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Structuring Product Family Variability Through DSM-Informed Parametric CAD Modeling

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Abstract: Manufacturers increasingly need differentiated products without losing the economic advantages of internal standardization. However, product families that evolved through incremental CAD practice may be stored as disjoint legacy variants rather than as an explicit family structure. This paper presents a proof-of-concept, DSM-informed workflow that retrospectively reconstructs commonality, variability and dependencies across assembly, part and CAD-feature levels and translates them into a single parametric master model. The advancement lies in bridging scattered legacy CAD data and structured product family representation. The method is demonstrated on two industrial variants and its current manual and scalability limitations are discussed.

Keywords: product family, 3D modeling, platform design, feature-based design, master model

1 Introduction

Manufacturing companies increasingly need to offer differentiated or customized products while preserving the internal standardization required to control engineering and production costs. Product-family strategies address this tension by combining common elements with controlled variation. However, the practical availability of a product family on the market does not necessarily mean that the corresponding engineering data are organized as a coherent family. In many industrial contexts, product variants have been developed incrementally and independently in response to successive customer or market requirements. As a result, the CAD repository may contain a collection of separate 3D models in which common parts, variable dimensions, alternative features and dependencies remain implicit. The products constitute a family from a functional or commercial perspective, but the dataset represents them as disconnected individual designs. This condition is particularly consequential for SMEs, which may lack the resources required to manually restructure extensive legacy product data before introducing more advanced engineering-information systems. Transforming such a fragmented dataset into an explicit product family representation can provide benefits beyond the reduction of repetitive CAD modelling. A structured master model can make commonality, variability, geometric relationships and configuration states more accessible, thereby creating a more suitable basis for subsequent model-based systems engineering activities, PDM/PLM implementation and other lifecycle-information workflows. Where relevant attributes are available, the structure may also facilitate the extraction of geometry, material and configuration information for subsequent LCA inventory compilation. These downstream applications are regarded here as potential benefits of improved data organization, but are not implemented or evaluated in the present study. Against this background, this paper investigates how an existing and scattered set of product variants represented by independently developed 3D CAD models can be retrospectively reorganized into a single parametric master model representing the product family. The study addresses the following research question: How can a DSM-informed analysis of existing CAD variants support their consolidation into a unified parametric master model that explicitly represents family commonality, variability and dependencies? The proposed method compares the variants hierarchically at assembly, part and CAD-feature levels and translates the identified correspondences and differences into reuse, parameterization and feature-configuration decisions. Its distinctive contribution is therefore the transition from disconnected legacy CAD models to a persistent family-level representation, rather than the development of a new DSM formalism or a fully automated product configurator. The remainder of this paper is organized as follows: Section 2 positions the proposed work relative to product-family and platform design, DSM-based modularity and commonality analysis, product configuration, PLM-supported product architecture management, and parametric CAD reuse and master-modelling approaches. Section 3 presents the proposed retrospective product family structuring method, including the cross-variant DSM analysis and its translation into CAD master-modelling decisions. Section 4 demonstrates the application of the methodology to a door-lock product family. Finally, Section 5 summarizes the findings and conclusions of the study.

