Proceedings of the ASME 2009 International Design Engineering Technical Conferences &
Computers and Information in Engineering Conference
IDETC/CIE 2009
August 30 - September 2, 2009, San Diego, California, USA

DETC2009-86983

PRODUCT LIFECYCLE MANAGEMENT: A SURVEY

Wei Liu
Concordia Institute for Information Systems Engineering
Concordia University, Montreal, Canada
Michael Maletz
Virtual Vehicle Research Center, Graz, Austria

Yong Zeng *
Concordia Institute for Information Systems Engineering
Concordia University, Montreal, Canada
Dan Brisson
Mecanica solutions, Montreal, Canada

ABSTRACT

This paper presents an overview of the field of Product Lifecycle Management (PLM). Though PLM has many facets, this paper mainly focus on the business drivers, requirements, concept and components behind the PLM as well as the technical foundations and the status of PLM academic research and industry solutions. Furthermore, a holistic roadmap of PLM is presented. The future research trends and challenges are finally discussed.

1 INTRODUCTION

PLM is a systematic concept for the integrated management of all product related information and processes across the extended enterprise through the entire lifecycle, from concept and design, to production, distribution, maintenance, and retirement [1, 2]. It emerged in late 1990's after nearly twenty years of technological evolution from Computer Aided Design (CAD), engineering data Management (EDM) to Computer Integrated Manufacturing (CIM), Product Data Management (PDM) [3, 4]. PLM extends PDM in scope from product design to the entire lifecycle [5], and covers not only single manufacturer but also extended enterprises. Compared with other enterprise solutions, PLM is focused on product and support innovation [6-9], while ERP mainly works on achieving best enterprise resource utilization; supply chain management (SCM) concentrates on the supply chain; and Customer Relation Management (CRM) pays more attention to the customer, as shown in Table 1.

With the adoption of PLM, enterprises can gain many benefits including mass customization, high quality, reduced project failure rates, increased and quick innovation, faster delivery, higher plant uptimes, effective management and use of corporate intellectual capital, effective communication among different groups at dispersed locations, minimized manufacturing costs, less industrial and commercial waste throughout every phase of the product life cycle, and more environmentally aware [1, 7, 10-13]. For example, IBM-Dassault's PLM Solution, ENOVIA VPM, enabled Dassault Aviation and its 27 partners in North America and Europe to collaboratively design the Falcon 7X business jet. Furthermore, 7 months were sufficient to assemble the aircraft instead the usual 16 for comparable aircrafts [14].

Table 1. Comparison of selected solution approaches

Applications	Focus	Goal	Lifecycle
ERP	Employees	Control	Produce/Assemble
SCM	Suppliers	Control	Produce/Assemble Storage/Distribution
CRM	Customers	Optimization	Produce/Assemble Storage/Distribution Use/Maintain
PLM	Product	Innovation	Concept/Design Produce/Assemble Storage/Distribution Use/Maintain Disposal/ Reuse

Over the last few years, PLM has attracted a lot of attentions from industry and research. There are increasing studies providing state-of-the-art review on PLM regarding to its fast continuous development. Abramovici(2002) [3] and Huang (2004) [15] presented state-of-the-art PLM evolution, concept, functionalities, role, development trends, and examples of research projects. Ravi(2005) [16] explored a broad scope of PLM and discussed case studies and research issues focused on the implementation and deployment of PLM beyond the development of technology. Ming(2005) [10] proposed a full scenario of technology solutions for PLM based on the analysis of business drivers, industry requirements, limit of current solution, and recent academic and industrial state-of-the-art review in the domain related to PLM. Jun and Kiritsis, et al.(2007) [17] provided a review for

* Associate Professor and author of correspondence, Phone: (514) 848-2424#5801, Fax: (514) 848-3171, Email: zeng@ciise.concordia.ca.

operation issues of the closed-loop PLM as a part of PLM research issues.

This paper aims to organize current research (challenges, issues, methodologies and technologies, proposed by research groups, existing applications of PLM vendors, etc) following a proposed roadmap, which consists of extracted fundamental components in the environment of PLM, and relationship between those components.

The rest of this paper is organized as follows. Section 2 discusses the concepts of product lifecycle management by review current researchers' perspectives. In Section 3, product lifecycle management is decomposed step by step to investigate the fundamental components, and a holistic roadmap is subsequently proposed through creating connections between those components. In Section 4, current research and application status is summarized. Further research trends and challenges are analyzed in Section 5. Section 6 presents our final conclusion on the review.

