



25th ABCM International Congress of Mechanical Engineering
October 20-25, 2019, Uberlândia, MG, Brazil

COB-2019-1536

KNOWLEDGE-BASED SYSTEM TO AUTOMATE ELECTRIC MOTORS BI-DIMENSIONAL DRAWING AND THREE-DIMENSIONAL ASSEMBLY THROUGH PARAMETRIC MODELING

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***Abstract.** This paper presents the development of a knowledge-based system to automate the process of two-dimensional drawing and three-dimensional assembly of electric motors to clients in a multinational-level company. The originality of the system is due to the use of 3D parametric CAD models, which are dynamically modified according to the input data, and representation of the knowledge embed in the electric motors drawing elaboration routine through object-oriented modeling and rules. In order to unify the current different approaches to generate CAD documents and increase productivity, this work targeted a line of products with a significant market share in Brazil. The system validation was performed by domain experts, and indicates the possibility to automatically generate up to 98% of the current 3D CAD parts, and reduce the time to develop these models for the product line from 1,090 person-days to 89 person-days.*

***Keywords:** computer-aided design, parametric modeling, knowledge-based system, electric motor*

1. INTRODUCTION

Bi-dimensional drawings and three-dimensional assemblies are some of the most requested documents by clients in the context of electric motor design. However, the trend of services and projects to meet these customers' requirements meticulously (Kamal and Irani, 2014) is hampered by, but not exclusively, the cost of manual labor involved into the elaboration of drawings and company's policies to restrict the information provided to the client in order to prevent information leakage. Hintz (2018) approaches this problem through a Model Based Definition (MBD), where the 3D model becomes the single source of truth of the product development process. Nevertheless, the potential productivity gains and reduction on the number of managed objects proved unsatisfactory.

The objective of this paper is to present the main concepts of a knowledge-based system (KBS) to automate the process of bi-dimensional drawing and three-dimensional assemblies of electric motors through parametric modeling. This work was developed in a division of electric motors of the company WEG Electrical Equipment S.A, a multinational headquartered in Brazil, which is named in the citations throughout this document as target company.

1.1 Problems regarding the current method of electric motors drawings from a configure-to-order perspective

The configure-to-order concept aims to enable the user to define the product configuration at the time of ordering, and the supplier to perform this configuration upon receipt of the order. In this Design for Mass Customization - DFMC context, the use of Product Configuration Systems (PCS) is an important factor to achieve benefits of the approach, due to improvements in knowledge management and control of product variants (Myrodia et al., 2017). In order to offer variants of its products, the target company internally uses the SAP variant configuration PCS. As an example of benefit from this PCS, the Bill of Materials (BOM) is calculated through vertical lookup and auxiliary functions on the SAP table of values database, and the interface between components is verified through an auxiliary KBS called BOM Quality Assistant (Massirer, 2007). Although the combination of all modules, i.e., components set, and parts is not

possible due to the dependency of changes (Schuh et al., 2017), the high customization and possible combinations between components associated with DFMC concepts enable combinatorial explosion of possible products.

The client documentation and 3D assemblies cannot present industrial details in order to mitigate Intellectual Properties (IP) leakage. For this reason, Customers View Models (CVM) are elaborated to provide useful information to the customer and control the IP. These CVM are simplified versions of more sophisticated models, such as Basic Part Models (BPM), which represents the product geometry in an idealistic state, and Accurate Part Models (APM), which contains manufacturing constraints.

The current system used in the elaboration of Special Motors Drawings (SMD, i.e., drawing of motors not foreseen during the elaboration of the product line or platform) is based on the positioning of two-dimensional CAD models, which represent a set of components in a given view. However, two distinct cases may occur according to the product line: individually elaborated scale or off-scale models. In addition to the high maintenance of both approaches, it does not contemplate three-dimensional assemblies, which require manual preparation of 3D CVM.

In order to illustrate problems related to these two approaches, this section presents data for two of the most important target company's product lines according to the number of sales: line (a), which uses individually elaborated scale models, and line (b), which uses off-scale models. For commercial reasons, the names of both lines are omitted.

Some case studies allow a better understanding of the problem. The implementation of the standard or optional (S/O) projects, i.e., configurations foreseen during the elaboration of the product line or platform, of line (a) in the current 2D SMD system requires the preparation of 13,698 2D CAD models. In order to accomplish that, it is necessary 1,090 person-days, besides 105 person-days to register these models into the company's systems. At the time that the data for this work was collected, 2,181 two-dimensional models had been developed for this line, a task that required 161 person-days. It is worth mentioning that the vast majority of these models were modeled during the line/platform development, which increases its time to market. After the line/platform releases, the task is performed according to the demand. For comparison, line (b) has 2,598 2D CVM, a process that required 187 person-days. Moreover, within a one-year period, 75,632 SMD were elaborated in the target company.

