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ORIGINAL ARTICLE

Model-based definition design in the product lifecycle management scenario

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Abstract Model-based definition (MBD) is a new strategy of product lifecycle management (PLM) based on computer-aided design (CAD) models transition from simple gatherers of geometrical data to comprehensive sources of information for the overall product lifecycle. With MBD, most of the data related to a product are structured inside native CAD models, instead of being scattered in different forms through the PLM database. MBD aims are suppression of redundant documents and drawings, better data consistency, better product/process virtualization, and better support for all computer-aided technologies tasks under engineering and manufacturing disciplines. Developing MBD today, for a medium- to large-sized company in the automotive and aerospace sectors, deals primarily with its fundamentals: data structures. Companies need a common approach to structure data in reusable, unified forms inside native three-dimensional CAD models. For this reason, this research work has been developed by focusing the attention on a method for supporting the MBD implementation by the use of the quality function deployment approach. In order to analyze the efficacy of the proposed approach, it has been validated in the aerospace and defense domain where companies deal with complex products, characterized by a large amount of data exchange, and where collaborative design is a fundamental practice.

Keywords Model-based definition · Product lifecycle management · Computer-aided design · Paperless engineering · Product virtualization

1 Introduction

Today, industrial companies have to introduce new products into the market on time and on budget, and they have to respect the environment in terms of reduced fuel consumption, noise, …, sharing risks with partners and suppliers. These challenges are meant to introduce a new way of working, based on innovation and global collaboration, both internally among different disciplines and externally between operations, administration, and maintenance and its suppliers. One of the main leverages to achieve this aim is enabling a new business paradigm through pervasive 3D (three dimensions) to support activities from engineering, manufacturing, operations, and in-service domains [1].

Nowadays, products can be designed, simulated, and validated directly in the virtual domain with the help of computer-aided design (CAD), computer-aided engineering (CAE), and computer-aided manufacturing (CAM) software using 3D interaction and simulation. Moreover, 3D tools may also be used for manufacturing planning, simulation-based validation, work instruction authoring, and delivery to the shop-floor workforce. This new approach adds to traditional product data management (PDM) systems new functionalities to explicitly manage products, processes, and resource objects, as well as the relationships between them, according to configuration and effectiveness.

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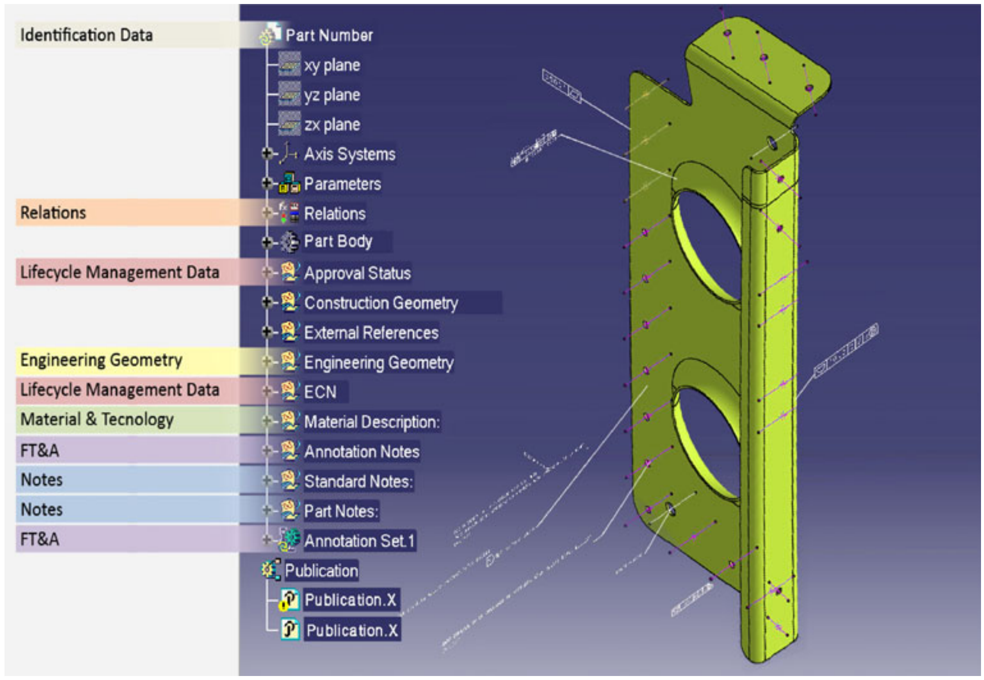

Fig. 1 Product lifecycle approach example with an MBD approach

This new integrated and information-driven approach is named product lifecycle management (PLM) and is a controlled method allowing manufacturing companies to manage their products across their lifecycles, from the idea of product to the end of its life [2, 3]. PLM is an extension of PDM and represents the missing link between CAD, digital manufacturing, and simulation. PLM represents the virtual world and interfaces with the enterprise resource planning (ERP) system supporting the physical side of modern manufacturing along the supply chain.