2 CAD Modelling and Product Family Structuring

Research on product-family and platform development has extensively addressed the need to reconcile external product variety with internal commonality and production efficiency. These approaches typically start from customer requirements, market segments, product architectures or an already recognized set of related products and aim to determine suitable levels of part sharing, modularity and platform differentiation (Jiao et al., 2007; Simpson et al., 2011; Baylis et al., 2018). Related commonality and modularity methods analyse products, parts and interfaces to identify standardization opportunities and platform candidates. DSM-based approaches represent dependencies among predefined product elements and use clustering or coupling analysis to support modular architecture decisions (Eppinger and Browning, 2012; Qiao et al., 2017; Xiao and Cheng, 2016; Wilschut et al., 2018). These contributions provide systematic support for determining what should be common, modularized or differentiated. However, they generally operate at the product-architecture, part or interface level and do not directly translate relationships among independently developed CAD variants into a unified parametric family model. Within CAD research, feature-based parametric modeling is widely used to generate related product variants from shared geometric descriptions. Product families may be organized around typical products, component families and reusable part models enabling new designs to be generated without rebuilding each product from scratch. Template- and Platform-based approaches illustrate this principle. Siddique and Zhou (2002), for example, proposed a product family template integrating configuration and parametric design information and proved to automatically generate family members CAD variants. Similarly, Claesson and Johannesson (2006) addressed integrated and configurable product and manufacturing models. These approaches show how a predefined platform or template can support efficient variant generation, but they generally assume that the common product architecture and its variation mechanisms have already been identified A particularly relevant earlier contribution is the work of Huang and Yip-Hoi (2003), which addresses parametric modelling from independently generated product datasets and discusses the reconstruction of a family representation by merging information observed in multiple instances. Product This is close to the starting condition considered in the present research. However, their work focuses on part-family machining process plans rather than on the hierarchical consolidation of complete product variants at assembly, part and CAD-feature levels. Moreover, it does not pursue the construction of a single persistent master assembly intended to represent the common and variable structure of the complete product family. The present research therefore builds on the general principle of recovering family knowledge from existing instances but applies it to the restructuring of industrial 3D CAD variants and to their translation into a family-level master model. Other CAD-family approaches formalize the family through declarative or constraint-based representations. Van der Meiden and Bronsvoort (2007, 2009) define a family in terms of variables shared by the members and constraints expressing invariant relationships among those variables. Individual members are generated by solving the corresponding constraint systems. These approaches provide a rigorous definition of family membership and variation but require the variables and constraints to be explictly formulated. History-based parametric models also introduce challenges related to model quality, reusability, topology inconsistency and reference instability under parameter change (Wang and Nnaji, 2005; Camba et al, 2016). Such issues are directly relevant to the robustness of master models but do not resolve the preceding problem of identifying which elements of independently developed variants should become shared, parameterized, optional or variant-specific. Knowledge-Based Engineering (KBE) and product-configuration research extend parametric modeling by encoding design rules, formulas, manufacturing restrictions and configuration constraints in CAD models (Gembarski et al, 2016). Product-family knowledge models may also use design structure matrices and domain mapping matrices to relate product family knowledge to parametrically defined modules (Yu and Zhan, 2009). Configuration-grammar approaches similarly provide formal representations for configurable products in advanced CAD environments (Deciu et al, 2007). More recent configurator research represents the product family as an explicit solution space consisting of modules, parameters, constraints and dependencies, from which valid configurations and associated documentation can be generated (Helo, 2006; Haug et al., 2019; Alfnes et al., 2026). These methods are effective once product knowledge has been formalized, but that formalization may require substantial preliminary work, including product standardization or redesign for configurability. They therefore primarily exploit an existing structured family definition rather than recovering it from disconnected CAD models. The “digital master” concept effectively links configuration knowledge to CAD regeneration states. Gembarski, (2022) describes a digital master assembly containing the possible part and feature occurrences, which are activated or suppressed according to the selected product configuration. This resembles the intended output of the present work. The difference lies primarily in the starting point and in how the master structure is obtained. Configurable digital-master approaches assume that the relevant components, options, constraints and configuration logic have already been identified. The present research instead begins with a collection of legacy CAD variants in which such family knowledge remains implicit and seeks to reconstruct the master structure through systematic comparison. PLM-supported modular product development addresses the subsequent management of product architectures, multiple product structures, interfaces, CAD files and non-geometric lifecycle information (Bruun et al., 2015). PLM systems can therefore manage the structured family representation produced by a master-modelling process. They do not, however, inherently determine how separate legacy variants should be compared or how their geometric differences should be translated into parameters, optional features and variant-specific branches. Likewise, design-module reuse approaches address the capture and representation of reusable design knowledge, but often assume that understandable modules or reusable structures are already available (Lundin et al., 2017). The work most closely related to the proposed method is M-ARM, developed by Wong and Wynn (2024). M-ARM analyses existing product-family members through their functions, parts and CAD features and generates alternative redesign routes and CAD activities for developing a new variant. It therefore demonstrates the value of feature-level comparison across existing family members. Its primary output, however, is redesign guidance associated with a target variant. It does not aim to consolidate the analysed variants into a single persistent parametric model representing the common and variable structure of the existing family.

Overall, the literature provides methods for designing platforms, analysing commonality and modularity, formalizing configuration knowledge, constructing reusable parametric models, managing product information and generating new variants. However, these approaches generally start from an already defined product-family architecture, an explicit configuration model, reusable geometric modules or a specific redesign objective. Less attention has been given to the preceding industrial condition in which a product family exists commercially and functionally but is represented in the engineering dataset as a disjoint collection of independently developed 3D CAD variants. The present research addresses this gap through a retrospective product-family structuring method. It applies an adapted cross-variant DSM at assembly, part and CAD-feature levels to recover latent commonality, variability and dependencies and then translates these relationships into reuse, parameterization and feature-configuration decisions. Its distinctive output is a unified and persistent parametric master model representing the existing family, which may subsequently provide a more structured basis for configuration, MBSE, PDM/PLM and lifecycle-information workflows.

