Integration of Design Tools and Knowledge Capture into a CAD System: A Case Study

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Abstract: Conceptual design phase is partially supported by product lifecycle management/computer-aided design (PLM/CAD) systems causing discontinuity of the design information flow: customer needs – functional requirements – key characteristics – design parameters (DPs) – geometric DPs. Aiming to address this issue, it is proposed a knowledge-based approach is proposed to integrate quality function deployment, failure mode and effects analysis, and axiomatic design into a commercial PLM/CAD system. A case study, main subject of this article, was carried out to validate the proposed process, to evaluate, by a pilot development, how the commercial PLM/CAD modules and application programming interface could support the information flow, and based on the pilot scheme results to propose a full development framework.

Key Words: knowledge-based engineering, axiomatic design, QFD, FMEA, CATIA V5.

1. Introduction

The information managed by product lifecycle management (PLM)/computer-aided design (CAD) systems is mainly connected with embodiment design and detail design phases [1,2]. Information related to the conceptual design phase is mainly limited to requirement specification documents and system architecture diagram documents. This situation leads to a lack of support for design tools used along the conceptual design phase: quality function deployment (QFD), functional decomposition, product structure decomposition, and failure mode and effects analysis (FMEA); and to discontinuities in the design information flow: stakeholder requirements – functional requirements (FRs) – design characteristics – key design characteristics – design parameters (DPs), and geometric DPs. This research investigates this problem and proposes a knowledge-based (KB) framework to integrate QFD, axiomatic design (AD), and FMEA into a commercial PLM/CAD system.

The integration of design tools used along the conceptual design phase is an issue that companies developing PLM systems are targeting. For instance, CATIA V5 provides the product functional definition (PFD) module to create a graph representing functional relationships among product components. It uses three concepts: subsystem, functional object, and action. But prior to its use, both the functional and physical decompositions of the product have to be defined. The module allows documenting the product structure with its associated functions rather than support the design tasks dealing with product functional modeling. CATIA V5 also provides the product function optimization (PFO) module to create a combined functional and physical view of the product and an interaction matrix of the different components. The PFO module is based on the theory of inventive problem solving (TRIZ) to help in the search for possible physical principles to improve the design. Starcevic et al. [3] follow a systematic design process to design a robot for biomass processing, and report the use of CATIA PFO for functional analysis optimization.

Several research groups aim at implementing functional modeling into CAD systems, and different works are in the development phase [4]. Commercial implementations cover documenting the product structure (e.g., CATIA PFD). Zheng and Chin [5] propose integrating QFD within CAD systems to establish a link between quality characteristics and part characteristics. Zheng et al. [6] point out that the integration of FMEA with computer-aided systems is still one of the problems that exist in the implementation of the FMEA tools. At a higher abstraction level, Prasad [7] explained the lack of integration between information technology tools used in the product development environments, proposing a wide concept named: intelligent information system (IIS), which encompassed the combination of computer-integrated manufacturing, knowledge management, and concurrent engineering. The IIS concept relies on six levels of techniques, methods, and information enrichment, where QFD is included in the Level 2 (modeling and analysis tools), FMEA is included in the Level 3 (predictive tools), and KB tools comprise the Level 4.

When considering the integration of the AD methodology into a CAD system, Ferrer [8] illustrates how the AD matrices could be incorporated into a CAD application. PLM/CAD systems provide tools, but they do not provide a step-by-step guidance on how to follow a particular design methodology, e.g., AD. This issue and the existence of a demand for software systems helping designers to improve their way of work were discussed by Prasad [7].

Design for Six Sigma (DFSS) is an integrating methodology for techniques and tools such as QFD, FMEA, AD, design of experiments (DOE), robust design, Pugh's matrix, TRIZ, etc. [9]. Dickinson [10] presents the integration of AD into the DFSS develop phase *via* the link between QFD and the AD concept of FRs. Gonçalves-Coelho et al. [11] proposed the used of AD principles during the creation of the QFD first matrix to improve the definition of FRs. Del Taglia and Campatelli [12] propose the use of QFD to capture information about functions that can be later used to define FRs according to the AD Theory. The link between AD and FMEA is also the subject of different research works. Pappalardo and Naddeo [13] have studied relationships of cause and effect propagation through DPs (cause) and FRs (effect). Hassan [14] shows the key characteristics taken out of FMEA and deployed as a product tree in an analogous way as AD does with the zigzagging process of DPs. Ginn et al. [15] discuss how QFD and FMEA can be integrated by combining top–down and bottom–up approaches. Torres et al. [16] relate AD, QFD, and FMEA by using information from QFD and FMEA to create both functional and structural decompositions.

The proposal of a KB framework requires defining a way to integrated knowledge into the design flow: QFD–AD–FMEA. Considering the concepts defined by Prasad [7], it requires the integration of tools belonging to KB (Level 4) with the design flow tools belonging to modeling and analysis (Level 2), and predictive (Level 3). In this research, the integration of the KB level with the other two levels is carried out in two stages. In the first stage, a KB methodology is used to capture and document knowledge created along the design flow (QFD–AD–FMEA: design tools that belongs to Level 2 and Level 3). In the second stage, the knowledge previously captured and the KB methodology are used to develop *ad hoc* knowledge-based applications (KBAs) in the development environment of a commercial PLM/CAD system. 'Methodology and software tools Oriented to Knowledge-based engineering Applications' (MOKA) [17] was developed to formalize the representation of knowledge and to assist in the development of KBAs. Skarka [18] makes use of MOKA and CATIA knowledge modules to automate the creation of a generative geometric model. The development was constructed on the basis of geometrical modeling to manage fixed dimensions and product configurations. It optimized the design through engineering rules to obtain the best design according to the FRs provided by the user inputs. MOKA illustration, constraint, activity, rule, and entity (ICARE) forms were used to capture and formalize knowledge. Entities and rules were adapted to work with the physical and functional structure of the product. Khodja et al. [19] implemented the MOKA ICARE forms into a CAD system to share and reuse process planning knowledge by different experts.

This study uses MOKA to propose a KB approach to integrate information from QFD, FMEA, and AD into a commercial PLM/CAD system. Based on the literature review, it can be concluded that it is an innovative approach. The research methodology followed in this study is presented in the next section.

2. Research Methodology

The proposal of a KB framework to integrate QFD, AD, and FMEA; into a commercial PLM/CAD system comprises defining a design process, its associated information flow, the knowledge structure to support it, and the development framework. Figure 1 shows the methodological approach used.