Today, 2D drawings have different views and are often inadequate in many different aspects. Designers and engineers require virtual prototypes and mockups to understand the complexity of their designs and verify it

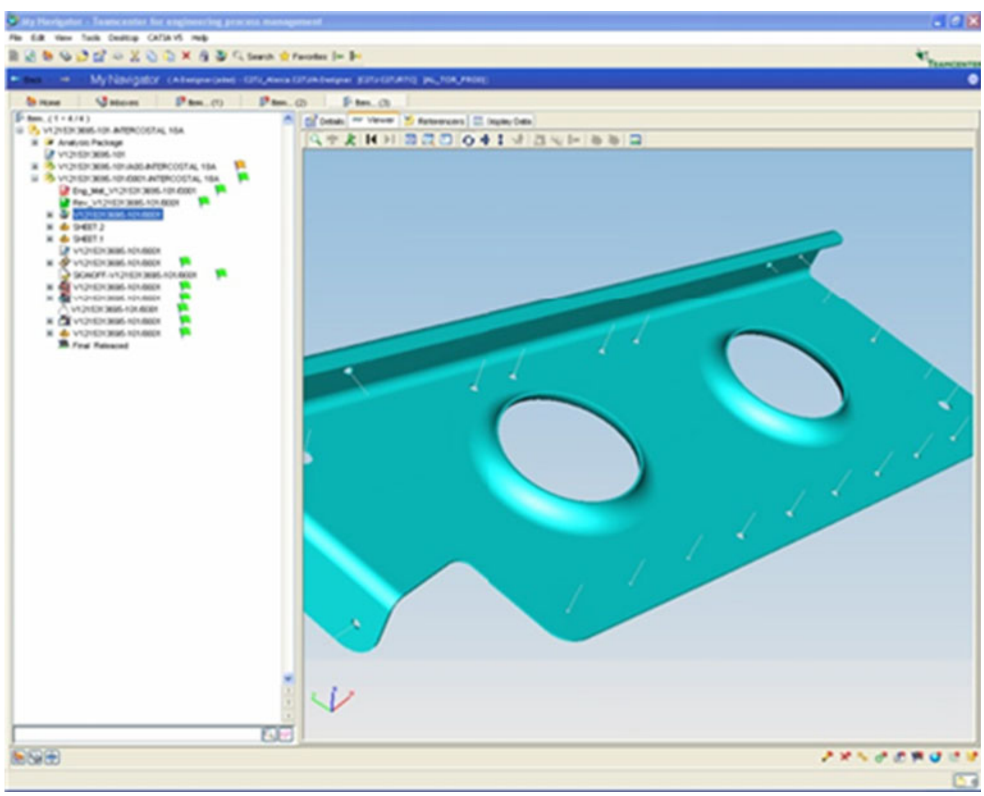

Fig. 2 Product lifecycle approach example with a non-MBD approach

[4]. Digital mockup (DMU) allows examining the features of the design, accessing surface issues of manufacturability, and assessing the visual and manual accessibility of instruments and human ergonomics constrains using virtual reality "power wall" by integrating design and reviewers' movements [5]. Moreover, digital manufacturing allows production engineers to provide a clear view of the production environment and to validate planning and manufacture processes even before building a product [6, 7]. With this approach, a huge amount and variety of data are generated and must be managed. Data has to be available to all people involved in a project in the form they need and can work with. Data may be in several different formats and in several different versions. This is possible only if a good interoperability between PLM/PDM products (i.e., Teamcenter) and CAD systems (i.e., CatiaV5) is available.

Due to this, it is necessary to manage a set of relations to provide consistency of data spread across different media and formats. This is the core feature of modern CAD and PLM systems, sometimes referred to as "associativity." Thanks to associativity, all pieces of information are linked: alterations of a part may influence the whole set of data through defined behaviors and controls [8]. This has been considered the main way to preserve data consistency until recent times. With modern PLM, characterized by a high number of documents, data types, and processes involved, CAD and PLM associativity mechanisms become intersected, leading to an extremely complex net of relations. More data sources and relations require more interfaces. More interfaces means more points of failure.

This is one of the reasons why PLM is undergoing a general transformation towards better standardization, data consistency, and concentration on a few robust sources. MBD is part of this strategy.

2 Model-based definition

Model-based definition (MBD) is a new way of managing engineering and business processes using 3D models as complete sources of information for design, production, distribution, technical documentation, services, and the overall product lifecycle.

With MBD, most of the data related to the product is stored in the 3D CAD model, instead of being scattered in different forms throughout the PDM database. The 3D CAD model becomes the one and only reference document for the main engineering and manufacturing phases. Data remains consistent because it is stored in a single form/repository. Associativity is drastically reduced and mainly concentrated inside the CAD environment. Computer-aided technologies (CAx) application are providing a more comprehensive set of data, allowing better integration and task automation.