2 PLM CONCEPT

PLM has been diversely understood, and conceptualized in terms of knowledge management, strategy, and technology, etc. For example, Ameri and Dutta [18] define PLM as a knowledge management solution for product lifecycles within the extended enterprise, while CIMdata defines PLM as, "a strategic business approach that applies a consistent set of business solutions in support of the collaborative creation, management, dissemination, and use of product definition information across the extended enterprise from concept to end of life – integrating people, processes, business systems, and information." [19]. Similarly, Edwards[20] defines PLM as "management of a series of business processes, enabled by collaborative applications that manage a portfolio of products … to maximize market share and profitability". However, in the technological context, PLM is often defined by PLM solution vendors as a piece of technology, which can interoperate with other solutions [21].

Garetti [22] subsequently identified common elements in the previous definitions, such as (i) business process strategy, (ii) collaborative approach and (iii) role of Information and Communication Technology (ICT) systems, and proposed a multi-layered and multi-disciplinary definition that "PLM is a new integrated business model that, using ICT technologies, implements an integrated cooperative and collaborative management of product related data, along the entire product lifecycle".

Nevertheless, a more comprehensive PLM analysis is needed to cover the exhaustive features of product lifecycle management, especially innovation.

3 PLM COMPONENTS & ROADMAP

To fully understand PLM and identify its features, we stepwise decompose product lifecycle management in this section. In the first layer, product lifecycle management could be literally decomposed to product, product lifecycle, and product lifecycle management.

3.1. Product

A product is traditionally considered simply as the tangible, physical entity that people can buy or sell. However, its definition is extended further as the enterprise environment changes. Three levels of a product are well known in the marketing area. They are [23, 24]:

The core product: not the physical product. It represents the benefit of the product that makes it valuable to customer.

The actual product: the tangible, physical product.

The augmented product: the non-physical part of the product. It may contain information and detailed representations of the actual product.

Baïna et al. [25] conceive their dual view of product: the physical product and the informational product that handles all information associated to the product. The physical product interacts with physical entities (people, processes, machines, transport equipments, etc.) in the environment throughout entire product lifecycle (see section 3.2) , while the informational product interacts with computational environment for production control, quality assessment and traceability management [25], etc. The physical product can be distinguished according to different types of industry, such as mechanical products, electronic products, aerospace & defense products, automatic products, software, etc. The informational product also refers to product information or product data, which can be categorized in several ways, such as lifecycle phase and feature, as shown in Table 2.

Table 2 Diverse informational product categories

Source	Category
Schedit et al. [26]	• Static data: it is generated at the beginning of product life and rarely changes during the lifetime of the product. Normally the static data includes: BoMs, specific component identification, hazardous materials, material content, take-back information, disassembly attributes (e.g. sequence and tools) and recycling information, etc. • Dynamic data: occurs during the distribution, usage and end-of-life. Usually usage data forms the major part of the dynamic data and covers use patterns, environmental conditions and servicing actions.
Baïna et al. [25]	• Product Structure: a hierarchical decomposition of a physical product. • Product features • Product attributes: intrinsic properties of the physical product, such as weight, height, and material. • Product properties: information that is assigned to the product, such as identifier, production date. • Product States: a product passes throughout several states that describe its history. Such state is defined using tuples (attribute, value and propriety, value).

3.2. Product Lifecycle

Lifecycle is an inherent attribute of the physical product. Although a generally accepted product lifecycle definition, from design to retirement, already exists, in many cases the product lifecycle is still not a very clear and exact concept[2]. It can be seen from a number of different aspects and understood in many different ways depending on the frame of reference of the persons defining it (see Table 3).

It is important to distinguish between product lifecycle and business process, because in many cases, these two concepts are used interchangeable. Business processes are a set of acts that performed by organizations to carry out the product lifecycle as shown in Figure 1. A comprehensive business process has been proposed including product market strategy, product portfolio planning, product platform planning, customer requirements, product specification, conceptual design, detailed design, design analysis, prototyping and testing, process planning, inventory management, sourcing, production, inspection, packing, distribution, operation and service, disposal, and recycle [10, 27].