Based on the literature review and industrial practices, a process and its associated information flow was defined (activity A1). The information flow is shown in Figure 2. A case study (activity A2) was carried out to validate the proposed process: test the information flow continuity, capture the knowledge associated with the case study execution; to evaluate, by a pilot development, how commercial PLM/CAD modules and application programming interface (API) could support such information flow, and based on the pilot scheme results to propose a full development framework.

3. Case Study and Pilot Development: Design of a Clutch System Part

Figure 2 shows the proposed information flow comprising the design tools: QFD, AD, FMEA, and the knowledge capture using MOKA. The product design begins with the identification of the customer needs then QFD is used to link them with design

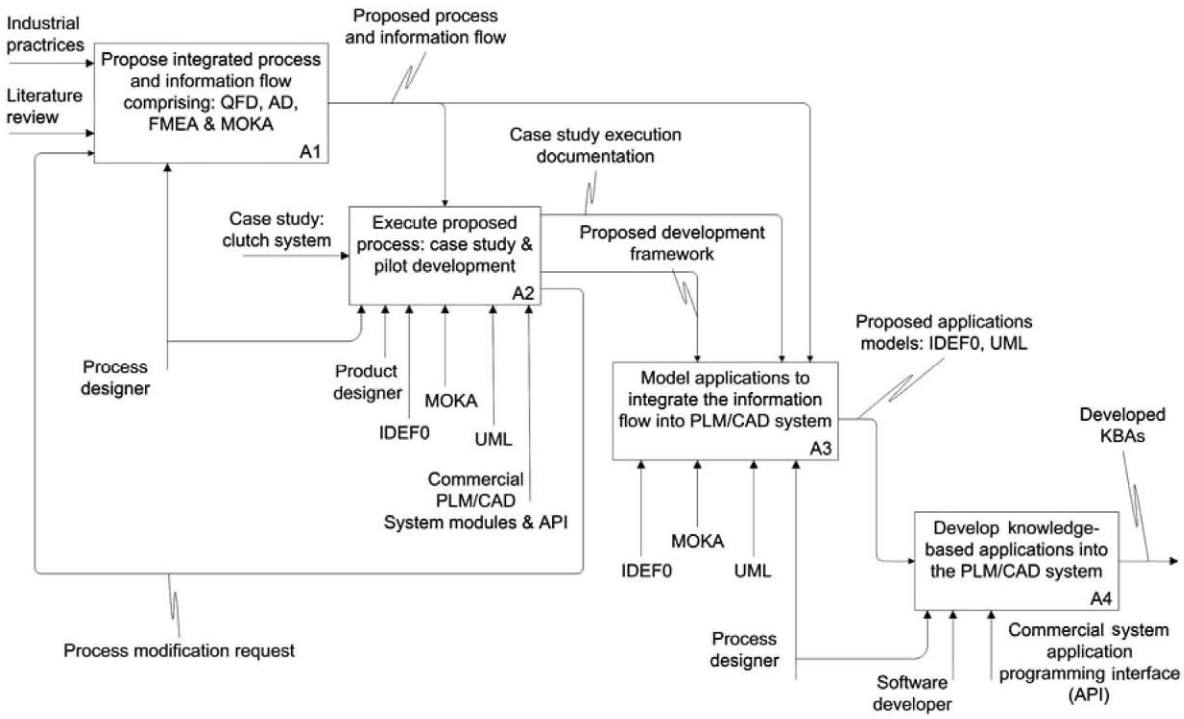

Figure 1. Methodology used in this study.

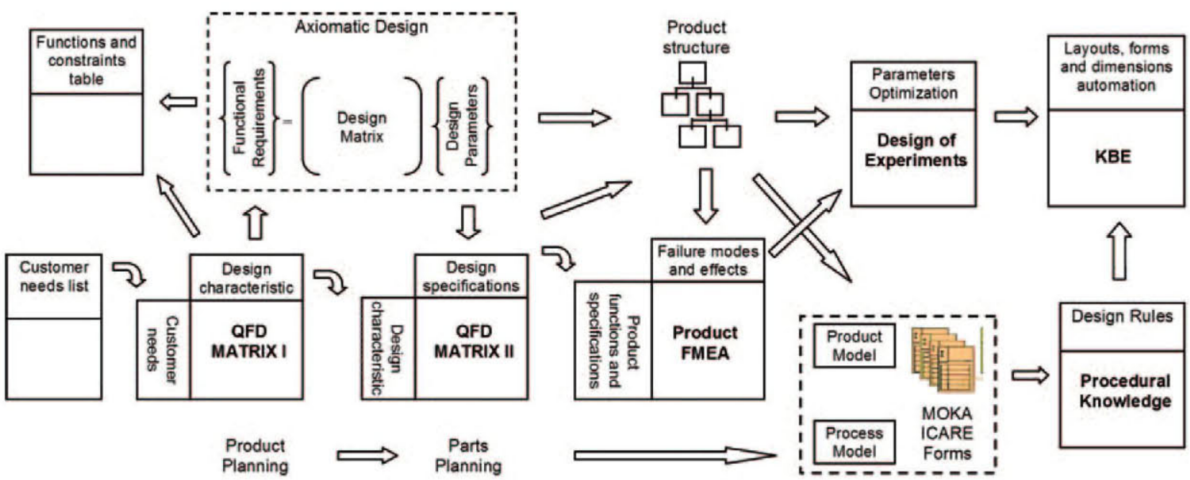

Figure 2. Proposed information flow to integrate: QFD, AD, FMEA, and MOKA.

characteristics. Design characteristics are expressed in the form of product functions and they are used to derive top-level FRs. From the top-level FRs, a top-level product structure can be defined, which corresponds to the top-level DPs. Physical principles have to be identified to satisfy the top-level FRs and DPs. Different physical principles lead to different decompositions both in the functional and physical domains. The product structure is defined through the FRs and DPs mapping. Then, product FMEA can be created. DOE can be used to optimize the most important parameters that define the design solution and satisfy the requirements. At each step, MOKA ICARE forms are created to document design knowledge.