Thanks to a unified data structure and a comprehensive mapping of parameters (geometrical, technological, etc.), engineering information is made accessible and reusable without manual re-input of data. Moreover, data standardization allows repetitive tasks to be automated, usage methodology to be streamlined, and know-how to be translated into coded templates. Therefore, detailed simulations (logical, functional, and mechanical) can be developed from a single data source. For the manufacturing disciplines, the use of 3D models as comprehensive product/process data repository speeds up simulation tasks and makes them more controlled. Annotations can be translated into CAM machining processes or coordinate measuring machines controls.

MBD is, at its core, a way of gathering and managing product/process data inside of a 3D model, in the form of annotations, parameters, and relations.

Modern CAx softwares are already capable of storing this data as parameters (Fig. 1) and of managing them in the same way as geometrical entities (with some exceptions).

PLM groups this data in ordered containers (items, forms, datasets, etc.) managed with external attributes, relations, accessibility criteria, and rules.

In a non-MBD environment (Alenia Aeronautica and IE4EC documents), engineering data related to one item (part or product) can be fragmented into the following datasets (Fig. 2):

- A single 3D model (geometry master reference)
- Drawing sheets (2D drawing with dimensions and tolerances for manufacturing shop floor)

Table 1 Product-oriented MBD (scenario I)

3D model as primary master source for geometries
Generative/associative 2D drawings for manufacturing and maintenance departments
No modifications allowed on drawings

Table 2 Process-oriented MBD (scenario II)

2D drawing suppression
3D model only authoritative source for geometries and tolerances
Introduction of 3D FT&A
Manufacturing lines with LEV systems for visualization and markup

Table 3 Enterprise-oriented MBD (scenario III)

Native 3D CAD models are the only authoritative source for geometries, tolerances, material, technology and lifecycle data
Introduction of manufacturing/maintenance notes in 3D models

- Item master form (containing identification and life-cycle management data, manual, and standard notes)
- Revision form (containing the engineering change/revision data)
- Material form (containing material and technology data)
- Stresssheets(containingthereportofthestressanalysis)
- Weight sheets (containing the report of the weight/inertia analysis)
- Sign-off form (containing all the workflow inspection signoffs)

2.1 The MBD scenarios

MBD is the result of a gradual transformation of PLM in terms of data structures, tools (hardware and software), processes, and methods. At present, there is not a unique approach employed by the industrial context; however, the different perspectives employed could be collected and synthesized into three different scenarios.

The first scenario has already been used in automotive and aerospace industry with the wide adoption of 3D as the authoritative source of geometrical data. 2D drawings are still used (in manufacturing plants, technical documentation, etc) but directly generated from 3D models. Alterations on drawings are not allowed. If necessary, modifications have to be made and validated through the 3D model so that the drawing can be regenerated [9].

Thishasbeenmadepossiblebymodernandhighlyaccurate3D CADsoftwares(DassaultSystemesCATIA,SiemensNX,…).For instance, the CATIAV5 Standard Scale for mechanical design allowstheproductsizeupto1kmandaccuracyupto1µmgenerative, associative,parametric,andfeaturebased.Besides,3Dmodeling has become faster, more precise, and more automated than 2D drafting(Table1) [5].

The second scenario of MBD (Table 2) focuses primarily on 2D drawings suppression for a paper-reduced PLM where drawings are replications of data from native 3D models. They only add information about explicit dimensions, tolerances, and manufacturing annotations. Present-day CAD technologies make it possible to support 3D functional

Table 4 Product-oriented MBD (scenario III)

	KRs	Absolute importance	Relative importance [%]
Data	Accessibility	2	5
	Centralization	1	3
	Coherence	5	14
	Standardization	3	8
Tools	Flexibility	2	5
	Integration	1	3
	Migration	3	8
	Security	5	14
Processes	Parallelization	3	8
	Traceability	2	5
	Virtualization	2	5
Methods	Development	3	8
	Simplification	1	3
	Standardization	3	8
	Coding in tools	1	3

Table 5 Process-oriented MBD (scenario III)

	KRs	Absolute importance	Relative importance [%]
Data	Accessibility	2	6
	Centralization	1	3
	Coherence	5	15
	Standardization	2	6
Tools	Flexibility	1	3
	Integration	1	3
	Migration	2	6
	Security	5	15
Processes	Parallelization	2	6
	Traceability	3	9
	Virtualization	2	6
Methods	Development	4	12
	Simplification	1	3
	Standardization	2	6
	Coding in tools	1	3

Table 6 Enterprise-oriented MBD (scenario III)

	KRs	Absolute importance	Relative importance [%]
Data	Accessibility	2	6
	Centralization	1	3
	Coherence	5	14
	Standardization	3	8
Tools	Flexibility	1	3
	Integration	1	3
	Migration	2	6
	Security	5	14
Processes	Parallelization	2	6
	Traceability	3	8
	Virtualization	2	6
Methods	Development	4	11
	Simplification	1	3
	Standardization	3	8
	Coding in tools	1	3

