAD design (usually performed by R&D department) and going through industrially spread Product Lifecycle Management (PLM) software implying feature modeling in-line with second generation of PLE [6]. Exploiting the knowledge gained between the product variants, the proposed methodology aims to reuse information so as to accelerate the DWI authoring process, while ensuring uniformity of information between different sequences.

3. System architecture and description

The complete system architecture to propagate product variability to digital work instructions can be divided into four major components, being CVM4Product (Central Variability Modelling for Product), CVM4Assembly (Central Variability Module), CAD2DWI (DWI authoring tool), and Content repository. Figure 1 below shows an overview of these components and how they interface with each other.

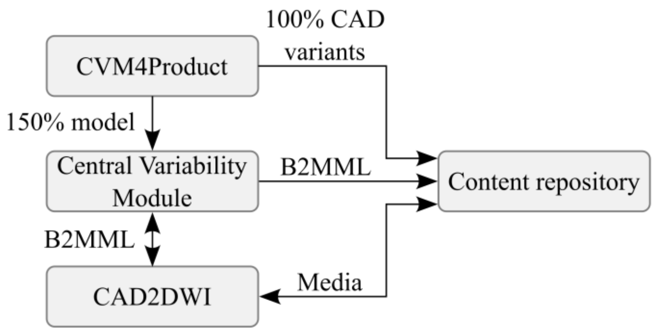

Fig. 1: System architecture overview

At first, the CVM4Product module is used to indicate the variability of products within a product family. From there, a 150% model and the 100% CAD variants can be exported, both in terms of structure and of geometries. The term '150%' refers to a model that contains the information of the entire product family and from which the information of each specific variant can be extracted. The information of each variant is then referred to as "100%". From CVM4Product, the 100% product-specific CAD models are exported to the 'Content repository', while the 150% model (which contains information regarding the feature model, the 150% BOM lines and the variant specifications) is exported to the 'Central Variability Module'.

Variability in products also results in variability in assembly information. The latter is generated using the DWI authoring component, in which digital work instructions can be generated. In the Central Variability Module, the logical links are made between product variability (coming from CVM4Product) and assembly variability (coming from CAD2DWI), with similarity analyses also being performed. In this way, maximum reusability of information is obtained so that the method engineer is relieved of repetitive work.

Finally, all necessary information is stored back in the content repository, from which all information on product variability and associated variable digital work instructions can be retrieved in an operational context.

3.1. CVM4Product

Initially, in the CVM4Product (Central Variability Modelling for Product) a feature model is defined. Such a feature model indicates which variabilities are possible in the product family (e.g., several sub-assemblies that can be interchanged, depending on the chosen variant). Next, within the CVM4Product part, the link is made between the feature model and the 150% Bill Of Material (BOM). A 150%BOM consists of a BOM of the entire product family from which every possible variant can be further filtered out for the user to focus on. The link between this 150%BOM structure and the feature model indicates which BOM parts (or in other words subassemblies) are applicable when selecting certain features. As a final step within CVM4Product, the variant configurations are defined, indicating for each specified variant which features of the feature model are active (and therefore which BOM lines are active). An example is presented in section 5 (Validation use case) on the targeted product family.

Within an industrial context, the CVM4Product component is typically handled by an R&D engineer. Additionally, existing Product Lifecycle Management software can possibly be used to set up the feature model, 150%BOM and variant configurations [14]. From such PLM software, the 100% product-specific CAD structures can be exported to the Content repository (e.g., in JT file format [15]). The 150% model information (consisting of information from the feature model, the corresponding BOM lines and the specified variant configurations) are exported from CVM4Product to the Central Variability Module (e.g., in XML format) [16]. A link between the two is preserved, so as to effectively manage product information and geometries

3.2. CVM4Assembly

To manage assembly information for multiple variants within a product family, the CVM4Assembly module is introduced. The primary function of this module is to merge variant assembly sequences and to facilitate the reuse of already configured information for similar product features. Using the industrial standard ISA-95 as a starting point [17], a generic data model for managing assembly instructions for product variants is developed.

As a first step, the assembly product structure is created and linked to the CVM4Product feature tree. Two types of material definitions are defined: assembly and part. A mechanical assembly is a stable collection of interconnected parts. However, a part definition may occur multiple times in an assembly. To address this, the material component class is introduced to instantiate parts in an assembly. In this way, material components are uniquely identifiable entities that are part of an assembly and thus correspond to one BOM line defined in the CVM4Product.