The case study is focused on the design of a pressure plate for a friction clutch. It starts in the functional domain with the general functions of the clutch to carry out a product functional decomposition. The proposed method is applied manually step by step to create the different matrices for QFD, FRs and DPs mapping, and product FMEA. At the lowest level in the DP tree, the set of entity, constraint, and rule forms is used in a pilot KB development. The pilot scheme follows the development process defined in Hunter et al. [20] that combines integrated definition for function modeling (IDEF0), MOKA, and unified modeling language (UML). The pilot scheme is implemented by making use of the software system modules and their API.

3.1 Design Process Documentation Through Design Tools and MOKA

The design process begins with the identification of the stakeholders' (customers') needs and the design characteristics to satisfy such needs. This step is documented in the QFD matrix I, named product planning. The list of demanded needs for a product arises from considering scenarios of use and answering questions such as: 'what is the purpose of it?,' 'why is it needed?' Vehicles with a mechanical transmission system need an element to allow engaging and disengaging power and speed from the engine crankshaft to the gearbox input shaft. The clutch system allows transmitting the rotational movement, characterized by rotation speed, torque, and power [21]. A clutch system is used for several purposes: to transmit rotational movement from the engine to the gearbox, to interrupt the motor power transmission to the transmission system, to allow shifting gears manually, and to allow progressive and smooth engagement between the engine and the gearbox. Stakeholders' needs are named in the left column of the QFD Matrix I (Figure 3). After gathering stakeholders' needs, it is necessary to classify them and to structure them according to priorities. Then, it is possible to define the link with design characteristics (Figure 3).

Considering AD from customers' needs, the definition of FRs is derived. The definition of the FRs was conducted following the method proposed by Ríos et al. [22]. A function corresponds with an active verb that executes an action on or to an object. Qualifiers specify the conditions in which the action is executed, delimiting it by a numerical value with units of measurement. Constraints are conditions that modify the verb action. In this case, the root node of the functions and constraints is: function – transmit rotational movement – speed and torque; Constraints – engage/disengage, deaden vibrations, soften start, and dissipate energy.

Following AD, an FR tree and its linked DPs tree have to be created. In each decomposition level, it is started with an independent FR and the search of a corresponding DP. Trees are created by decomposing each level of FRs and DPs (Figure 4). At the top-level definition, a DP that satisfies a FR can be a product subsystem. The constraints identified in the root node turn into FRs, since high level constraints can be turned into functions of lower level. Applying this top–down approach, it is possible to link FRs with the product structure (Figure 4).

At this high decomposition level, DPs are black box generic subsystems that required to be investigated to 'identify' or 'propose' possible physical principles to be used. Physical principles must fulfil the FRs. 'Identify' refers to sequential design and 'propose' refers to creative design. At this stage, top-level constraints derived from the type of vehicle should be considered to identify/propose a suitable physical solution. The constraints derived from a sport car vehicle would be different from the ones derived from a heavy truck. Such constraints will allow specifying constraints (qualifiers) associated with each FR in the second FR level, e.g., the torque range to be transmitted expressed by two

		Design characteristics								
		The cushioning and filtering the engine vibrations	Absorption of energy	Torque capacity	Wearing and friction	Size and rotation volume	Fixation and assembly to the vehicle	Progressivity at engaging	Defusing by over torque	Mechanism of engage and disengage
Customer needs	Comfort at engaging	9	1	3				9		3
	Progressive starting of vehicle	3						9		3
	Does not produce slipping and shuddering	3	3	9	9			1		1
	To produce little noise	3		3		3	3			3
	Easy to assemble					3	9			1
	To protect the transmission								9	3
	Low cost	9	3	9	3	3	1	9	3	9
	Reliable and safe performance	3	9	9	3		3	1	9	3
	High durability		9	1	9					9

Figure 3. QFD matrix I, product planning.

numerical values (min, max) and its associated unit of measurement.

Several types of clutch systems exist to connect a driving shaft to a driven shaft to transmit energy, according to their physical principle the main types can be grouped into three categories. Mechanical clutches based on the use of the force of friction generated between two surfaces having a high coefficient of friction between them and being heavily pressed together in the normal direction. Hydraulic clutches based on the fluid pressure generated by the circulation of a fluid in a loop from an impellor (connected to the driving shaft) to a turbine (connected to the driven shaft). Electromagnetic clutches based on the application of electricity to generate electromagnetic attraction between the driving and the driven parts. The physical principle of solution determines the product functional decomposition and the relation between FRs and DPs.

Representing a physical system in a hierarchical tree allows locating, within the product tree, the definition level where decisions are made to define the solution concept. In this case study, a friction mechanical clutch was chosen. Following AD method, the product tree is developed with the zigzagging process.

When decomposing DPs into lower levels, it is possible to integrate several DPs into a single part that will satisfy several FRs. In this case, the product tree is different from the functional tree generated when applying AD. In the case study, the pressure set satisfies three FRs: engage/disengage, transmit torque, and dissipate energy. Moving downward in both trees, the clutch diaphragm, a component of the pressure set, satisfies two FRs: transmit action/reaction and provide load. This is because the clutch diaphragm integrates two of the physical principles, lever arm and Belleville washer; these principles allow the pressure set to engage/disengage and to transmit torque. Similarly, the pressure plate satisfies several FRs located at different levels in the functional tree: dissipate energy, provide friction contact surface, provide surface for lever arm reaction, and provide surface for loading Belleville washer (Figure 4(b)).

To map the product FRs to the subsystems and components of the solution implies that the solution concept has been already developed from the QFD Matrix I. Figure 5 shows the components planning matrix (QFD Matrix II) applied to the clutch pressure set and its components.

According to FMEA and QFD, key characteristics (KCs) or critical characteristics can be shape properties, materials and dimensions with their tolerances [23]. KCs and DPs are not necessarily geometric parameters. To integrate AD methodology within a CAD tool, DPs must be transformed into geometric parameters and then used in the geometric definition of the part. Table 1 gives an extracted version of the FMEA applied to the clutch pressure set functions.

In the case of the clutch, a FR of the pressure set is to transmit torque – xxx Nm. The torque to transmit is a load applied to the pressure plate multiplied by the action middle radius in the clutch disc. Such load depends on the distance between the support points of the coned disc ring. In this way, the torque is linked to the dimension affecting its value, and such dimension is a geometric parameter.