Table 7 Product-oriented MBD scenario

KRs			A	A′	Specifications MBD data types						
			Absolute importance	Relative importance (%)	Identification data	Lifecycle management data	Material and technology	FT&A	Notes	Relations	Engineering geometry
Data	KR-D-1	Accessibility	2	5.0	3	3		1			
	KR-D-2	Centralization	1	3.0	3	3	9	1		1	1
	KR-D-4	Coherence	5	14.0	1	3	1	1		1	
	KR-D-5	Standardization	3	8.0	3	3				3	3
Tools	KR-T-1	Flexibility	2	5.0	3	1	3	3		3	3
	KR-T-2	Integration	1	3.0			1	3		3	
	KR-T-3	Migration	3	8.0		1	3	9		9	1
	KR-T-4	Security	5	14.0		3	3	3			3
Processes	KR-P-1	Parallelization	3	8.0				3			
	KR-P-2	Traceability	2	5.0	1	3	9	3			1
	KR-P-3	Virtualization	2	5.0			3	9			3
Methods	KR-M-1	Development	3	8.0		1	3	3		1	1
	KR-M-2	Simplification	1	3.0	1	1		3			1
	KR-M-3	Standardization	3	8.0	3		3	3		3	3
	KR-M-4	Coding in tools	1	3.0		3		9		9	
MBD data type, type absolute importance					112.8	154.9	263.6	389.2	0.0	172.8	179.7
MBD data type, type relative importance (%)					8.9	12.2	20.7	30.6	0.0	13.6	14.1

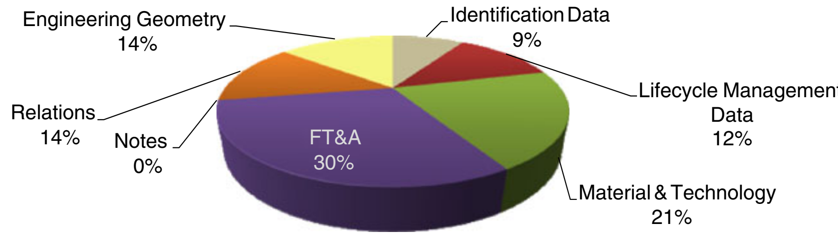

Fig. 3 Product-oriented MBD scenario

tolerancing and annotations (FT&A), thus eliminating the need of drawings.

This allows huge time savings in design, a leaner PDM, and better data consistency. In substitution of the drawings, a wide infrastructure of low end viewers (LEVs) is required for shop floors to access data previously provided in paper form [10]. This is now possible thanks to more affordable and effective wireless/portable technologies [11].

A third scenario of MBD is emerging (Table 3). Not only FT&A but also material, technology, process, and lifecycle data are going to be embedded in 3D models. This is the path followed by the most advanced aerospace companies for two reasons:

- The current generation of CAx softwares has reached maturity: they support and promote MBD as a driver for integration and task automation.
- PLM is facing a fast growth in scope and complexity. Managing product data "from requirements to retirement," especially in the aerospace industry, is now demanding for general simplification and standardization [12].

3 The proposed methodology: driving an efficient and sustainable MBD data structure

MBD is not a tool. It is a way of managing product data that a company has to tailor within its PLM framework.

For this reason, standards and common practices should be defined so as to create a common language for modeling and data management.

The only standards currently available for MBD are those related to FT&A: ASME Y14.5 2009 [13] and ISO 1101:2004. They contain rules and guidelines for 2D and 3D geometrical dimensioning and tolerancing.

No other standard has yet been established, mainly because current MBD has been heavily software driven and customized on specific PLM mechanics.

Technical literature lacks in publications on this topic. MBD is often confused with the mere FT&A without realizing its full extent. Many works have already analyzed the benefits of paperless engineering, 3D publishing, and light 3D visualization [14, 15] that are the most visible manifestations of MBD. Other papers have focused on specific CAD solutions and software, but only a few ones have analyzed the MBD data structure, proposing a methodology for supporting its development.

Considering that, at present, companies dealing with PLM manage their business process according to one of the scenarios described in the paragraph above, the proposed analysis wants to provide a series of guidelines to develop a sharable MBD data structure in each scenario.

In order to succeed in this aim and to provide a reliable MBD structure, the quality function deployment (QFD) method [16] has been employed. Thanks to the involvement of stakeholders, sharing CAD and PLM knowledge in a thematic community (Integrated Environments for Engineering Capability—IE4EC) but dealing with different complex products, the QFD can support the MBD data structure and its key specifications.

This task can largely be accomplished by focusing on time and cost savings; however, attention has to be paid also to the sustainability aspects in order to guarantee that the provided guidelines are really operative and able to create a common methodology for structuring data into a reusable, unified form compatible with 3D models.