3 DSM-based Approach to Generate CAD Models for Product Families

With reference to the above challenges, this research proposes a DSM-informed analysis of existing CAD variants in order to support their consolidation into a unified parametric master model that explicitly represents family commonality, variability and dependencies. The approach is meant to allocate both common and variant-specific parts within the product family, parametrize critical CAD features; organize them within a unified 3D model and facilitate their reuse, enabling a variety of hidden opportunities. From opening the door to Engineering-To-Order approaches to a wiser management of resources and production. For the sake of clarity, within the paper we adopt the following definitions for the above-mentioned concepts:

Assembly: it refers to the CAD model that represents the family. It is composed of subassemblies and/or parts. The assembly master model describes all the product variants by means of parameter changes;

Part: a 3D model (or its real counterpart) which is monolithically structured and cannot be further decomposed into more elementary pieces without compromising its integrity. The master model of a part describes all the part variants used within the family.

(CAD) Feature: a geometrical characteristic of the 3D part model, which contributes to defining its morphology and that corresponds to a geometric transformation in the space (e.g. extrusion, hole, rib, etc.);

Sub-assembly: a 3D model (or its real counterpart) which combines parts into a more complex element concurring to the product functionality.

Entity: any of the above, interchangeably, especially when referred to them as CAD assets.

3.1 Scope definition and selection of product variants

The process begins with a clear definition of the objective of implementing the master modelling technique. At this stage, the scope of the project, expected outputs, and the type of product variations to be handled are understood. This ensures that the modelling approach remains structured and aligned with design and manufacturing goals. The methodology (Figure 1) starts with selecting the appropriate family of products. This selection must be done carefully so that a large set of parts within the family share very similar geometry, structure, and overall design intent. The parts belonging to the product should not vary significantly in shape or fundamental features, as expected within an actual product family. However, as for a product family, these products differ because of minor feature changes, dimensional variations, or scaling. Choosing such a family ensures that a single master model can effectively control and represent all variants without unnecessary complexity. Once the product family is selected, the next step is to identify the specific product variants that need to be described by means of a product-level master model. Within these variants, it is to be expected that some parts do not vary, which might avoid the need for them to be modeled by means of a parametric part-level master model. Many parts, in fact, may remain identical across all variants and therefore do not need parametric control. These common parts should be identified and separated. The focus should be primarily on assemblies, sub-assemblies or parts that exhibit variation across the family and would benefit from parameter-driven design. After identifying these, their detailed analysis is carried out. This involves studying their geometry in terms of features and dimensions within the product. Special attention is given to understanding how each part differs from others in the same family.

3.2 Cross-variant DSM construction and coding rules

The comparison is supported by an adaptation of the Design Structure Matrix approach and helps in identifying patterns of variation and establishes a foundation for defining parameters later in the master modeling process. In a conventional DSM, rows and columns normally represent the same set of elements belonging to one system, and matrix entries describe relationships among those elements. In the present method, rows and columns represent corresponding entities in different product variants. The resulting representation is therefore referred to as a cross-variant comparison DSM. This is meant to show geometrical relation between the different assemblies and/or parts between two products belonging to the same product family. Before constructing the matrix, corresponding elements are paired according to their functional and architectural roles. At product level, the compared entities may be assemblies, sub-assemblies or parts. At the more detailed level, the compared entities are CAD features belonging to corresponding parts. The diagonal cells describe the geometric relationship between paired entities, whereas off-diagonal cells describe relevant interfaces or dependencies among different entities. The matrix codes are defined in Table 1.