CVM are prepared manually from BPM and then assembled, resulting in simplified 3D CAD assemblies. Until the period of elaboration of this work, 1,103 3D assemblies of line (a) were available on the website. For this product line, based on the S/O combinations, it is calculated 503,316,480 possible 3D assemblies with distinct external details. According to this number, under the current system (i.e. without considering the prototype), it is estimated that it takes 11,000 years to implement every S/O feature. Moreover, it is necessary an inconceivable volume of data to store these documents. In other words, this figure makes impracticable to present all 3D models on the website.

According to changes in regulations and internal policies, previously elaborated drawing became obsolete. However, modifications in the company's database take excessive resources. For the majority of design modifications in the current SMD system, the time required for a single modification in a drawing is about 10 minutes. Nevertheless, taking into account the several functions performed by an employee, data from 2015 shows that only 37 SMD can be reviewed per-day-per-person. For this reason, when drawings modifications are necessary, the target company approaches the issue by first updating the most requested projects, and modifying the remaining according to demand. For instance, aiming to correct the representation of the drains and greasing system position in some product mounting positions, 491 drawings were modified and 444 became obsolete in the database. Therefore, there are many obsolete drawings in the database, which jeopardizes the orientation of the decision-making process outcomes to previous validated solutions.

There are considerable losses related to non-quality costs. Internal indicators from 2016 to 2018 show that the relation between the costs related to guarantees, wastes and rework, and the Net Operating Income - NOI ranged from 1,210% to 1,613%. Although efforts have been made to decrease these indicators, it does not reflect the unnecessary workload, which increases the projects idle time and demands the allocation of qualified professionals to tasks involving development and improvements.

1.2 Related work

This work takes inspiration in several works related to projects with a large number of combinations of modules and parts, and consequentially design solutions. Hintz (2018) presented a work based on MBD concepts in which the main objective was to reduce the number of drawings and therefore to reduce the number of managed objects and manual labor that goes into the process, improving the usage of data and objects that are created in engineering organizations, but are used in many other functions throughout the enterprise. However, throughout the first pilot tests, it was found out that the productivity gains in the product development sectors or departments are considerably small. Nevertheless, gains were found in various downstream processes where accurate 3D model information was necessary, such as mold design and product inspection. Furthermore, the author emphasizes the possibility to convert BPM and APM long after they have been released into CVM, making these simplified models available at the time that the part is internally released for production. In the developed project, it is highlighted the importance to have managed relationships between parts and documents as well as part-to-part relations that need to be maintained to allow all functions to access the most up-to-date product and documents information. Johansson (2008) work is related to the design automation system for production preparation applied to rotary draw bending process, which encapsulates problems of mass-

customization and variant rich products. In this project, a modular structure of the knowledge base is applied, aiming a system with a high degree of flexibility. The author states that it is possible to implement heuristic and analytical knowledge into the CAD-integrated KBS using feed forward chaining and rule-based or object-based knowledge representation, and the use of object-oriented programming - OOP has proven to be a fruitful way to make the design automation highly flexible. Beach et al. (2015) address the automation of regulatory compliance checking in the construction sector through a rule-based semantic approach, presenting a methodology that allows the domain experts, who understand regulations, to work together using software tools to produce the computer executable rules. Therefore, it allows the domain experts to create and maintain their own systems, within a semantic domain that is familiar to them.

The proposed KBS combines forward chaining rules and object-oriented modeling to encapsulate information about product parts, assembly and drawing, with parametric models to cope with the combinatorial explosion of possible CVM. This approach allows the generation of CVM from few CAD models, therefore reducing the number of documents handled and improving the control of these documents, as detailed in the next sections.

2. KNOWLEDGE-BASED SYSTEM PROTOTYPE DESCRIPTION

The guidelines of this work were established according to heuristics of target company's experts in the domain of electric motors drawing. The system originality is due to the use of simplified 3D parametric CAD models, which are remodeled and automatically positioned in a unified 3D environment according to input data processed in a rule engine. Furthermore, the system retrieves the views from these 3D models, and repositions the dimensions and notations in a 2D drawing. Finally, it has to enable introduction of 3D BPM, with automatic assembly and drawing elaboration. Based on these features, some expected improvements for the new system are defined:

- Automated elaboration of assemblies and drawings;
- 2D drawing views retrieved from 3D models;
- Productivity gains through parametric models, which can be modified through rules;
- Better control of CAD details and reduction of errors through the use of validation rules;
- A unified platform for generating documents for clients, manufacturers and website.

The user communicates with the KBS prototype through a graphical interface developed in HTML. The PCS entries are the input data, and project-specific data not covered by the PCS, such as shaft dimensions, can be manually changed. The data is processed by a dynamic-link library that contains the inference engine, which communicates with the SAP in order to retrieve information. Once documents are generated, results are presented to the user.