The next step is defining the tasks required to assemble a product. A work definition describes all information needed to perform a unit of work (e.g., an assembly task) and the assembly sequence through a workflow. The assembly sequence consists of multiple assembly steps (workflow nodes) where material components are inserted. Each workflow node contains the instructional information needed to perform the assembly and may have a reference to a child work definition. In this way, work definitions can be arranged hierarchically. Four work definition types to define this hierarchy for an assembly product are introduced:

- *Product family work definition*: root definition for a product family that contains the merged assembly sequence of all configured product variants
- *Product variant work definition*: root definition for a product variant that contains the assembly sequence for one product variant (i.e., filtered from product family work definition)
- *Product feature work definition*: assembly sequence that corresponds to one specific product feature defined in the CVM4Product feature model (reusable over multiple product variants)
- *Subassembly work definition*: assembly sequence for a subassembly that can be reused over multiple product families (reusable over multiple product features, may correspond to another product family work definition)

Product family work definitions are constructed iteratively by adding product variant configurations individually. When the first variant configuration variant is added, the initial product family work definition is created, and assembly steps are divided over product feature work definitions via the material component link to the product feature model. To accelerate the instruction authoring process, already available information can be retrieved from the CVM4Assembly module. Via a similarity search, based on the material information linked to the assembly steps, available assembly sequences and instructional information that may be reused for the new variant are identified and returned to the instruction authoring tool. When the configuration of the new variant is completed, the information will be merged into the existing product family work definition.

3.3. Authoring digital work instructions for product variants (CAD2DWI)

A digital work instruction authoring tool was developed, so as to enable the user to effectively create step-by-step instructions that explain the sequence and the method of assembling the product. As the majority of human operated manual tasks in assembly operations revolve around inserting parts following an axis, the authoring tool focuses on that function. The authoring tool user is envisioned to be a "method

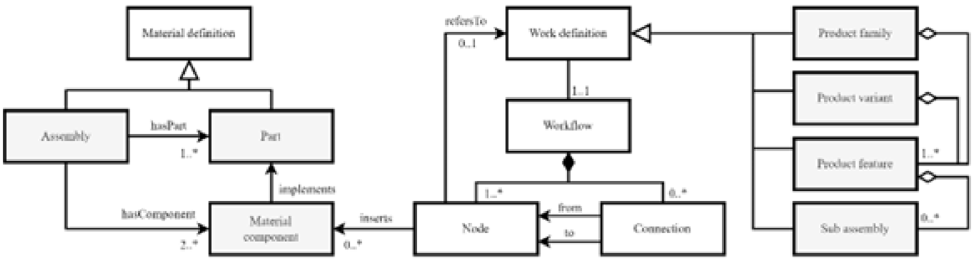

Fig. 2: Variability Model

engineer": someone responsible for creating processes and defining the manual operation behind it. To accelerate the instruction generation process, an algorithm for automatic definition of the process is also introduced [3]. The algorithm uses heuristic rules, evaluating if a part is visible/ can be removed with no obstruction, and adds it next to the disassembly sequence. Additionally, it groups sequentially parts/ steps that are close, trying to provide a more usable sequence. Nonetheless, the user is capable of altering the sequence and manually adding steps to it, so as to complete the sequence.

To be accurately defined, each assembly step constitutes of the (dis-)assembly animation (axis and direction), a general text description of the task at hand, point-anchored annotations that the user may define and also, if available, the Product and Manufacturing Information (PMI) that the product geometry carries from the design phase. The latter two are optional. The instructions author is called to evaluate the PMIs and check if they need to be included in the assembly instructions, as they may reflect to other aspects of product manufacturing (e.g. parts manufacturing). The user may also add annotations, including text and even media files (photos, videos), and additional checks to be performed in important checkpoints of the process.

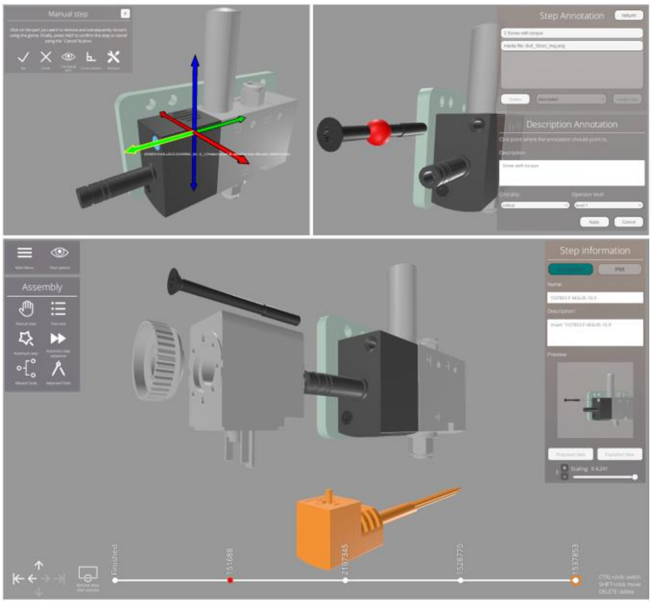

Fig. 3: Digital Work Instructions authoring tool interface

After the process is completed, the user may export the result in an XML file which implements the ANSI/ISA-95 and ANSI/ISA-88 standards [17], together with each step details, the added media files, geometries (even separated per step) and optionally illustrations (videos and images) that show the animation per step. The latter is useful for depicting the instructions in 2D screens. The result is then pushed to the Central Variability Module, and each part's information is mapped against the product family structure. Moreover, any media files included (e.g., videos explaining a process) are pushed to the content repo, where larger files are managed.