3.1 Defining key requirements

Thanks to the availability of the IE4EC group, a first survey, targeted to specific users, have been implemented involving companies dealing with the three scenarios described above. This step has been developed in order to identify, through different refining passages, the main requirements that the different company domains (requirements and compliance, conceptual engineering, design, manufacturing engineering, simulation and validation, digital manufacturing, test and QC, sales and distribution, maintenance and repair, disposal and recycling) underline as key points in the management of engineering and business processes [17].

Starting from the first feedbacks obtained, it has been possible to see that the most significant feedbacks have been provided by engineering, manufacturing, and PLM support domains. More in detail, interesting data have been obtained in the following areas:

- Engineering and manufacturing domain
  - Functional design: product breakdown into functional/logical modules.

Table 8 Process-oriented MBD scenario

KRs			A	A′	Specifications MBD data types						
			Absolute importance	Relative importance (%)	Identification data	Lifecycle management data	Material and technology	FT&A	Notes	Relations	Engineering geometry
Data	KR-D-1	Accessibility	2	6.0	3	3		1	3		
	KR-D-2	Centralization	1	3.0	3	3	9	1	1	1	1
	KR-D-4	Coherence	5	15.0	1	3	1	1	1	1	
	KR-D-5	Standardization	2	6.0	3	3			1	3	3
Tools	KR-T-1	Flexibility	1	3.0	3	1	3	3	9	3	3
	KR-T-2	Integration	1	3.0			1	3		3	
	KR-T-3	Migration	2	6.0		1	3	9		9	1
	KR-T-4	Security	5	15.0		3	3	3	1		3
Processes	KR-P-1	Parallelization	2	6.0				3	1		
	KR-P-2	Traceability	3	9.0	1	3	9	3			1
	KR-P-3	Virtualization	2	6.0			3	9	3		3
Methods	KR-M-1	Development	4	12.0		1	3	3	1	1	1
	KR-M-2	Simplification	1	3.0	1	1		3	3		1
	KR-M-3	Standardization	2	6.0	3		3	3	3	3	3
	KR-M-4	Coding in tools	1	3.0	3			9	1	9	
MBD data type, type absolute importance					136.3	194.5	293.6	248.0	142.1	122.8	144.7
MBD data type, type relative importance (%)					10.6	15.2	22.9	19.3	11.1	9.6	11.3

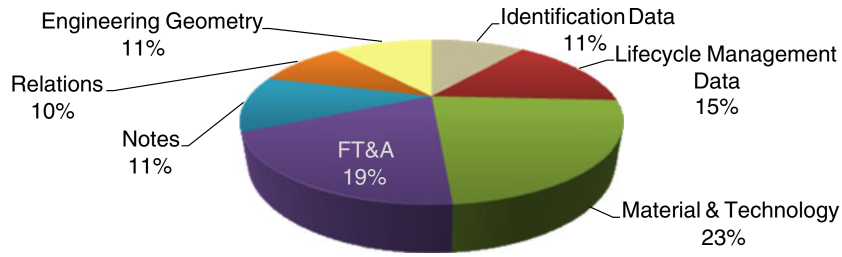

Fig. 4 Process-oriented MBD scenario

- Mechanical design: part/product structural modeling.
- Tooling design: tools/manufacturing stations structural modeling.
- System/equipment design: electrical, tubing, piping, and mechatronic systems.
- Analysis: static, cinematic, electrical, fluid dynamics, etc.
- DMU and design review: manufacturability, assembly, ergonomics, and maintenance analysis.
- Process simulation: plant and process automation.
- BOM/BOP development.

- PLM support domain
  - PDM
  - Workflow management
  - Document management
  - Process data management
  - Training and education

Requirements acquired in these identified domains can be divided into four different categories:

- Data [KR-D]: requirements related to data format/structure and methods of processing/exchange/storage.
  - [KR-D-1] Accessibility: speed and ease of retrieving and processing data. Moreover, the capability to share, notify, and propagate changes in a collaborative framework.
  - [KR-D-2] Centralization: concentration of information in a few repositories, without any dispersion, duplication, and costly procedures for alignment/synchronization.
  - [KR-D-3] Consistency: keeping data reliable, updated, and synchronized with all the sources.
  - [KR-D-4] Standardization: keeping data structures uniform, readable, and capable to be translated across the widest range of platforms/software.
- Tools [KR-T]: CAx, PDM/PLM required features and interfaces.
  - [KR-T-1] Flexibility: wide range of usages and adaptation capability to preexisting infrastructures and methods.
  - [KR-T-2] Integration: transferring data and interacting with other tools without degrading, altering, or duplicating the information.
  - [KR-T-3] Migration: compatibility with similar tools and different versions. Capability to upgrade data without alterations.
  - [KR-T-4] Security: the capability to protect and segregate data according to user's access credentials.
- Processes [KR-P]: process planning and simulation requirements.
  - [KR-P-1] Parallelization: process subdivision into structured flows.
  - [KR-P-2] Traceability: real-time measurement and control over processes.
  - [KR-P-3] Virtualization: tests and analyses completely validated in the virtual domain.
- Methods [KR-M]: methodology and knowledge automation requirements.
  - [KR-M-1] Development: methodology creation and management for end users and supporting personnel. Transformation of knowledge into standard procedures.
  - [KR-M-2] Simplification: streamlining methods, cutting redundant controls, and reducing repetitive manual tasks.
  - [KR-M-3] Standardization: keeping methods uniform, quality controlled, and extensively applicable.
  - [KR-M-4] Coding in tools: transforming knowledge into generative templates and integrating automated procedures into software.