The KBS prototype was developed in Maestro (Java programming language), an intellectual property shell of the target company. In addition, auxiliary systems and computational languages compose this KBS. SolidWorks is the CAD platform to elaborate three-dimensional models. DriveWorks is an add-in that allows the elaboration of rules to change the constructive and dimensional characteristics of these models. This extension (Visual Basic .NET programming language) executes rules in the SolidWorks Application Programming Interface - API. Furthermore, some changes in the API have been made to meet the project needs. For instance, this procedure was necessary for the system to automatically identify special views and position text notations. In order to understand the KBS architecture, it is first necessary to comprehend the interaction between the auxiliary systems that comprise it, presented in Fig. 1.

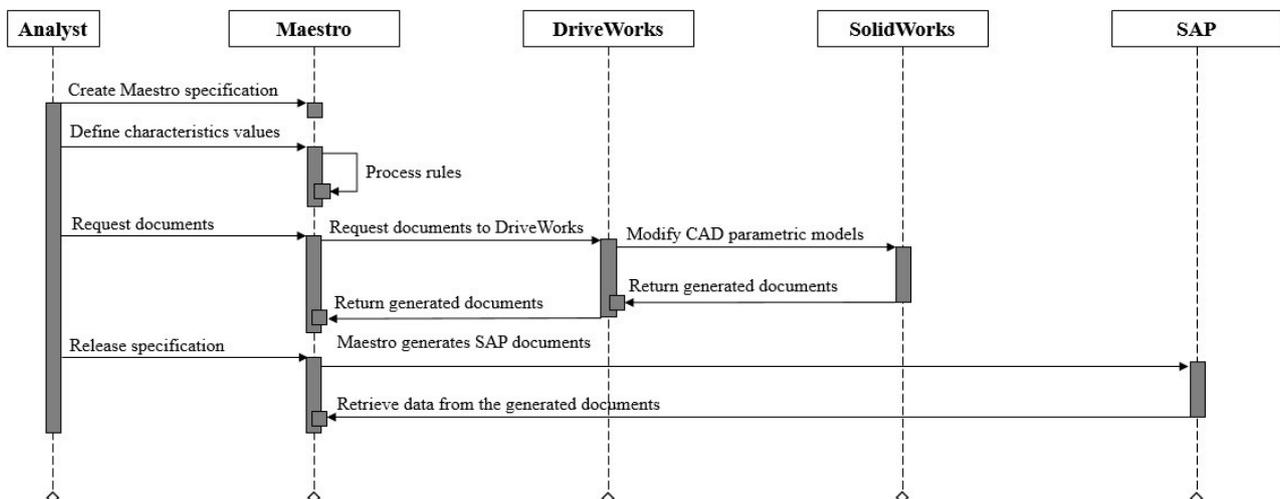


Figure 1. Automatic drawing generation process.

The process is divided into four main tasks: create specification, define characteristics values, request documents and release specification. First, the project specification is created in the Maestro, which contains the product configuration imported from the SAP PCS. From this configuration, the rule engine activates and executes rules, resulting in the values that describe the configured product CAD parts, assembly and drawings. The DriveWorks uses these values to modify the CAD parametric models, developed in SolidWorks, and generate documents. It is important to note that this add-in is mainly used to apply the Maestro outputs in the CAD models, i.e. the rules that represent the knowledge are implemented in the Maestro shell. At the end of the process, the documents are uploaded in the SAP platform. As complement to Fig. 1, Fig. 2 shows a representation of the system.