4. System Integration

Figure 1 shows the system architecture overview. All interfaces in between the different architecture parts are established using REST API calls [18]. As indicated in the Figure, some of these interfaces are using the B2MML markup format, which is an XML implementation of the ANSI/ISA-95, Enterprise-Control System Integration, family of standards (ISA-95), known internationally as IEC/ISO 62264 [19]. In short, the ISA-95 standard is an international standard for the development of a general interface between business and control systems in diverse industries using a variety of processes. By using ISA-95, a consistent terminology can be applied so that all the different interacting people and systems can use consistent information models. The usage of a common information model and data exchange format, which also follows an industrial standard, allows the different interacting entities to more easily exchange information across processes and systems, while facilitating any further integration of the proposed approach.

The instructions authoring platform is a desktop application developed using Unity [20], so as to provide the user with an easy-to-use interface that supports 3D geometries, even from CAD software, and the import/ export of data in various formats, facilitating integration with various market available solutions. In the current framework, the export is an xml file, formatted under the B2MML format [21].

5. Validation use case

The proposed approach is then validated on a use case of a product family of a drilling equipment support product, of which the feature model can be seen in the Figure below.

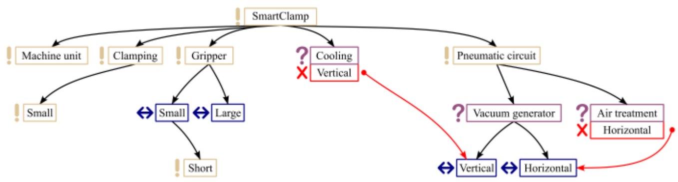

Fig. 4: Feature model for the use case product family

The brown exclamation marks show features that are mandatory for the correct function of the product, the purple question marks indicate features that are optional and are possible under specific configurations, and the blue double arrows indicate that one of several options must be chosen. The red crosses indicate conflicting features that cannot be active simultaneously; this could be linked with physical restrictions on their positions on the final product. Initially, PLM software is used to define the feature model and link the features to the 150% BOM structure. The 150% BOM structure is derived from the 150% CAD structure, which in turn is realized using conventional CAD (Computer Aided Design) software. Then, the specific variants are defined, indicating which features are active for each variant. Three variants of the product will be studied in the validation phase. The variants were selected carefully so as to share some features but still have some distinguishable differences. Table 1 below shows which features are active for every variant of the targeted use case.

Table 1. Overview of what features are active for every variant

Feature	Variant 1	Variant 2	Variant 3
Machine unit	●	●	●
Clamping	●	●	●
Clamping Small	●	●	●
Gripper	●	●	●
Gripper Small	●	○	●
Gripper Large	○	●	○
Gripper Short	●	○	●
Cooling	○	●	●
Pneumatic Circuit	●	●	●
Vacuum Generator	●	●	●
Vacuum Generator Vertical	●	○	○
Vacuum Generator Horizontal	○	●	●
Air Treatment	●	○	○

At this point, the 150% CAD, 150% BOM structure, the links from that BOM structure to the features, and the variant specifications are available. With that information, the 100% variant-specific CAD structures can be filtered out from the 150% CAD and exported in file format to be used for DWI authoring. The Figure below gives an overview of the corresponding 100% CAD structures for every variant of the validation use case.