Each of these domains has been assigned an importance level, in a scale from 1 to 5, to identify correlations with the MBD specifications related to the involved scenario (Table 4, 5, and 6).

3.2 Defining specifications

In order to define which MBD structure specifications can satisfy the key requirements (KRs) identified by the survey

Table 9 Enterprise-oriented MBD scenario

KRs			A	A′	Specifications MBD data types						
			Absolute importance	Relative importance (%)	Identification data	Lifecycle management data	Material and technology	FT&A	Notes	Relations	Engineering geometry
Data	KR-D-1	Accessibility	2	6.0	3	3		1	3		
	KR-D-2	Centralization	1	3.0	3	3	9	1	1	1	1
	KR-D-4	Coherence	5	14.0	1	3	1	1	1	1	
	KR-D-5	Standardization	3	8.0	3	3			1	3	3
Tools	KR-T-1	Flexibility	1	3.0	3	1	3	3	9	3	3
	KR-T-2	Integration	1	3.0			1	3		3	
	KR-T-3	Migration	2	6.0		1	3	9		9	1
	KR-T-4	Security	5	14.0		3	3	3	1		3
Processes	KR-P-1	Parallelization	2	6.0				3	1		
	KR-P-2	Traceability	3	8.0	1	3	9	3			1
	KR-P-3	Virtualization	2	6.0			3	9	3		3
Methods	KR-M-1	Development	4	11.0		1	3	3	1	1	1
	KR-M-2	Simplification	1	3.0	1	1		3	3		1
	KR-M-3	Standardization	3	8.0	3		3	3	3	3	3
	KR-M-4	Coding in tools	1	3.0		3		9	1	9	
MBD data type, type absolute importance					97.0	185.6	240.8	390.8	202.7	236.7	192.7
MBD data type, type relative importance (%)					6.3	12.0	15.6	25.3	13.1	15.3	12.5

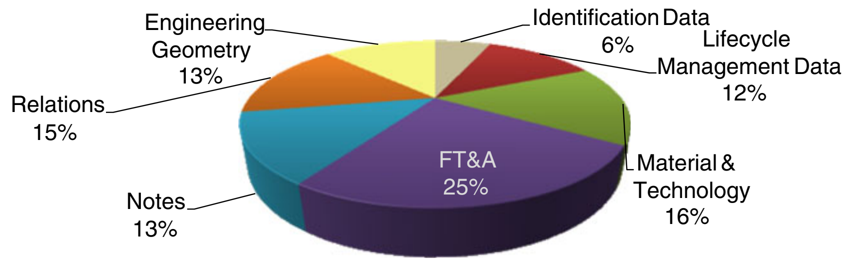

Fig. 5 Enterprise-oriented MBD scenario

and considering that the MBD development deals primarily with data structures, MBD data types have been investigated. This investigation has been carried out by analyzing a 3D model sample, inside of IE4EC (50-part 3D models), for each of the three scenarios described before. A structured list of parameters has thus been obtained; for each of them, their average number and percentage of distribution inside of the models have then been calculated. This data has then been standardized and divided into eight types:

- Identification data (metadata)
  - Part number (ID code complying with naming convention)
  - Nomenclature
  - Product description
  - Definition
- Construction geometry and general parameters
  - Features
  - Geometrical parameters
- Lifecycle management data
  - Dataset UID (internal ID code for PLM database)
  - Dataset version (internal progressive code for data versioning inside of PLM database)
  - Approval status\repository (PLM model repository)
  - Approval status\document rev (progressive code set by revision)
  - Approval status\status (status inside of a given workflow)
  - Approval status\status date (date when the current workflow status has been assigned)
  - ECCN\ECCN (engineering change notes for current revision)

Table 10 Product-oriented MBD scenario

Identification data	\Part number
	\Revision
Lifecycle management data	\Dataset UID
	\Dataset version
	\Approval status\status
Material and technology	\Material description
	\Material heat treatment
	\Material standard manual
	\Material X\density
	\Technology
FT&A+	\Annotation set X\views\…
	\Annotation set X\captures\…
	\Annotation set X\datums\…
	\Annotation set X\reference frames\…
	\Annotation set X\geom tolerances\…
	\Annotation set X\notes\…
	\Annotation set X\dimensions\…
Relations	\Relations\formula XX\…
	\Relations\formula YY\…
Engineering geometry	\Engineering geometry\stock size\…
	\Engineering geometry\datums\…