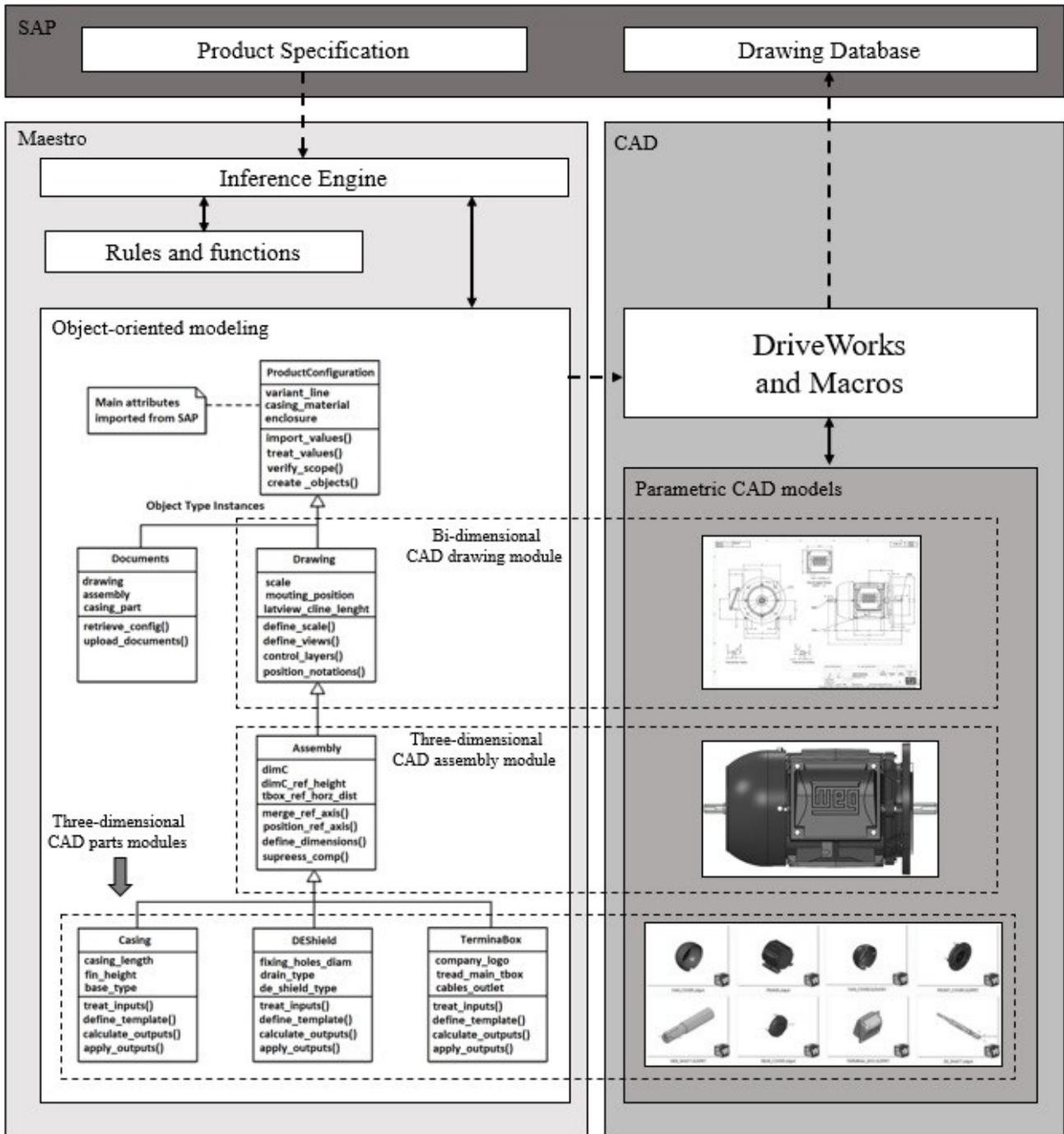


Figure 2. KBS prototype knowledge representation and processing flow.

Part of the knowledge is represented via object-oriented modeling, which aims to emulate the drawing elaboration flow (part → assembly → drawing) performed by domain experts. This representation scheme makes possible an expandable and modular architecture based on the nature of the drawing elaboration problem, in which each class

calculates specific project information, i.e., each class is dedicated to remodel some CAD models. As shown in Fig. 2, the bottom part of the class diagram contains information about product components. For the sake of clarity, only a simplified representation of the classes with information about the product casing, drive end shield, and terminal box are presented in this figure. The class that contains information on how these parts will be assembled is shown as Assembly Class, and the class that contains information on how the views and dimensions will be retrieved from this assembly is presented as Drawing Class.

A central control rule was defined to handle the sequence of rules activation. This central control rule determines the facts used to control the rule matching process (Giarratano and Riley, 1994; Silva, 1998). The underlying goal of this controlled processing is to ensure that all the information necessary to process the next step has already been calculated. For instance, it is necessary to define the assembly dimensions before generating the drawing. Figure 3 presents the central control rule and the rule groups (dark grey) defined here according to their control facts, and the main tasks performed in each rule group (light gray), as detailed in section 2.1.

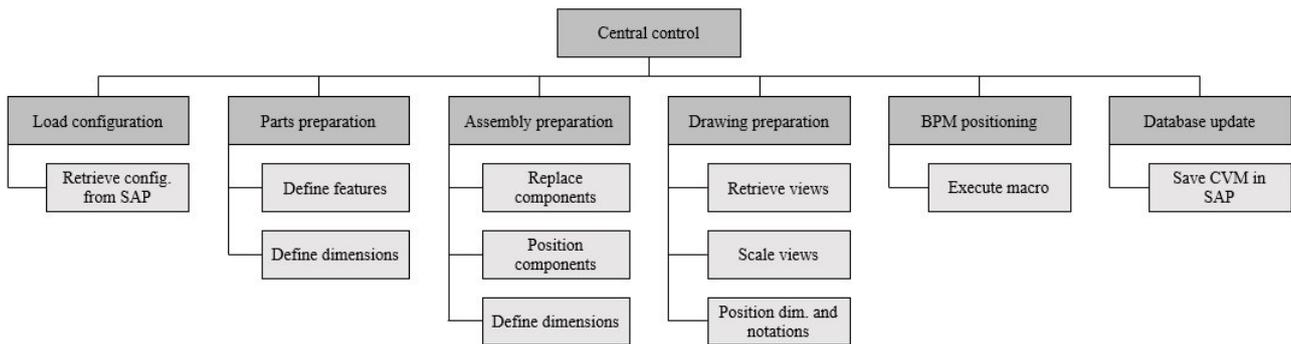


Figure 3. Central control rule and rule groups.