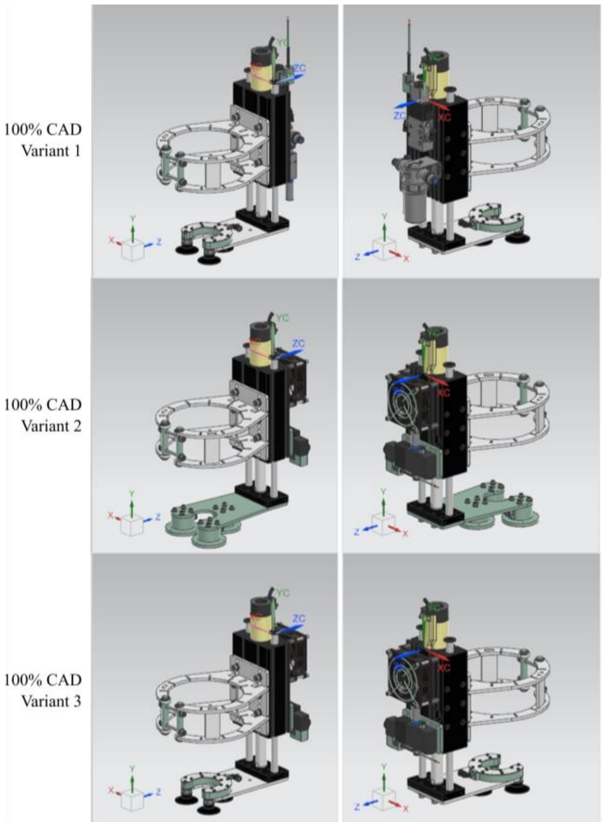

Fig. 5: 100% CAD for the three product variants

After that, the 150% model (150%BOM, feature model, and variant configuration) is introduced in the Central variability Module, which automatically identifies similarities between variants, as presented in the following Table.

Table 2. Variant (V) similarity analysis on the validation case

	V1	V2	V3
V1	1.00	0.14	0.33
V2	0.14	1.00	0.60
V3	0.33	0.60	1.00

Then, a method engineer is called to generate the DWI for each variant from scratch using the authoring platform, so as to record the required time to do so. The user is called to generate the sequence for all sub-assemblies/ parts, evaluate the inclusion of PMIs embedded in the CAD file, and add any other annotations and checks needed for the operator to be able to complete the assembly. The additional checks added serve as quality checkpoints, which the operator (or a supervisor) may use to ensure that the assembly has been correctly completed. As the users select a part/ sub-assembly, they are quoted to select the axis and direction of disassembling the part. The inversion of the sequence and the direction will result in the assembly instructions.

Then, the method engineer is called to generate a sequence for one of the variants (Variant 3), but first importing the already generated instructions from a previous sequence that shares an increased level of similarity. This way the information reutilization is maximized and thus reduces the time required to define the instructions for some steps. Based on the analysis presented in Table 2, information from Variant 2 are loaded, as that variant is the most similar one. As depicted below, 86 assembly steps were mapped on the new variant and their information (assembly direction, description, annotations, PMIs) are loaded.

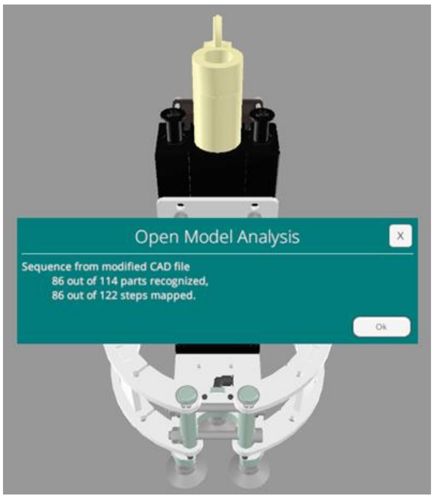

Fig. 6. Importing instructions from another variant.

After importing the method engineer is called to check that the imported information is valid for the new product variant, which consumes some time but still substantially less than re-defining the sequence from scratch. The time required for each approach is recorded and presented in the Table 3 below.

Table 3. Time required to generate DWI

Variant	V1	V2	V3	V3 using V2
Time	13’	10’	9’	6’20’’

The time required for each variant is reducing after each iteration, as the user is also getting the hang of the authoring tool, but there is a clear reduction of time when the suggested similarity methodology is introduced. The time required to define the sequence when importing the existing information is reduced by 30%, while still considering information validation and sequence update by the user. The proposed methodology enables the user to reuse a significant amount of information that saves a lot of time and ensures that the assembly sequences have a uniformity, which would also facilitate the operator. Moreover, if more variants (or a product family with more variants) were considered, the possibility to have more similar variants, and thus the amount of reused information, would also increase.

6. Conclusions and next steps

This study presents a framework that enables the generation of digital work instructions and facilitates the re-utilization of information inside a product family. The proposed approach for modelling the product family enables the management of the variants and supports the definition of similarities. The Central Variability module detects the similarities between the different variants under the same product family, and maps them in a way that highlights common parts, leading to information re-utilization. The presented authoring tool enables the creation of DWI, enriched with annotations and media files, and their export in a reusable format, combined with 3D geometries. Exploiting the instructions generated for other variants in the same product family, it accelerates the authoring process and ensures uniformity of information. The authoring process export is then stored, available for modifications, information reuse and for operators to use.

Future work will focus on expanding the proposed approach so that it also gives suggestions between variants based on part similarity, based on a certainty threshold, expanding the pool of reused information and further accelerating and automatizing the authoring process. Additionally, the possibility to expand this function to parts reused between families, for example bolts and washers, will be explored.

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