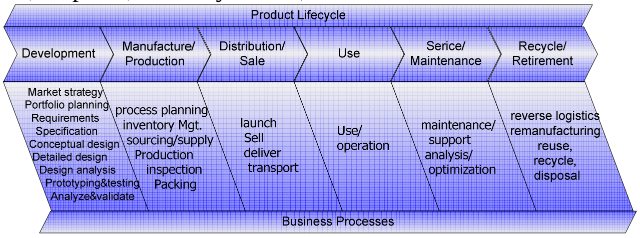

Figure 1. Map business processes along product lifecycle

Table 3 Diverse lifecycle definitions

Perspective	Phases division
Marketing [28]	• Introduction, growth, maturity, and decline
Resource [8]	• Natural resource extraction, resource processing, resource use, product use, and resource/waste management (reuse, recycle or dispose).
Manufacturer [8]	• Imagination, definition, realization, support, and retirement
User [8]	• Imagination, definition, realization, use, and disposal.
Product evolvement process	• Alting (1993) [29]: need recognition, design development, production, distribution, use, and disposal. • Kriwet et al (1995)[30]: acquisition phase, utilization phase, and recycling phase. • CIMdata (2002)[19]: product definition, production definition, and operational support. • Kiritsis (2003) [31]: beginning of life (BOL): design and production; middle of life (MOL): logistics (distribution), use, service, and maintenance; and end of life (EOL): reverse logistics (collecting), remanufacturing (disassembly, refurbishment, reassembly, etc.), reuse, recycle, and disposal. • Thimm et al. (2006)[32]: Market Requirements, Product concept, detailed design, process plan, prototype, production, warehousing, Maintenance, and disposal/recycling.

3.3. Product Lifecycle Management

Management is the act of getting people together to accomplish desired goals. Therefore, there are at least five interrogatives that need to be considered in the product lifecycle management.

When: the phase in which management occurs.

Who: people, organizations that involved in PLM.

What: the objects to be managed in PLM.

Why: challenges, motivations and the objectives of the PLM.

How: the functionalities and technologies supporting PLM.

Each interrogative will be discussed in detail as follows:

When

Product lifecycle phases: development, manufacture/ production, distribution/sale, use, service/maintenance, recycle/ retirement.

Who

From the role player viewpoint, stokeholds involved in the product lifecycle management can be classified into eight groups: developers, suppliers, manufacturers, transporters, distributors, customers, maintainers, and recyclers[33, 34]. Diverse stakeholders play different roles in variant product lifecycle phases, as shown in Table 4 where new features in PLM compared to traditionally understanding. Since 1989, the early involvement of suppliers in new product development has been concerned in the literature [35-37] due to its positive effects on the speed and flexibility of product development. Subsequently, a broader involvement of more roles in each product lifecycle phases has obtained growing attention, to improve product quality, shorten lead time, and reduce cost. For example, Chen et al. [38] stressed the importance of the feedback from product usage, maintenance phases to the designers for more innovations, as well as the requirement of other role players' involvement in the product development phase for better needs satisfactions.

What

Basic objects to be managed in PLM fall into three categories: physical product, information product, business processes. To manage them yet derives additional corresponding objects to be managed, such as people and IT tools, as informational product is managed generally by IT tools, and business processes are essentially inseparable from people. Example product information is also extended as follows [39]:

- Customer Information: requirements, configurations, quality issues.
- Portfolio Information: programs, schedules, resources deliverables.
- Design Information: schematics & drawings, CAD models, software/firmware, design reviews.
- Purchasing Information: pricing, part/BOM costs, price history.
- Supplier Information: approved vendors, preference/ status, availability.
- Manufacturing Information: bills of materials, Mfg. instructions revisions.
- Service Information: corrective actions field instructions Service BOMs.
- Compliance Information: regulatory, standards, audits.

Figure 2 shows how IT tools are dispersed along the product lifecycle [40].

Why

There are many challenges for effective management of whole product lifecycle. According to Ameri and Dutta[7], internal push consists of the need for product innovation, customer intimacy and operations excellence, while external forces include globalization, mass customization, shrinkage in product life cycle, push into the supply chain and environmental issues. Other challenges increased outsourcing, geographically dispersed design teams[10]. Previously mentioned challenges are all associated to objects of PLM, which can be classified in the Table 5.

Table 4. Role Players in the product lifecycle phases

	development	production	distribution	use	maintenance	disposal
customers	√ major players			√ major players	√ players	
developers	√ major players	● players	● players	● players	● players	● players
suppliers	● players	√ players			● players	
manufacturers	● players	√ major players			● players	
distributors	● players		√ major players			
transporters	● players		√ players			
maintainers	● players			√ players	√ major players	
recyclers	● players					√ major players

note: ● new features √ original features

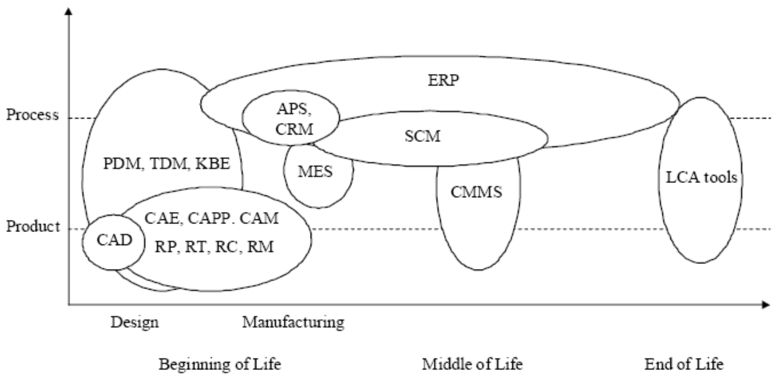

Figure 2 Map of IT tools along the product lifecycle[40]