2.1 Prototype modules description

The KBS presented in this work has to cope with several formats of knowledge representation, such as variant tables, forward rules and object-oriented modeling, as well as the communication between platforms programmable in distinct computational languages. For instance, SAP is programmable in ABAP, Maestro in Java, and DriveWorks in Visual Basic .NET.

Although a detailed explanation about each parametric CAD model, functions to calculate its dimensions, rules to select its features, and so forth could be fruitful from an implementation perspective, this paper is only focused on presenting the main concepts of this KBS. Therefore, for the sake of clarity, throughout this section the system architecture is described as modules, which are represented by dashed lines in Fig. 2. Each module encapsulates data structure along with the functions and procedures needed to manipulate the data.

2.1.1 Three-dimensional CAD parts modules

Customers View Models are simplified versions of Basic Part Models. This statement implies that efforts are made during the model elaboration to compromise mitigation of Intellectual Properties leakage, usefulness of the information provided to the client, and computational cost reduction. As an example of modeling simplification, the CVM that represents the motor casing has no internal details because this information contains several IP not useful to the client, and increases computational cost. In the other hand, details such as flange fixing holes position and diameter are accurately represented because this information is necessary to verify the product coupling.

Parametric CAD models are elaborated specifically to be modified through rules. As shown in Fig. 4, features can be shown or hidden without errors. In addition, features dimensions of these models can be modified. After processing all the modification rules of the model, the parametric CAD model becomes a CVM.

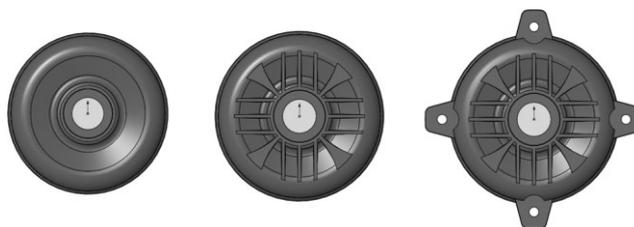


Figure 4. Three instances of a parametric CAD model.

In order to elaborate 3D parametric CAD parts, it is necessary to identify all the variations of features that compose a production part, identify the most recurring features and define the scope of each parametric model, i.e. the range of products that can be generated from this CAD model. The phase of dimensions acquisition of the production parts aims to assign values to any dimension that visually influences the SDM. In the phase of 3D parametric parts modeling, efforts are made to eliminate errors that may occur with variations of features and dimensions through rules. In addition, some dimensions are altered by equations introduced directly into the three-dimensional part, reducing the number of rules implanted in the rule engine. For example, the length of a reinforcement chamfer of the casing base is equivalent to 24.5% of the total length of the casing.

The parts templates are controlled by rules implemented in the Parts Class. These parts modification rules process the input data and apply the output data to the parametric CAD model, changing its features and dimensions, resulting in a new non-parametric CVM. In addition, functions such as vertical and horizontal lookups are used to search in auxiliary variant tables, which are not included in Fig. 2 for the sake of clarity. This approach simplifies the system maintenance because it allows to use matrixes to organize relationships between variables. For instance, the outer diameter of a flange depends only on its type (e.g. FF-115 and C-120) and the motor size, and therefore this dimension may be obtained by searching in the corresponding rows and columns of a table.

2.1.2 Three-dimensional CAD assembly module

In order to have a better control of the assembly template through rules, some parametric modeling guidelines are defined. The 3D assembly template is composed of arbitrary 3D Basic Part Models, and each part has a coordinate axis with standardized name and orientation and is a pair with a coordinate axis inserted in a sketch of the parametric assembly. They are referenced to the drawing origin, i.e., there is no coupling between components. Moreover, each dimension and crop view is defined in a dedicated sketch. This approach allows the elaboration of rules of positioning and dimensioning for different scenarios. Furthermore, the KBS prototype incremental expansion is simplified because the rules are not directly related to the 3D CAD part used.