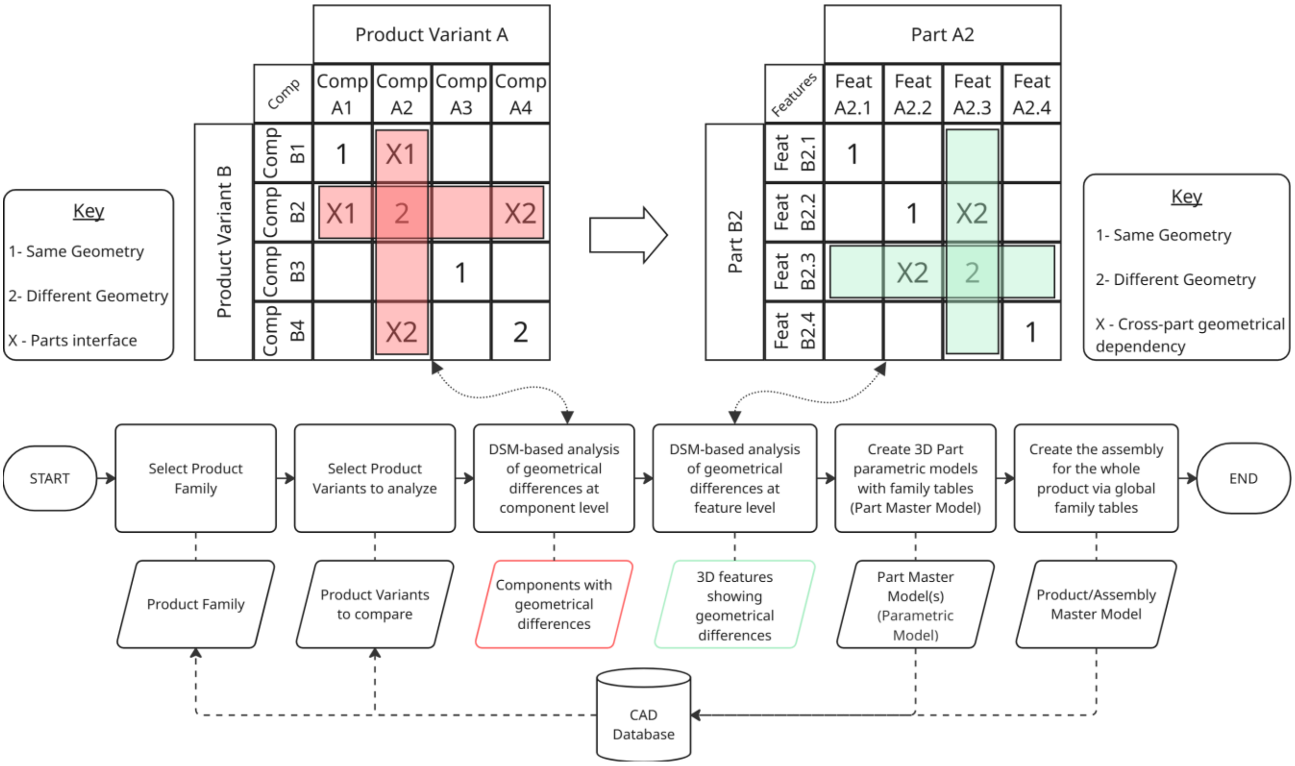

Figure 1. The DSM-based methodology to highlight geometrical similarities and differences in product families and support the development of the master models

Table 1. Coding rules for the cross-variant comparison DSM and correspondent CAD modeling decision

Matrix position	Code	Meaning	Consequence for CAD
Diagonal	1	The paired entities are geometrically equivalent according to the defined criterion	The entities can normally be reused unchanged in the master model
Diagonal	2	The paired entities correspond functionally or architecturally but present a geometric difference	The difference must be classified and translated into parameterization, feature activation/suppression, alternative geometry or a variant-specific solution
Off-diagonal	(blank)	No relevant interface or dependency has been identified	No relationship needs to be represented in the master model
Off-diagonal	X1	The same interface or dependency exists in both variants and is geometrically equivalent	The relationship can normally be retained unchanged
Off-diagonal	X2	The interface or dependency exists in both variants but differs in geometry, position or parameterization	The relationship must be explicitly managed through parameters, constraints or alternative configuration logic

A value of 1 on the diagonal indicates that the corresponding entities are geometrically equivalent under the adopted comparison criterion. Such entities can normally be reused unchanged in the master model. A value of 2 indicates that corresponding entities differ geometrically and therefore require further analysis to determine whether the difference should be represented through a dimensional parameter, an optional feature, an alternative feature definition or a variant-specific element. Off-diagonal entries record relationships among entities. An X1 entry indicates that the same interface or dependency is present in both variants without a relevant geometric change. An X2 entry indicates that the relationship is present in both variants but differs in geometry, position or parameterization. Empty cells indicate that no relevant relationship has been identified between the corresponding elements. For every entry coded as 2 or X2, the analyst records the CAD evidence supporting the classification, such as the compared geometry, feature-tree definition, mating interface, drawing or dimensional specification. In this study, geometric equivalence at part level requires corresponding entities to present the same geometry, topology and relevant interface definition. At CAD-feature level, equivalence requires the same feature type, geometric role and parameter values. A difference in dimension, position, feature presence or feature definition is therefore coded as 2, even when the difference can subsequently be represented through a parameter. Non-geometric attributes, such as material, are not used to determine geometric equivalence and are recorded separately. Because the relationships considered in the present application are treated as reciprocal and the entities are arranged according to the same correspondence order, the resulting matrices are displayed symmetrically. Symmetry is therefore a consequence of the adopted representation and should not be interpreted as an inherent property of every possible cross-variant comparison matrix.