Another example is the thermal resistance that determines the pressure plate functionality to dissipate heat (xxx KJ) due to the friction. The dissipation depends on the plate volume and type of cast iron. The plate volume can be linked to geometric parameters. Both examples show the link between: function, FR, DP, and geometric parameter. The extract from the FMEA table showed in Table 1 indicates the relation between DPs and KCs. Figure 6 shows an example of

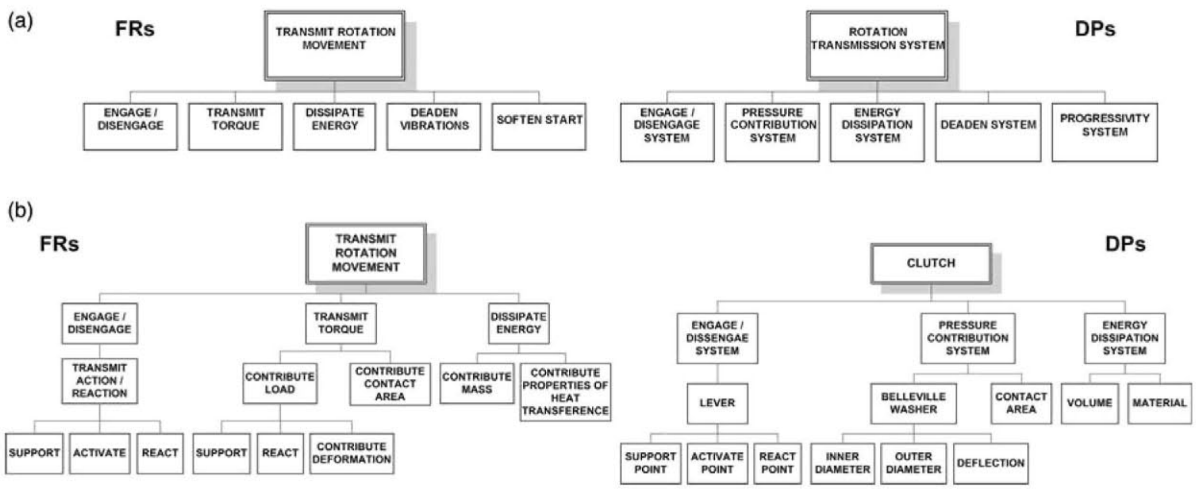

Figure 4. Mapping between FRs and DPs.

		Design specification						
		Clamp load in pressure plate	Average radio of load application	Thermal resistance	Lever ratio	Rotation volume	Bearing load	Weight and material of pressure plate
Design charact	Absorption of energy	1		3		3		9
	Torque capacity	9	9	3	3	9		3
	Wearing and friction			9				9
	Size and rotation volume	9	9			9		9
	Rapidity in gear changing				3		3	
	Mechanism of engage and disengage				9			

Figure 5. QFD matrix II parts planning.

Table 1. Subset of the pressure set FMEA.

Function	Failure mode	Failure effect	Failure cause	Current controls	Critical charact.	*O*	*S*	*D*	PRN
Torque transmission	Not torque transmission. Slippage at new	Slippage rejected	Clamp load at new inadequate	Clamp load curve in pressure plate specification	Clamp load at new (N)	3	8	5	120
Disengage	Not disengage	Customer complaint	Little pressure plate lift	Pressure plate under load specifications	Minimum lift (mm)	2	8	6	96
	Disengage point too near to lift point	Customer complaint	Little pressure plate lift by inadequate pressure plate fulcrum	Pressure plate fulcrum specifications	Minimum lift (mm)	3	8	4	96
Thermal resistance	Deformation in friction face	Discomfort unsatisfied customer	Inadequate material	Pressure plate material standards	Pressure plate material	3	6	5	90
	Fast wearing by high temperature	Clutch changed until estimated lifespan	Low thermal mass in pressure plate	Pressure plate thickness specifications	Pressure Plate thickness (mm)	4	6	5	120

Pressure plate function	Pressure plate functional Requirement	Physical principle	Pressure plate design parameter
Apply load in clutch disc	Pressure plate load in N	Belleville washer support	Fulcrum high and diameter
Release clutch disc	Pressure plate lift in mm	Lever relation	Fulcrum high and diameter
Dissipate heat	Heat dissipation in KJ or Kcal	Heat transfer	Volume and material

Figure 6. Relationships: function – FR – physical principle – DP; in the pressure plate.

the identified relations: Function, FR, physical principle, and DP, applied to the pressure plate component.

The proposed information flow (Figure 2) was applied to the pressure assembly. It allowed documenting the design process through the different design tools: QFD, AD, and FMEA; and MOKA ICARE forms. Carrying out such process step by step was possible to validate the continuity of the information flow.

3.2 Pilot Development Definition for Information Flow Integration into PLM/CAD System

The next step in the case study was to evaluate, by a pilot development, how the information flow could be supported by PLM/CAD modules and an API. The pilot scheme was divided into three phases: conceptual design and functional decomposition, embodiment design and solution optimization, and detail design and design automation by a KB development.

An IDEF0 model was created to represent the design process of the clutch [16]. The clutch product model comprised both the functional and the physical domains [16], and it was documented in the MOKA ICARE forms created during the design process. At this point, the benefit of having used MOKA from the very beginning of the design process paid off. Figure 7 represents the link between the process and the product models for the case study.

The pressure plate can be decomposed into geometric solid features. These solid features have characteristics defined by parameters. A detailed part tree showing its structural levels was created (Figure 7 (1)).

The activities to carry out the pressure plate design were part of the IDEF0 clutch design process model (Figure 7 (2)) and they were further documented in MOKA Activity forms. An activity can use an entity as an input, output, or trigger. A link can be defined between forms. As an example, one particular activity is 'Pressure plate casting selection;' the corresponding MOKA activity form describes how to carry out the activity. The component 'Pressure plate casting' is described in a MOKA Entity form (Figure 8 (1)). Rules to be applied when executing the pressure plate casting selection activity are defined in the corresponding MOKA Rule form (Figure 8 (2)).

3.3 Pilot Scheme Implementation into PLM/CAD System Modules

Considering CATIA V5 as a representative commercial PLM/CAD system, the aim was evaluate how to implement the pressure plate design process into the system. Skipping the interactive geometry definition modules, the ones that could be used along the design process are: PFD and PFO in the conceptual design phase; product engineering optimizer (PEO) in the embodiment design phase; and product knowledge template (PKT), knowledge expert (KE), and knowledge advisor (KA) in the detailed design phase.