The assembly template is controlled by rules implemented in the Assembly Class. These assembly rules select the parts in situations that a class may present more than one output (e.g. the drive end shield class may generate a normal DE shield template or a FF flange template). In sequence, the arbitrary parts that compose the 3D assembly template are replaced by previously generated Customers View Models or parts introduced in the system directory, and positioned, as exemplified on the left side of Fig. 5. In addition, assembly rules organize the dimensions and position its baselines. A CVM assembly is shown on the right side of Fig. 5.

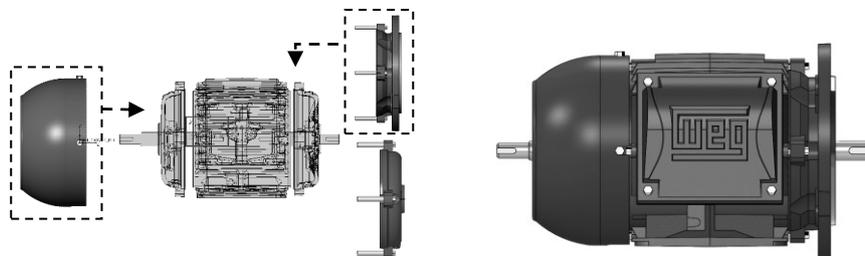


Figure 5. Three-dimensional assembly template preparation.

2.1.3 Bi-dimensional CAD drawing module

The 2D drawing template is a CAD drawing file with all possible drawing notations, e.g., dimensions and centerlines, and complementary views, e.g., section and projection, which are imported from the 3D assembly. Editable and repositionable notations and symbols are added to the two-dimensional drawing. Furthermore, the 2D model uses a layering system to improve the control of some specific dimensions, such as centerlines and center marks pattern.

The drawing template is controlled by rules implemented in the Drawing Class. These drawing rules position and control dimensions and component/assembly views, and regulate the scale. Again, auxiliary variant tables contain data related to the representation layout, such as which dimensions should appear in each drawing view based on inputs such as terminal box position and product mounting position. In addition, through drawing rules organized in an OOP format in the CAD platform API, fit-type tolerances and drawing annotations are controlled.

2.2 Production components

The system should allow the introduction of Basic Part Models. For this reason, rules are driven according to the presence of a BPM in the project. These CAD models are positioned and oriented through reference axis, similar to the 3D Customers View Models. The extension of the file is then identified in the system, which may vary between parts

and assembly. Furthermore, alterations in the CAD system API allows to identify and display special dimensions introduced in the BPM. Briefly, this system has three main stages: the construction of the model, the scanning of specialties in the assembly and the alteration of these specialties in drawing. Extra views are automatically introduced in the drawing if the BPM required this information. As recurrent examples, there are cut view for vibration sensors and the key of special shaft-ends. In order to do that, the system identifies special sketches in the 3D assembly through a standardized name, and shows positions and scales these views.

2.3 Prototype incremental development and the target company's design methodology

The KBS prototype follows an incremental development strategy, which is suited to cope with the system expansion and complexity. This approach implies that the phases of acquisition, representation and implementation of knowledge and system validation are conducted in cycles. In this, the KBS functionalities are increased through the development of new parametric models, implementation of rules to change its dimensional and constructive characteristics, and adjustment in the assembly and drawing rules, as described in the bullets. Moreover, at the end of each implementation cycle, the compliance of the results is reevaluated (Waterman, 1986).

- Define features and their dimensions of BPM that affect the SMD, and elaborate 3D parametric models;
- Elaborate rules to modify the 3D parametric models dimensions and features;
- Elaborate rules to position the 3D generated parts in the assembly template, and change its dimensions;
- Elaborate rules to modify 2D drawing views, dimensions and notations.

Due to the industrial nature of the problem addressed in this work, the evaluation of the prototype effects in the current design methodology is mandatory. The development of electric motors lines and platforms in the target company follows a concurrent engineering methodology based on the work of Rozenfeld et al. (2006), in which teams from different areas, aiming to complete the mandatory deliverables to start the next step, carry out parallel or sequential activities (Fig. 6). In this process, it is necessary to identify the CAD elaboration phases and the stakeholders. Detailed information about the target company's project methodology can be found in Haselein (2018).

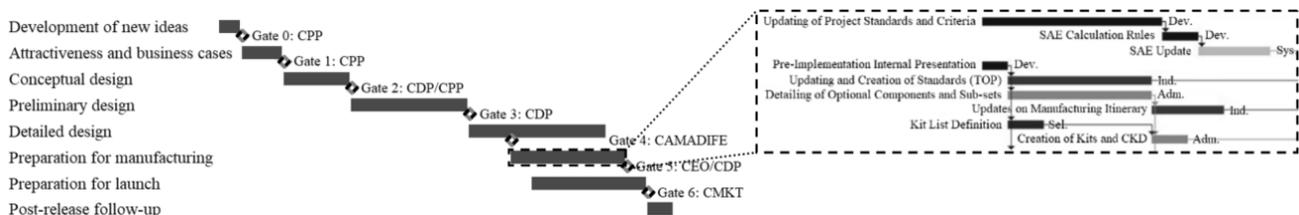


Figure 6. Development stages of electric motors lines.
Source: Adapted from PMO Marketing WMO, 2017.