3.3 Master model implementation and verification

Once the family structure and the required modeling decision have been defined, the master model is implemented into an appropriate CAD environment. The selected software must support parametric modelling, family/configuration tables (whose functionality is available with different [commercial] names in the largest majority of CAD tools), and robust assembly management. These capabilities are required to represent dimensional variation, alternative feature states and part selections while maintaining consistent relationships among the elements of the product family. . The parts and assemblies extracted from existing CAD variants are imported, reused or remodelled within the master model environment. The assembly is then reorganized to establish consistent positioning, orientation, interfaces and parent-child relationships. This restructuring is necessary because independently developed variants may use different modelling sequences, references or assembly structures, even when their parts perform corresponding functions. The variability identified through the cross-variant analysis is subsequently implemented through dimensions, relationships, constraints and configurable feature or part states. Parameter relationships are checked to ensure that modifications propagate correctly and do not produce regeneration failures. The resulting parameter values, activation states and part selections are collected in a family table, where each row in the table initially represents one of the analysed product variants. The configurations generated from the family table are finally compared with the corresponding original CAD models by checking part presence, relevant dimensions, feature states, interfaces and successful regeneration. Detected inconsistencies lead to a revision of the parameters, constraints or configuration logic. This verification confirms that the master model reproduces the analysed variants, but does not demonstrate the validity of untested combinations or its scalability to the complete product portfolio.

4 Proofing the Methodology: a Master Model for Domestic Appliance Product Family

4.1 Door-locker variants for washing machines and related variants

The application of the proposed methodology was carried out by selecting a family of door-lock parts for washing machines, manufactured by one of the key global market players in the field. This product series comprises a range (more than 10 variants) of safety-critical devices designed for front-loading washing machines. These variants were chosen because they share the primary function and broad architecture while exhibiting similarities as well as geometric and structural variations at sub-assembly and part level, also resulting into difference at the CAD feature level. These devices function as instantaneous safety mechanisms that control the locking and unlocking of the machine door, thereby preventing the operator from coming into contact with the rotating drum during operation. The methodology, for sake of simplicity, applies the approach to two random variants in the family. They exemplify the motivating data condition: independently developed models whose family commonality and variability are not explicitly represented. The resulting master model demonstrates the feasibility of recovering and formalizing that latent structure for a bounded subset; it is not claimed to cover the complete portfolio. Unchanged elements are reuse candidates rather than automatically standardized parts. The structured model may provide a cleaner basis for later systems modelling, PDM/PLM management and access to geometry, material and configuration data for LCA inventory compilation, but those downstream uses are not evaluated here. Each door-lock unit is composed of three major subassemblies (Figure 2).

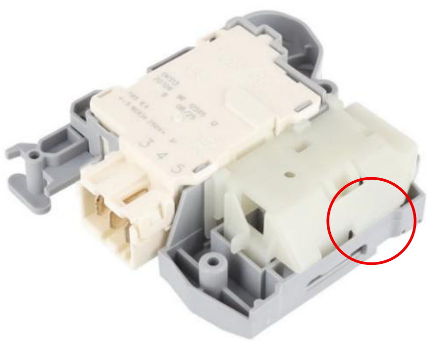

Figure 2. an example of door-lock as seen from the outside. The grey part is the visible part of sub-assembly A. The white parts are the visible parts of sub-assembly B. The translucent part is the visible part of sub-assembly C.

One primarily governs the mechanical interaction with the washing machine it is customized for (sub-assembly A), one houses the electrical and control elements (B), while the last one shields some of the moving parts (C). Upon further decomposition, primary subassemblies consist of numerous smaller internal parts, each contributing to the overall functionality of the system. Such complexity is here omitted to ensure clarity.

4.2 Cross-variant DSM-based identification of similarities and difference for two door-locker variants

For this application, two representative variants of this product family were selected: these will be referred here as variant ALPHA (α) and BETA (β) to ensure confidentiality. A detailed evaluation of the parts across the two variants was carried out by implementing the Design Structure Matrix (DSM) technique, as mentioned in Section 3.2 and the main parameters in consideration were with respect to both their functional roles and geometric characteristics. Figure 3 displays the key similarities and differences between variants (left) at sub-assembly level and between the features of sub-assembly C (considered as such for coherence with the other sub-assemblies, but actually a part in the variant, as it is an entity that cannot be further decomposed into sub-parts)).