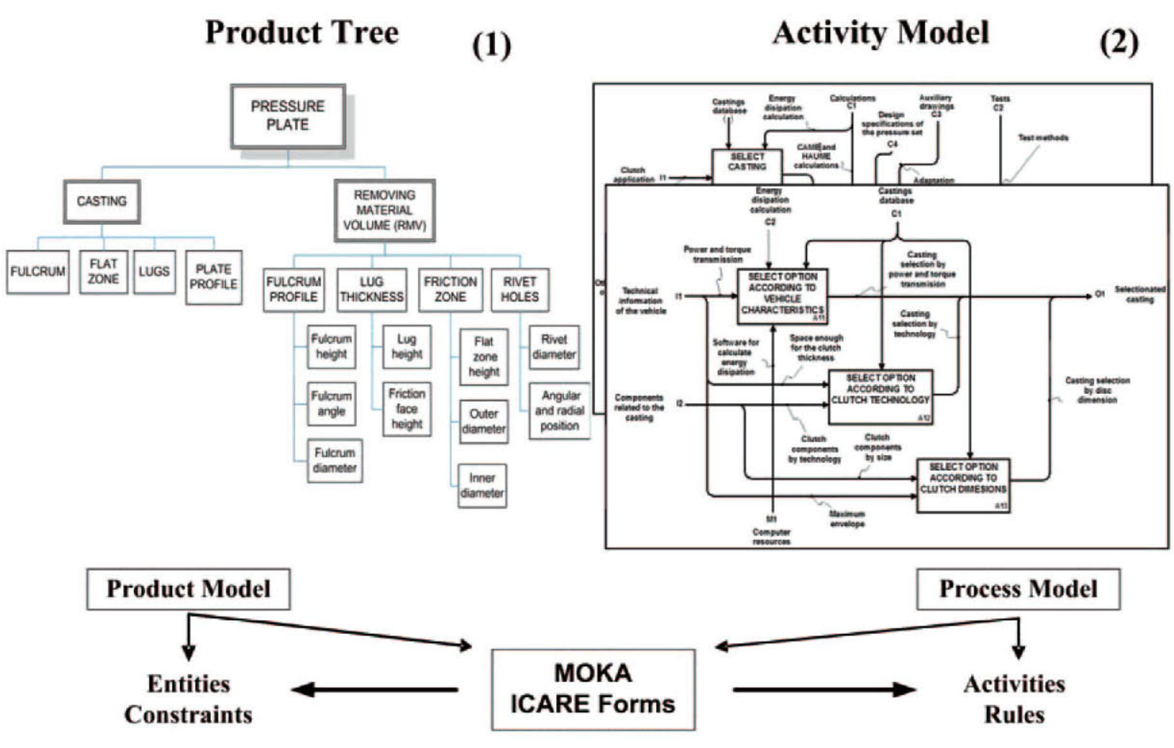

Figure 7. Case study process model and product model.

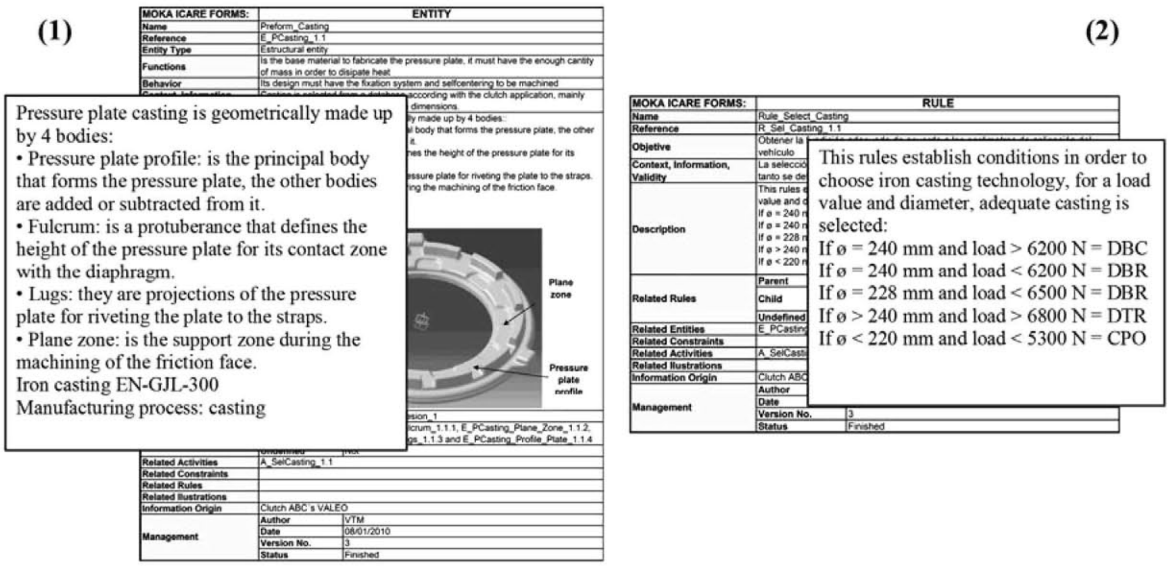

Figure 8. Entity and Rule forms applied to the clutch pressure plate.

The modules: PKT, KE, and KA; are intended to automate the geometrical definition of components by using parameters, formulas, design tables, and rules. These modules can be used to develop KBAs using a specific CATIA language based on visual basic for applications (VBA). These modules can be used at the detailed design phase where DPs are fully related to geometry generation.

3.3.1 PHASE 1: CONCEPTUAL DESIGN AND FUNCTIONAL DECOMPOSITION

Following the steps presented in Figure 2, several tasks were documented externally to the PLM/CAD system: creation of the QFD Matrix I, FRs definition and decomposition, DP definition and decomposition, creation of the FRs/DPs matrix, creation of the QFD Matrix II, creation of the product structure, and creation of the product FMEA matrix. CATIA PFD module helps to represent the functional relationships among the product components as long as both the functional architecture and possible working structures are already defined and the product decomposition in the physical domain is also addressed. A PFD diagram represents the functional relationships at a specific decomposition level and it is stored as a .CATSystem file (Figure 9). The decomposition of a component into a lower level is carried out in another file that is linked to the upper level one. The object elements (product components) can be linked with files representing the geometry.

Figure 9(1) shows the functional decomposition of the clutch system within the kinematics chain of an automobile transmission. The main function is to transmit a torque. Constraints on such function will restrict possible design solutions. Such constraints can be represented in a lower decomposition level.