The preparation of the CAD models occurs in three phases: detailed design, preparation for manufacturing and preparation for launch. In the detailed design phase, there are development of two-dimensional and three-dimensional CAD parts and assemblies, and production drawings by development-engineering teams. During the preparation for manufacturing, elaborated optional components and subassemblies are detailed, and the standards and design criteria updated. Regarding computer systems, product-engineering teams implement the SCP rules and search codes for automatic BOM elaboration rules. The preparation for the launch introduces the new line in the market by means of the elaboration of the plan of launching and creation of the technical and commercial material of divulgation.

Some changes in the current design methodology are necessary for the effective implementation of the concepts developed for the prototype in the development of new product lines. First, the elaboration of parametric models and rules to generate non-parametric models has to be finalized in the detailed design phase. Otherwise, there is risk of delaying the line development due to the time to verify the BOM elaboration rules. Furthermore, a methodology for mass verification of possible assemblies of the BOM should be elaborated.

3. PROTOTYPE VALIDATION

The automatic generation of three-dimensional Customer View Models from the product configuration was performed successfully. Project details have been omitted, as shown in the comparison between BPM and CVM generated by the new SMD system, presented in Fig. 7. In this figure, flanges and drip covers are visually similar and have interfaces with geometric equality, thus meeting the desired requirements of CVM.

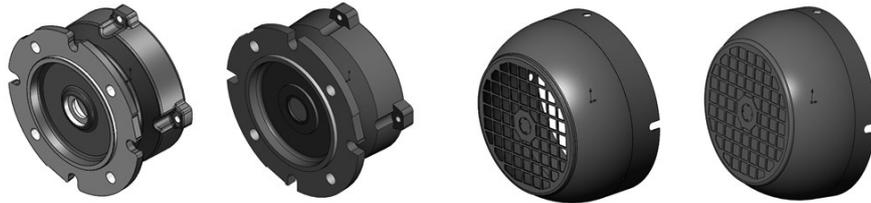


Figure 7. Three-dimensional BPM and CVM of a flange FF and a drip cover, respectively.

The system was able to automatic assembly the CVM. The left side of Fig. 8 shows an assembly of CAD models generated by the new SMD system. Besides visual similarity, the general dimensions are precisely the same to those established in the product datasheet. In addition, BPM or assemblies of these models were successfully introduced and positioned in the assembly, as shown in the right side of Fig. 8, in which a FF flange BPM was introduced.

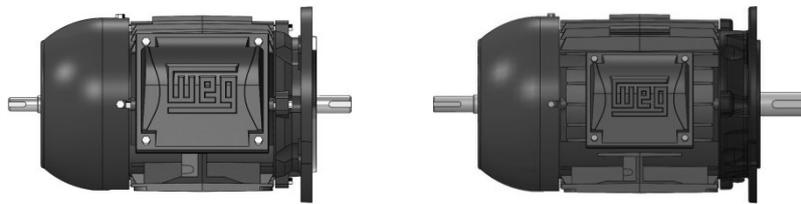


Figure 8. Three-dimensional assembly of CVM and addition of a BPM.

The generation of the drawing from the views of the 3D assembly was performed successfully, as exemplified in Fig. 9. The scale control and the positioning of the views worked correctly, dimensions required for the understanding of the SMD were selected as expected, test textual notations were automatically positioned, and the techniques developed for dimension positioning meet the project needs. Furthermore, special dimensions added to the production CAD models were automatically imported to the drawing, as exemplified in the cut views of the drive end shaft and non-drive end shaft.