Table 11 Process-oriented MBD scenario

Identification data	\Part number
	\Nomenclature
	\Revision
Lifecycle management data	\Dataset UID
	\Dataset version
	\Approval status\status
Material and technology	\Material description
	\Material heat treatment
	\Material standard manual
	\Material X\density
	\Technology
FT&A	\Annotation set X\views\…
	\Annotation set X\datums\…
	\Annotation set X\geom tolerances\…
	\Annotation set X\dimensions\…
Notes	\Standard notes\…
	\Part notes\…
Relations	\Relations\formula XX\…
	\Relations\formula YY\…
Engineering geometry	\Engineering geometry\stock size\…
	\Engineering geometry\datums\…

Table 12 Enterprise-oriented MBD scenario

Identification data	\Part number
	\Revision
Lifecycle management data	\Dataset UID
	\Approval status\status
	\Approval status\document rev
Material and technology	\Material description
	\Material X\density
	\Technology
FT&A	\Annotation set X\views\…
	\Annotation set X\datums\…
	\Annotation set X\reference frames\…
	\Annotation set X\geom tolerances\…
	\Annotation set X\dimensions\…
Notes	\Standard notes\…
	\Part notes\…
	\Revision notes\…
Relations	\Relations\formula XX\…
	\Relations\formula ZZ\…
	\Relations\formula YY\…
Engineering geometry	\Engineering geometry\stock size\…
	\Engineering geometry\datums\…
	\Engineering geometry\dimensions\…

- Material and technology
  - Material description
  - Material heat treatment
  - Material standard manual
  - Specific technology parameters, such as "bend radius" and "K-factor" for sheet metal or "line weight" and "tape thickness" for electrical cables, etc.
- Functional tolerancing and annotations (annotation sets in the 3D space grouped into specific views and captures containing)
  - Dimensions
  - Geometrical tolerances
  - Datums (reference planes for inspection)
  - Notes
- Relations (formulas and added parameters for design automation and engineering intent capture)
  - Capturing engineering intents means translating human know-how into specific rules and reusable templates.
- Engineering geometry
  - Preliminary geometry or reference geometry driving the modeling and detailing of the part/product.
- Application data
  - Specific data for a given CAx module accessing the 3D model, for example, joints or degrees of freedom for kinematic analysis.

All these data have been submitted to three focus groups, organized gathering together engineers and technicians working in homogeneous scenarios. These groups are aimed at analyzing the correlation between KR and MBD

Table 13 Aerospace and defense product-oriented MBD scenario

KRs			B Scenario I	C Proposed MDB data structure	D Improvement ratio
Data	KR-D-1	Accessibility	2	4	2
	KR-D-2	Centralization	1	2	2
	KR-D-4	Coherence	2	3	2
	KR-D-5	Standardization	2	3	2
Tools	KR-T-1	Flexibility	2	2	1
	KR-T-2	Integration	2	3	2
	KR-T-3	Migration	2	3	2
	KR-T-4	Security	2	4	2
Processes	KR-P-1	Parallelization	3	4	1
	KR-P-2	Traceability	2	3	2
	KR-P-3	Virtualization	1	3	3
Methods	KR-M-1	Development	1	2	2
	KR-M-2	Simplification	1	2	2
	KR-M-3	Standardization	1	3	3
	KR-M-4	Coding in tools	2	4	2

Table 14 Aerospace and defense process-oriented MBD scenario

KRs			B Scenario II	C Proposed MDB data structure	D Improvement ratio
Data	KR-D-1	Accessibility	3	4	1
	KR-D-2	Centralization	2	4	2
	KR-D-4	Coherence	2	4	2
	KR-D-5	Standardization	1	3	3
Tools	KR-T-1	Flexibility	2	3	2
	KR-T-2	Integration	2	4	2
	KR-T-3	Migration	2	3	2
	KR-T-4	Security	2	5	3
Processes	KR-P-1	Parallelization	2	4	2
	KR-P-2	Traceability	2	3	2
	KR-P-3	Virtualization	3	4	1
Methods	KR-M-1	Development	1	3	3
	KR-M-2	Simplification	2	5	3
	KR-M-3	Standardization	1	3	3
	KR-M-4	Coding in tools	3	4	1

specifications to improve the efficacy and efficiency of the MBD data structure currently used [18–20]. Thanks to the use of the independent scoring method, the work has been developed through the following stages:

- Establishing a weighted relation between KRs and specifications (the standard 1–3–9 scale has been used).
- Calculating the specifications absolute importance:

$$w_j = \sum_{i=1}^{n} d_i r_{ij} \tag{1}$$

where d_i is the KR relative priority, r_{ij} is the numerical relation between KR i and specification j, n is the number of KRs, and m is the number of specifications.