Considering a mechanical friction clutch, Figure 9(2) shows the decomposition of the clutch system into the next lower level. The clutch system object is linked to a CATSystem file where its decomposition is represented. One of the subsystems is the pressure set. Upper level constraints are transformed into functions in this next lower level. The last level of functional decomposition is showed in Figure 9(3). The pressure set is decomposed into single components: pressure plate, diaphragm, cover, coned disc ring, rivet plate-strap, rivet cover-strap, and straps. The pressure set object is linked to its corresponding CATSystem file.

The structural decomposition of the pressure plate leads to its form features and dimensions. The decomposition can be defined in a lower level PFD diagram that would be linked to the pressure plate object. In this lower level, the decomposition of the pressure plate consists of geometric features and parameters that fulfill the functions of the pressure plate. Such parameters correspond with the DP concept proposed by the AD Theory. For instance, the pressure plate lugs fulfil the function to fix the plate with the strap plates. This relation is presented in the Figure 9(3) as the function 'to fix' between the pressure plate and the rivet plate strap, which connects with the straps. The pressure plate object can be linked to a CATPart file where its parametric geometry is defined.

3.3.2 PHASE 2: EMBODIMENT DESIGN AND SOLUTION OPTIMIZATION

In vehicles with manual gear shifting, the transmission of torque is not permanent. To allow gear shifting, the

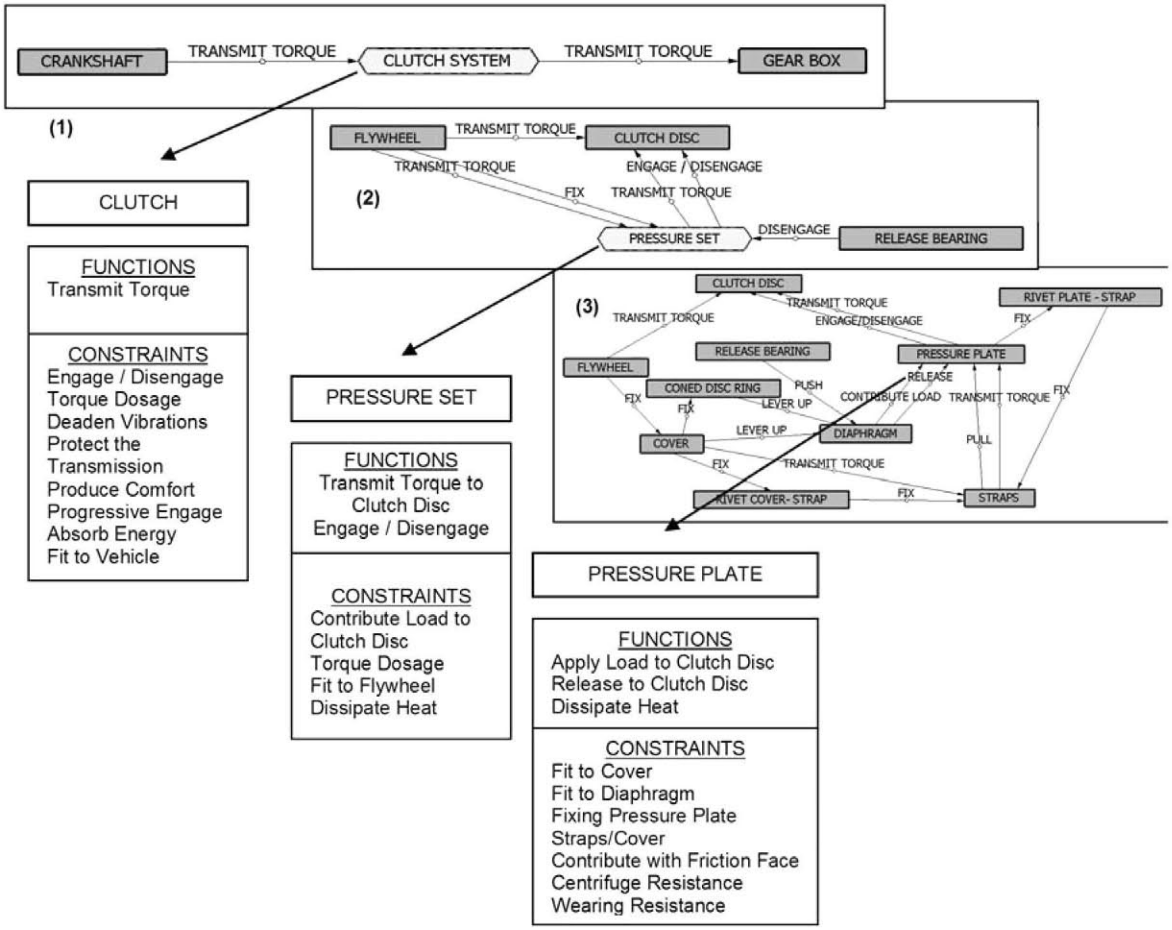

Figure 9. Clutch system a top–down relationships and CATIA PFD diagrams.

torque transmission has to be interacted. Allowing the interruption of the torque transmission is a constraint in the clutch main function. In the immediate lower level of the functional decomposition, two functions appear: disengage and engage (Figure 9(1)). The friction clutch functioning is based on the principle of lever. Schematically, the pressure set is a lever that can be moved axially in the direction of the axis of the clutch under the action of the pressure plate the diaphragm contributes load and applies it through the friction face of the pressure plate on the clutch disc (Figure 10).

The pressure set functions are: supply the needed load (xxx N) to transmit the torque (xxx Nm), engage, disengage, and dissipate energy. The pressure set is decomposed into: cover, diaphragm spring, pressure plate, rivets, strap plates, and coned disc ring (Figure 9(3)). Three main interactions determine the functioning of the pressure set: cover/diaphragm, cover/pressure plate, and diaphragm/pressure plate. The cover is decomposed into three main geometric zones: fixing base, cover fulcrum, and cover fixing bridges with pressure plate. The pressure plate is decomposed into three main geometric zones: plate body, plate fulcrum, and plate lugs. Considering a first class lever, the disengagement of the clutch is achieved by applying a force (xxx N) on the diaphragm through the release bearing that will make the pressure plate to move away a distance (xxx mm) from the clutch disc. The distance to release the clutch disc and the load on the diaphragm are based on the Lever Ratio. Since pressure set FRs are satisfied with the lever principle, then it is possible to identify the relevant DPs by analyzing the relation: FRs – Physical Principle – DPs. Prior defining the technology of the pressure set and the complete geometry of its components, it is possible to define a sketch containing the DPs (Figure 10). Four dimensional parameters were identified that affect the clutch FRs: release-bearing diameter, cover fulcrum diameter, pressure plate fulcrum diameter, and pressure plate fulcrum height (Figure 10). Since they affect the lever ratio, they were considered as KC and DPs.