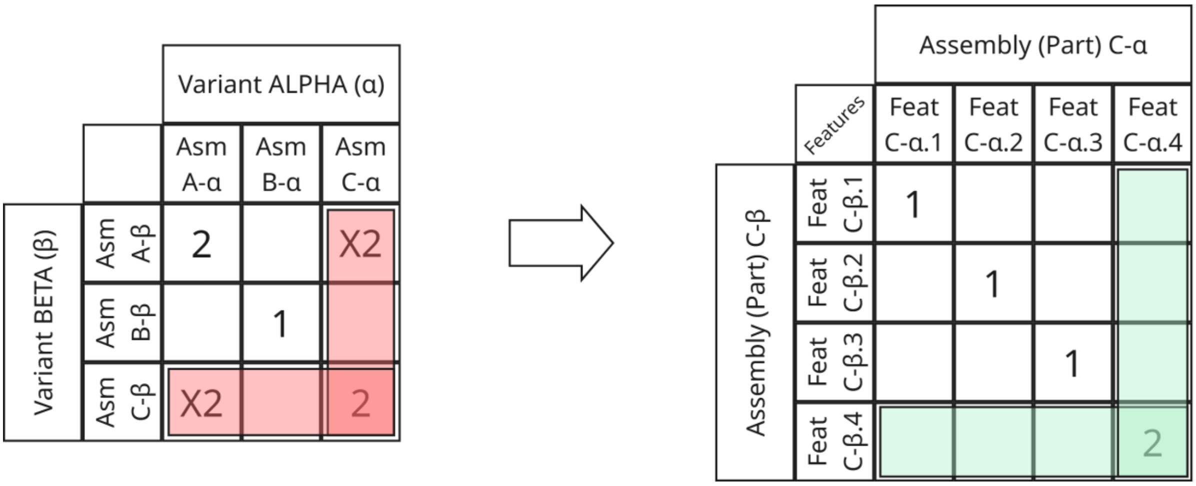

Figure 3. Similarities and differences both at product variant level (left) and at part feature level (excerpt - right)

From the cross-variant DSM, built using the codes presented in Table 1, it is possible to infer that the geometry of sub-assembly B is similar in both variants (α and β), while sub-assemblies A and C are the ones differentiating the product variants. This implies that the master model can be built more quickly by integrating a common entity (sub-assembly B) while accommodating adequate parametrization for sub-assembly A and C. The dissimilar entities are further broken down using the DSM technique to evaluate and assess the similar features and geometric dimensions, to efficiently develop the correspondent part-level master models, as for the example of Figure 3-right (sub-assembly C). In the excerpt of the complete CAD feature-wise DSM reported here (4 CAD features out of the 40+ of the whole part model), most of the features of sub-assembly C (as said, it should be better referred as Part C), do not significantly vary, except for Feature 4 in the two variants (C-α.4 ≠ C-β.4). This example concerns the features described in Figure 3-right, which correspond to the ones that define the geometry of the slot highlighted with the red circle in Figure 2. In general, to efficiently manage these similarities and differences, a unified master model has to be developed at part level for all the entities which present differences in sub-assemblies (A and C for the above example). Sub-assembly A, however, is not presented here for reasons of confidentiality and length, as it is more complex and rich in parts composing it, ideally adding one step to the methodology (cross-variant DSM analysis of sub-assembly A parts and then, for all the parts which are geometrically different, their cross-variant DSM analysis at feature level). The resulting part-level master models serve as a comprehensive representation of the parts which vary within the product family, incorporating both common CAD features shared across all variants and configurable elements that account for their differences. From the perspective of the parameters described by the features, these include both the ones introduced via sketches as well as CAD (volumetric) features. In general, this unifies the range of variation of existing parts within the same 3D model: beyond providing systematic control of parameters (and design choices), it reduces modelling redundancy and enable the scalability for future product development within the same family or other product data related applications.

4.3 Creation of master models and family tables at part- and product-level

Coherently with the methodology presented in Figure 1, the prescribed development of the part-level master model might be carried out through the development of a brand new 3D model to be created from scratch for full parametrization and flexible differentiation, or by reusing and modifying an already existing model describing a specific product variant. This mostly depends on several factors: the quality of existing product variant models, their modeling strategy and, as a consequence, their suitability for parametrization; the number of required modifications to any of the existing product in the family; etc. This decision strongly depends on the situation. As for the specific research question, the company that manufactures door-locks aims at unifying the design data management of their product variants into a comprehensive 3D model, as a way to unfold future business opportunities. Indeed, the products used for the case study already had their digital 3D model developed within PTC Creo, as this is the software used in the company. This CAD software also enables the management of variants by means of family tables, despite the largest majority of any other parametric CAD software offers the same functionality (e.g. configuration tables (SolidWorks/Autodesk Fusion), design tables (Catia,), etc.).