- Calculating the relative importance of the MBD data type for a given scenario:

$$w_{jr} = \frac{w_j}{\sum_{j=1}^{m} w_j}. \tag{2}$$

Table 15 Aerospace and defense enterprise-oriented MBD scenario

KRs			B Scenario III	C Proposed MDB data structure	D Improvement ratio
Data	KR-D-1	Accessibility	2	4	2
	KR-D-2	Centralization	3	5	2
	KR-D-4	Coherence	3	4	1
	KR-D-5	Standardization	3	5	2
Tools	KR-T-1	Flexibility	2	3	2
	KR-T-2	Integration	3	5	2
	KR-T-3	Migration	3	4	1
	KR-T-4	Security	3	5	2
Processes	KR-P-1	Parallelization	2	4	2
	KR-P-2	Traceability	3	3	1
	KR-P-3	Virtualization	2	5	3
Methods	KR-M-1	Development	2	3	2
	KR-M-2	Simplification	2	4	2
	KR-M-3	Standardization	2	4	2
	KR-M-4	Coding in tools	3	5	2

3.3 The methodology implementation

Working on the results coming from the QFD implementation on the IE4EC focus groups and considering each scenario, it is possible to ascertain that for those users working in scenario I (Table 7; Fig. 3), the most suitable solution, thus the one providing the most advantages in terms of cost and time reduction, seems to be FT&A, followed by material and technology.

For those users involved in scenario II (Table 8; Fig. 4), material and technology seems instead to have a greater importance (23%, while FT&A 19%).

In scenario III, notes and relations grow in importance because knowledgeware and process virtualization are better supported (Table 9; Fig. 5).

In relation with the suggestions arising from the QFD analysis, three core general-purpose MBD structures have been proposed for each scenario in order to integrate the scenario data structure with other information provided by the guidelines coming from the QFD results (Tables 10, 11, and 12).

4 Experimental validation: the aerospace and defense scenario

In order to understand if the results obtained with the application of the QFD could be applied to a general-purpose approach, another users' sample, different from those employed before and composed by people working in the aerospace and defense context, has been involved in the experimental validation.

The technicians employed in this validation step have been selected by focusing the attention on specific projects, mainly collaboration project between different companies involving one of the three scenarios described before.

After having employed the benchmarking approach of the QFD method, the users have been asked to express their satisfaction about both their current MBD approach and the proposed improved one coming from the implemented QFD. This evaluation have been done after they have been working on the same KR they employed for the previous approach, as it is suggested by the QFD approach.

The scale of evaluation ranges from 1 (marginally accomplished requirement) to 5 (fully accomplished requirement). In this way, it has been possible to obtain the KR improvement ratio 3:

$$D_i = \left(\frac{C_i}{B_i}\right). \tag{3}$$

Considering the results obtained (Tables 13, 14, and 15), it is possible to see that the QFD method can support the development of standardized MBD data structure. In each scenario, in fact, the improvement ratio, obtained comparing the actual MBD structured with the QFD proposed one, shows significant values.

5 Conclusions

MBD is a general evolution in designing, manufacturing, and the overall product/process data management flow: it involves data structure, tools, processes, and methods. Today, developing MBD for a medium- to large-sized company belonging to the automotive and aerospace sectors deals primarily with its fundamentals: data structures.

The first benefits granted by the introduction of MBD are time and cost reduction for engineering processes. As far as PLM is concerned, data centralization and format reduction leads to easier tool integration, workflow rules simplification, leaner document management, and general streamlining in PLM mechanics.

MBD is the full accomplishment of current-generation 3D CAD capabilities. It empowers all the parametric, generative, associative, and collaborative features of modern CAE and provides a consistent data repository: the 3D model itself.

For a long time, MBD has been underestimated and looked upon as a mere way to suppress 2D drawings and get a paper-reduced PLM. Nowadays, while current CAD solutions are in their late maturity phase, companies begin to grasp the real scope, complexity, and opportunities of MBD and are trying to develop their own. However, they often lack a global strategy and appropriate methods to support such a development.

Companies need a common methodology to structure data in reusable, unified forms inside of 3D models.

This paper addresses this need, offering, for the first time, a unified and objective approach based on the QFD model to define MBD.

Thanks to the use of the QFD approach, it has been possible to understand how MBD can provide business process management improvements. Considering the different working scenarios in which the industrial companies working in the PLM domain operate, three different scenarios have been analyzed. These three are the most significant because they synthesize the behavior of the majority of the companies dealing with the PLM domain. In order to reach a standardized MBD data structure, the paper begins by analyzing which improvements are necessary for each scenario in the current data structure. According to the results of this first analysis, data standardization and process virtualization proved to be significant for scenario I (product oriented), method simplification and data centralization for scenario II (process oriented), whereas methods coding in tools (knowledgeware), security, and flexibility for scenario III (enterprise oriented).

Our study defines a priority order for the steps that have to be followed to develop a MBD data model based on different scenarios' specifications.

A company can now drive its efforts and investments decisions on developing CAD-PLM features and interfaces that maximize the return on investment and bring true innovation to its product lifecycle.

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