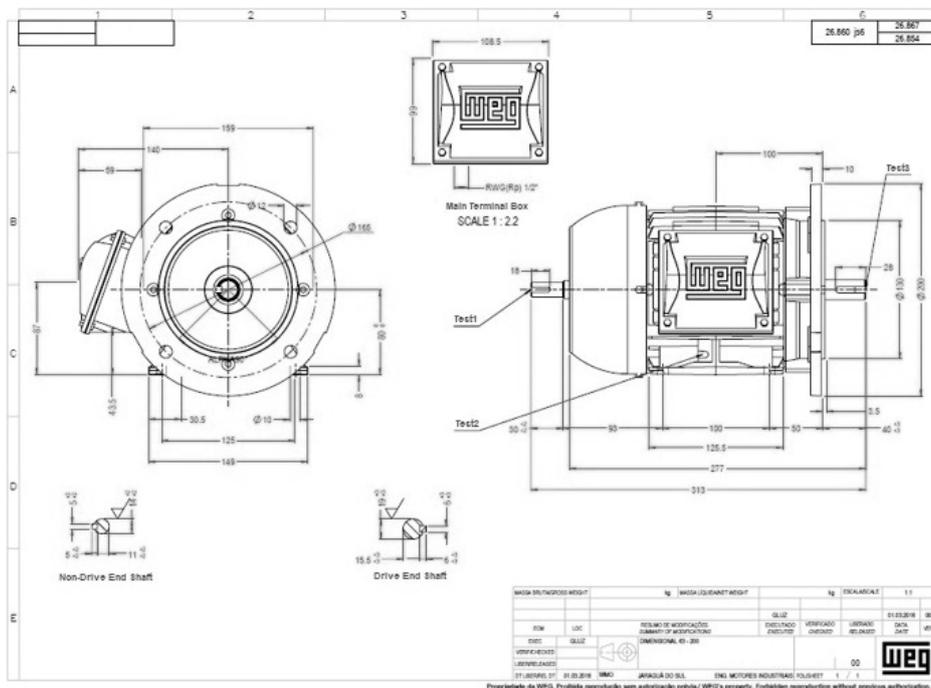


Figure 9. SMD generated by the KBS prototype.

The system identifies special views in the BPM. However, this feature is limited to specific cases, such as special shaft ends and vibration sensors. In order to plot views not contemplated by the system, such as the cut view of a temperature sensor, it is necessary to manually prepare the drawing.

The prototype automatically generates the majority of three-dimensional parts and assemblies. A Requirement Traceability Matrix - RTM is applied to evaluate the conformity and scope of the parts, assemblies and drawings generated. From these, the percentage of values of characteristics contemplated for the 3D parametric CAD models are the following: casing (97%), drive end shield (98%), flange FF (91%), non-drive end shield (95%), non-drive end shield type long (95%), drive end shaft (95%), rear end shaft (95%), and drip cover (94%).

The following number of 3D parametric CAD models required to automatic generate the S/O assemblies of the scope line is defined through the analysis of the drawings of each class: casing (2), drive end shield (1), flange (2), non-drive end shield (4), drip cover (2), shaft (1), terminal box (2), and terminal box cover (2).

The new SMD system enables alterations in big data. The average time to generate a SMD in this new approach is 70 s, which allows the revision of 34,560 drawings per month, against 740 in the current manual methodology. In addition, once the system has been implemented in line (a), it is able to generate all three-dimensional assemblies currently available at target company site in one day. Finally, the time to draw all possible S/O parts of line (a) using the new SMD system is reduced from 1,090 person-days to 89 person-days.

4. CONCLUSION AND FUTURE WORKS

This paper presented the development and validation of a KBS to automate the elaboration of electric motors bi-dimensional drawings and three-dimensional assemblies using parametric CAD models, and representation of the knowledge embedded in the routine of this document-making process through rules and object-oriented modeling. First, this approach matches the combinatorial explosion nature of the problem through the possibility of generating new parts by means of changing the parametric models constructive and dimensional characteristics. In addition, the generated components present simplifications that mitigate the information leakage and improve the SMD overall look due to the reduction of unnecessary features.

In order to have a higher level of computational system organization, rules control the results as much as possible. The concept developed for the assembly is based on the referencing of the CAD models and dimensions in relation to the origin. This approach allows control through rules, not linking this information to components. Drawing uses a similar concept, varying drawing properties through rules. This concept has proved to be consistent since it simplifies the parameterization, besides guaranteeing high flexibility since each property presents specific and independent rules.

Preliminary tests have shown that the introduction of BPM is possible, and the developed macro automatic repositions annotations, introduces fit-type tolerance, and identifies special dimensions and views. However, due to the large number of possible BPM, many of which yet to be elaborated, manual verification of each generated drawing is still necessary. In addition, the preparation of these models to be used in the system is relatively simple, requiring the introduction of a coordinate axis and the identification of special dimensions and special views.

There are drawbacks related to the new SMD system, which should be considered in the potential transition from prototype to a solution to elaborate new product lines and platforms. First, the proposed approach affects the current design methodology, requiring additional steps for the elaboration of parametric models and rules. Moreover, parametric models are more complex to elaborate and require recurrent revalidation.

Future works will aim to implement the KBS prototype and use it throughout the development of a product line in order to make simplified CAD models available at the time that the part is internally released for production. Thereby, it will be possible to determine the efficiency of this approach. Furthermore, new functionalities have to be implemented, such as automatic retrieval of cutting views of parts such as temperature sensors, and rules for verifying the conformity of dimensions and notations.

5. ACKNOWLEDGEMENTS

The authors would like to thank the Federal University of Santa Catarina - UFSC (Brazil) Postgraduate Program in Mechanical Engineering PosMec, and WEG Electrical Equipment S.A for their support in this project.

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