Figure 4 reports a subset of the parameters belonging to the CAD Feature 4 which vary between parts (Control 1, Control 2; Control 3; Control 4; Control 5), with some specific values meant to describe one of the specific part variants. The part-level master model , more in general, entailed a wider set of parameters (300+ dimensional parameters, most of which invariant) which are not reported here for confidentiality reasons and to keep the reading flowing. In any case, the generalized part-level master model integrates the proper features of both ALPHA and BETA part variants into a single parametric structure. The CAD features that require variation across different configurations are systematically parameterized and defined within a dedicated parameter table. Figure 4 also reports the specific variable type included in the parametrization, distinguishing numerical values which the designers can flexibly modify (Full in access column) from derived ones or assigned via other CAD functionalities (e.g. Locked). Fully accessible variables do not just define geometrical model variables (assigned as Real numbers), but also other part characteristics as material (described via strings), which might also differ across variants.

Name	Type	Value	Designate	Access	Source
PTC_VAL_IMP_PART_STATUS	String	OK	☐	Locked	ATB
PTC_MP_VAL_IMP_VOLUME	Real Numbe	4052.99096	☐	Locked	ATB
PTC_MP_VAL_IMP_AREA	Real Numbe	6470.98411	☐	Locked	ATB
PTC_VAL_IMP_SCORE	String	PASS	☐	Locked	Creo Param
CONTROL1	Real Numbe	4.4	☐	Full	User-Define
CONTROL2	Real Numbe	2.0	☐	Full	User-Define
CONTROL3	Real Numbe	4.02	☐	Full	User-Define
CONTROL4	Real Numbe	10.0	☐	Full	User-Define
CONTROL5	Real Numbe	6.0	☐	Full	User-Define
PTC_MASTER_MATERIAL	String	PTC_SYSTEN	☐	Full	User-Define
PTC_REPORTED_MATERIAL	String	List	☐	Locked	Creo Param

Figure 4. Parameter table – Sub-Assembly C Master

Moreover, the morphological variations are managed through a combination of feature-based and dimension-based parametrizations within the associated family table, as displayed in Figure 5. In fact, the two part variants also differ because of the presence of an additional protrusion close to a squared slot. The slot is present in both variants with different dimensions, while the protrusion is present in one variant only. As for this protrusion, 3D features which belong to some variants only, has to be activated (Y) or suppressed (N) besides modifying dimensional parameters. Still with reference to Figure 5, Local Group_2 is controlled using feature-based manipulation, allowing it to be enabled or disabled depending on the selected variant. This enables straightforward inclusion or exclusion of the feature without altering the overall part-level master model structure.

Look In: SUB-ASSEMBLY C

Type	Instance File Name	Common Name	F13998 LOCAL_GROUP_2	CONTROL2	CONTROL4	CONTROL5	CONTROL1
	SUB-ASSEMBLY C		Y	2.0	10.0	6.0	4.4
	SUB-ASSEMBLY C_V1		N	4.0	4.5	2.5	*
	SUB-ASSEMBLY C_V2		Y	2.0	10.0	6.0	4.8
	SUB-ASSEMBLY C_V3		N	4.0	4.5	2.5	*

Figure 5. Excerpt from the family table of sub-assembly C with 4 different parameter and feature combinations leading to different variants.

In addition, this part-level family table also enables the control of dimensional variations via parameterized variables assigned to key geometric features (coherently with the parameter table). These parameters, labelled as Control 1, Control 2, Control 4, and Control 5, govern critical dimensions of the internal clip of these part variants and the above mentioned features. By assigning appropriate values to these control parameters within the family table, the required geometry for each Sub-assembly C variant can be accurately generated from the master model. Figure 5 shows 4 sub-assembly C variants, including the configuration required for the ALPHA and BETA product variants. The other 2 instances have been developed to run a preliminary consistency check with parameter recombination and/or change across variants in the expected variation range, to verify the consistency of the CAD master model in terms of reconstruction errors. Despite not statistically relevant, the check did not generated any reconstruction error. The final configurations for this specific entity of the whole product are obtained by selecting the appropriate instance from the part-level family table, ensuring that each part variant is represented with its correct feature set and dimensions. The same approach can be repeated for all the relevant part variants that determine the geometrical differences between or among different product variants (e.g. as said for Sub-assembly A). Each of these parts will be characterized by its own part-level master model, parametrized and made adjustable as described above.