CATIA PEO module was used to conduct an optimization of the DPs. Having certain DPs, it is possible to conduct a 'what-if' optimization task prior to having the complete definition of the components. Because different solutions exist for the pressure set, to some extent, DPs can be independent of the technological solution adopted. DPs and relations (formulas)

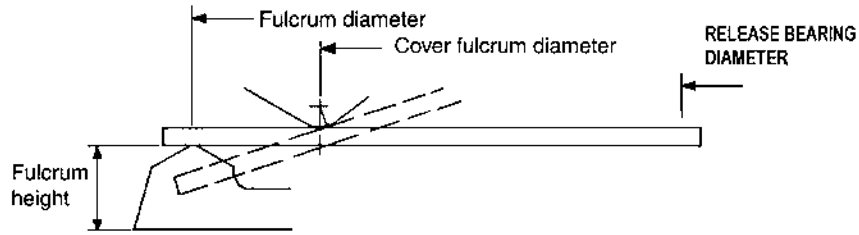

Figure 10. The principle of lever in the friction clutch.

were defined prior to execute the optimization. The objective was to optimize the value of a parameter (lever ratio) and to achieve an objective value. Based on the defined relations, the values of the free parameters were calculated: plate fulcrum height, plate fulcrum diameter, cover fulcrum diameter, and release-bearing displacement.

3.3.3 PHASE 3: DETAIL DESIGN AND DESIGN AUTOMATION BY A PILOT KB DEVELOPMENT

It is widely accepted that design automation comprises the development of some kind of KBA to support the designer along the decision-making process and to automate the generation of product geometry. The generation of geometry starts in the embodiment design phase and ends in the detail design phase. Since almost every commercial CAD system provides tools and a programming language for applications development, when design knowledge is captured and design rules are defined, it is possible to developed KBAs integrated within a CAD system. A particular KBA can generate the part geometric definition automatically and redesign it when needed.

In the two previous sections of the case study, the design process was carried out making use of a combination of design tools external to the commercial CAD system and modules integrated into the CAD system. Following with the case study, in this section, the objective was to undertake the implementation of a pilot KBA to automate the design of the clutch pressure plate into the commercial CAD system. CATIA VBA programming interface and KA module were used for the development.

The knowledge capture comprises: clutch architecture and technology, pressure plate casting pre-form, diaphragm calculations, interfaces and constraints between clutch components, and initial requirements (lever ratio, load in pressure plate). A set of ICARE forms were created to document it (Figure 8).

For the purpose of the pilot development, the pressure plate design is extracted from the IDEF0 design process model (Figure 7). The pressure plate design comprises three main tasks: A1 select casting, A2 determine pressure plate dimensions, and A3 validate pressure plate. The activity A1 was decomposed into: A11 select option according to vehicle characteristics, A12 select option according to clutch technology, and A13 select option according to clutch dimensions. The activity A2 was decomposed into: A21 calculate rivet hole diameter, A22 calculate friction zone, A23 calculate lug height and thickness, A24 calculate fulcrum diameter and height, and A25 calculate inner diameter.

The activities A1 and A2 were implemented into the CAD system making use of its API based on VBA (Figure 11). The task A1 refers to the selection of the appropriated casting for the pressure plate application. The task A2 refers to the pressure plate detailed geometric design, and it uses the parameters determined for the application of the pressure set, the clutch disc, and the flywheel.

For the activity A1 – Select casting, two parameters are used: engine torque (it depends on the vehicle type: sport, compact, sedan, etc.), and volume available for the clutch (it limits the maximum value for the clutch disc outer diameter and the fulcrum height). For a given engine torque, clutch disc outer diameter and fulcrum height, different technologies exist for the pressure set, e.g., DBR, DBC, and CP [21]. The selection criteria were defined in MOKA rule forms and implemented in VBA decision rules. The pressure plate manufacturing starts with a casting pre-form; the casting pre-form is machined to produce the final pressure plate. One casting pre-form can be used as input material for the manufacturing of more than one final pressure plate. The automated design of the pressure plate requires a prior selection of a pressure plate casting pre-form. Such selection was also implemented in VBA decision rules. A database with different types of casting pre-forms was created.

Using MOKA entity, constraint, and rule forms, the definition of the casting pre-form and the final pressure plate, their geometric and DPs, and rules were defined. Using CATIA KA module, the relations and formulas defined in the MOKA forms were implemented, linking DPs and the geometric dimensions needed to generate the final pressure plate. The generation of the final pressure plate design was implemented making use of CATIA API VBA. A set of operations are performed on

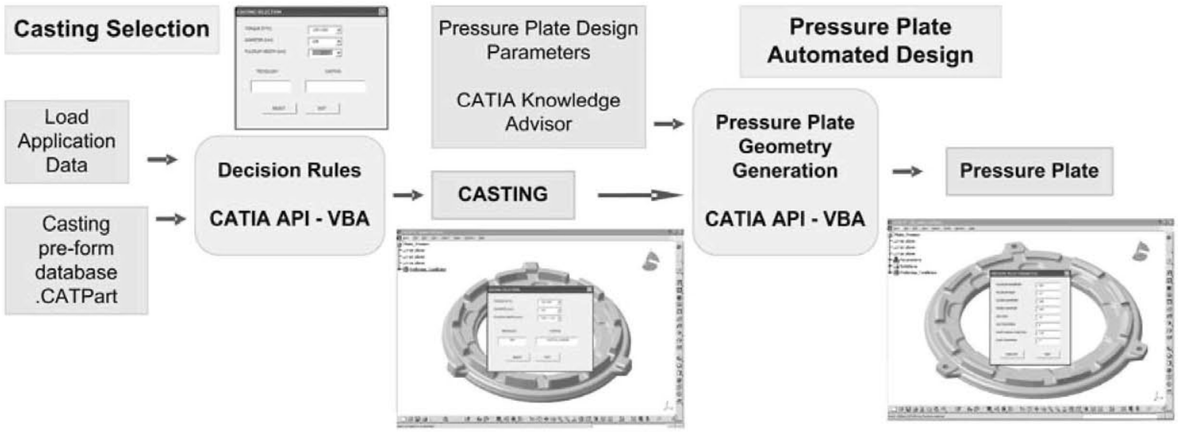

Figure 11. Generation of the pressure plate with the developed pilot KBA.