Then, the product-level master model is built by similarly applying the results of the cross-variant DSM analysis to all the parts of the product variants and integrate them within this fully flexible CAD model and its product-level family table. The different part-level master models are to be finally integrated into the product-level master model (i.e. parametric parts integrated into a parametric 3D model for the assembly). The three sub-assembly A, B, and C have been properly modeled, sub-assembly A and C also have their own master models which already integrate the variation required by product ALPHA (α) and BETA (β). Indeed, the model encompasses all common parts, the dissimilar ones associated with individual variants, as well as unique components characterizing specific variants (despite this example at sub-assembly level is not representative of this last condition). Figure 6 illustrates the structure of the product-level master model as it appears within PTC Creo for the product variant ALPHA (α). The product-level family table here adopts the same mechanism described above for selecting and configuring the parts required for a specific variant. Through systematic manipulation of parameters and feature states, the product-level family table facilitates the generation of individual configurations such as Product ALPHA (α) and Product BETA (β) from the unified model. Coherently with the activation and suppression of features described for the part-level family table, the product-level family table enables the suppression of parts which are present just in some of the product variants.

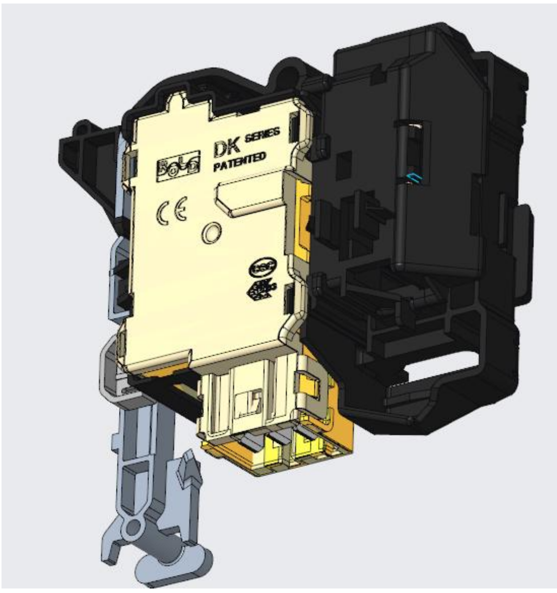

Figure 6. The top level master model for the whole door-lock. This representation reports all the suppressable features activated, while numeric parameters are representative of a single product variant.

This parametric and modular approach enables efficient handling of design variations, reduces redundancy, and enhances the overall robustness of the CAD modelling process for the DK product family.

5 Conclusion

This study investigated how independently developed CAD variants can be retrospectively reorganized into a unified parametric master model. The proposed workflow combines hierarchical cross-variant DSM analysis at assembly, part and CAD-feature levels with the subsequent implementation of common elements, dimensional parameters, configurable feature states and component selections in a family-table-based CAD structure. Its application to two industrial washing-machine door-lock variants allowed common and variable entities to be identified, part-level master models to be constructed, and the resulting configurations to be integrated into a product-level master model reproducing the analysed variants. Additional parameter combinations within the observed variation range were also regenerated without errors, although this preliminary check is not sufficient to establish the general robustness of the model. The main contribution to the state of the art lies in both the starting condition addressed and the resulting output. On the one hand, existing product-family and platform methods generally support planned commonality, modularity and platform decisions. On the other hand, product configurators and PLM approaches normally rely on already formalized product structures, rules and constraints and parametric CAD and design-reuse methods commonly assume that reusable models or modules have already been defined. CAD-feature-level redesign approaches, such as M-ARM (Wong and Wynn, 2024), start from existing family members but primarily generate redesign guidance for a target variant. In contrast, the proposed method starts from a fragmented repository in which a commercially recognizable product family is represented by disconnected legacy CAD models. The cross-variant DSM is used as a tool for analysis, to recover previously implicit commonality, variability and dependencies and to translate them into one persistent family-level parametric representation. The advancement is therefore not a new DSM formalism or a fully automated configurator, but a structured bridge from scattered CAD data to an explicit product-family master model. The proof-of-concept proposed by means of the case study demonstrates the feasibility of this transition for a bounded subset of the industrial family. It also shows how different types of variability can be managed without forcing every difference into dimensional parameterization: unchanged entities can be reused, dimensional differences can be parameterized, and presence–absence or morphological differences can be represented through configurable feature and component states. The resulting structure may provide a more suitable basis for subsequent MBSE, PDM/PLM and lifecycle-information workflows, including access to geometry, material and configuration data for LCA inventory preparation. These downstream applications, however, were not implemented or evaluated in the present study. The results must therefore be interpreted within the study boundaries. Only two variants from a family containing more than ten were analysed, while DSM construction and translation into CAD decisions relied on expert judgement. The study does not quantify reductions in modelling effort, prove the validity of untested configurations, or demonstrate scalability to the complete product portfolio. Future research should extend the analysis to additional variants, compare modelling and maintenance effort with current industrial practice, assess repeatability across analysts, and evaluate regeneration robustness as matrix and model complexity increase. Further developments may also automate the extraction of product structures, CAD features and dependencies from CAD or PDM/PLM data.

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