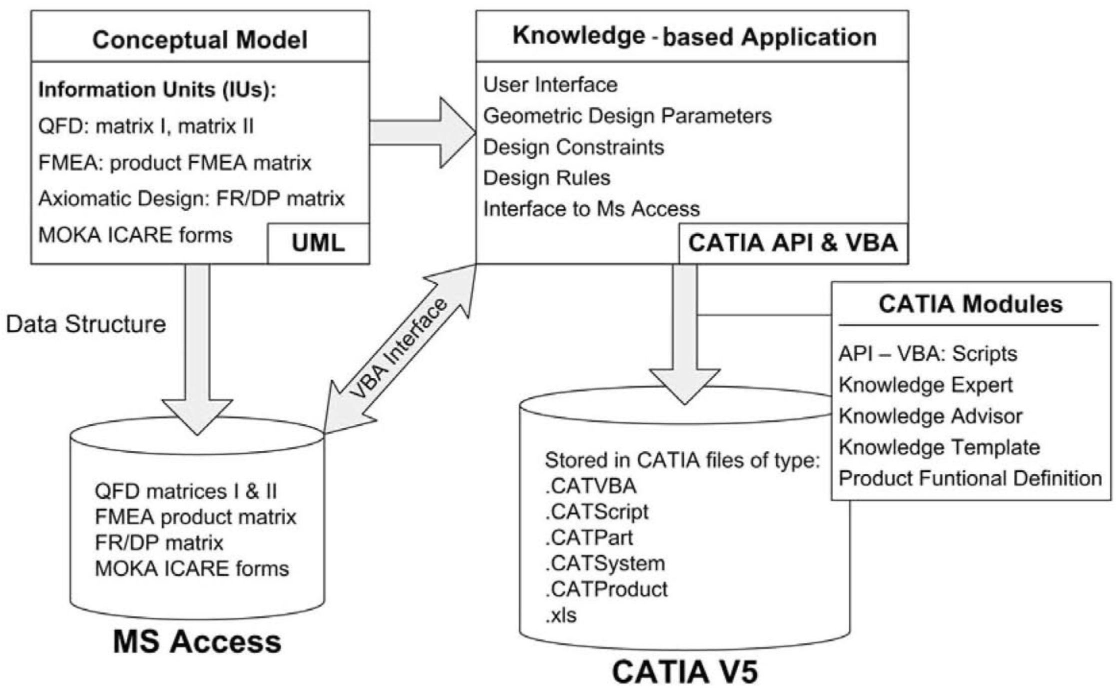

Figure 12. Development framework of the proposed integration: QFD, AD, FMEA, and MOKA.

the casting pre-form part to generate the final pressure plate part. The parameters used to define the pressure plate are: technology, casting pre-form part, outer diameter, inner diameter, fulcrum height, fulcrum diameter, lug height, lug thickness, rivet diameter, and rivet radial position. Recommendations for the fulcrum height and diameter are obtained from the analysis performed using CATIA PEO module. By means of applying a VBA Macro, the DP values are modified through the programmed code to directly change the values in the CATIA product tree. The user interface was fully integrated with CATIA and the user can input values of the DPs in a dialog box. Once the DPs are given a value, the final geometry of the pressure plate is generated automatically (Figure 11).

3.4 Proposed Development Framework to Integrate: QFD, AD, FMEA, and MOKA

As it was shown in the pilot scheme implementation (Section 3.3), there was a limited number of tasks and information flow that was supported by the PLM/CAD system modules. The pilot KBA helped to identify the potential of the software API to conduct KBA development and its possible interfaces with other applications. Since CATIA V5 is based on Microsoft OLE technology, it makes possible to integrate the CAD tool with a Microsoft database system (Access) to achieve a continuous design information flow.

Based on the results from the execution of the case study and the pilot KBA development, a full development framework to integrate: QFD, AD, FMEA, and MOKA is proposed (Figure 12). It starts with the creation of a conceptual model to define the information structures from QFD, AD, FMEA, and MOKA and their relationships. To facilitate its creation, concepts from each design technique are grouped into information units (IUs). The model integrating the IUs will be the support for the design information flow. UML is the modeling technique selected for this tasks and this work is currently in progress. The resulting model will be used to define the data structure needed in a database (MS Access) and to define the KB application integrated into CATIA V5. CATIA API and VBA will be used to create the kernel of the development.

Making use of CATIA API VBA, the interoperability between CATIA V5 and MS Access was tested in the pilot development. The user interface will be integrated with CATIA; the design rationale (MOKA ICARE forms), QFD matrices, AD, matrices and FMEA matrix will be stored in Access and linked with the materialization of the design carried out in CATIA *via* parameters and constraints in the product tree. This approach should allow us to have a continuous design information flow from the conceptual design phase.

4. Conclusions

The first aim was to evaluate how a design process integrating QFD, AD concepts, FMEA, and MOKA; it could lead to a continuous information flow when being supported by a commercial CAD system. The proposed design process was applied to a case study related to the design of a clutch system. It allowed identification of gaps along the information flow when using a CAD system: QFD matrices I and II not supported, AD concepts (FR, DP) not supported, and FMEA matrix not supported. The information flow: stakeholder needs–requirements–FRs–DPs–geometric DPs; was carried out using non-interoperable software applications leading to a broken information flow, reintroduction of data, and traceability problems.

In parallel to the execution of the design process, MOKA ICARE forms were used to capture design knowledge. This task was considered as a burden by the product designer, and it demanded a strong discipline to keep the application of the design tools and the documentation advancing at similar pace. At that point in the process, the benefit of using MOKA ICARE forms, instead of the current less structured way used by the product designer, was not recognized.

The next aim was to make use of such ICARE forms to develop a pilot KBA. Making use of the commercial PLM/CAD system (API and KB modules), a pilot KBA was created to automate the design of the case study component. Based on the results obtained in the case study, a development framework is proposed to integrate QFD, AD concepts, FMEA, and MOKA ICARE forms with a commercial PLM/CAD system. Currently, UML is being used to define the conceptual model needed to develop the KBA.

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