Table 5 Challenge classification

Objects	Motivations
Physical product	• Increasing complexity of products • Changes to products • Continuous innovations • Shrinkage in product life cycle
Informational product	• Considerable amounts of data • Secure data share/transfer between Different systems in different parties • Duplicated information • Reusing design knowledge • Product model data insufficiency • Incompatible data structures and lack of data associations[38]
Business processes	• Excellent operations • Increased outsourcing
stakeholders	• Changing custom requirements • Global collaborations • Customer intimacy • Geographically dispersed design teams • Global competition
IT tools	• Insufficient systems integration • Incoherent terminology

Table 6 Physical product self-management

Source	Functionality	Technology
Kärkkäinen et al. [41]	Delivery route self-control	Jini [42] Remote Method Invocation [43] Corba[44] XML documents RFID technology[45]
Zhekun et al. [46]	Reflect customer requirements	RFID tags
PROMISE [47]	Store lifecycle-related data on the product itself	RFID technology[48]
Kahn et al. [49]	Part residual value calculate for new recycling	RFID technology
Anke et al. [50]	Abnormal condition alert for maintenance	Product embedded information device
Parlikad, McFarlane[51]	End of life decision making	RFID technology
Meyer et al. [52]	Information handling Problem notification Decision making	Sensors RFID readers[48]

How

The management to the physical product can be divided to two different types in terms of management enabler. They are human-enabled management, and product self-management. Business processes can be regarded as a kind of acts belonging to the first type. The development of the information technology and artificial intelligence technology progressively makes it possible to manage product by itself. Table 6 presents corresponding literatures, functionalities and technologies. Meyer et al. [52] summarized three categories of functions in the product self-management: information handling, problem notification, and decision making.

Table 7 Informational product management

Functionality	Technology
Product information tracking and tracing	RFID technology[48], smart card[53], Bar codes[54], UPnP technology[55], biometric systems[56], EC-funded PROMISE project[9, 47, 57, 58], EC-funded ELIMA project[59] [60], EPC Network[61, 62], The Dialog platform[63, 64], World Wide Article Information [65]
Product information representation	Universal 3D, X3D, 3D XML, JT Format, PLM XML [66]
Product information searching	Shape similarity assessment algorithms[67], 3D shape searching techniques based on: global feature, manufacturing feature recognition, graph, histogram/distribution, product information, 3D object recognition [68] Structured document retrieval (SDR) technology[69]
Information exchanging and sharing	Product information modeling: product information modeling framework [12], Product specifications modeling [70], product structured modeling [71]
	electronic data interchange (EDI)
	CAD/CAPP /CAM integration: design-by-features approach[72], feature recognition[73], UML[38], STEP/XML[74] CAPP/CAM[33], PSRL for semantic interoperability [75], integration between knowledge based system and CAD/CAPP systems[76], integrating elements of CPI via PLM framework[77]
	Standards[74, 78-80], Standards for implementation languages: Basic, C, C++, Java, C#, FORTRAN, Prolog, Perl, Tcl/Tk and OpenGL, Information modeling standards: EXPRESS, UML, XML Schema, PSL, OWL, Security standards: Digital Rights management (DRM), PSL, SysML, STEP, EDI, ebXML, STEP/PLCS, SCOR Current PLM support standards: STEP, PLM XML, PML
Requirement management	product requirements classification [38] requirements computer-based representation [70]
Configuration management	a parameter-based approach for engineering change management (ECM) [81], a web-based system for engineering change management [82], engineering change evaluation process [83]
Knowledge management	knowledge Representation, knowledge capture, knowledge generation: data mining and data warehousing, knowledge dissemination[18], knowledge transformation [31], knowledge creation in NPD process [84], knowledge-based framework for integrating design and analysis activities [85], knowledge sharing [86]

According to Abramovici [87], available methods and tools for the informational product management in PLM can be clustered in following function groups: identifying, structuring, classifying, modeling, retrieving, sharing, disseminating, visualizing and achieving product, process and project related data. In addition, the authors are of the option that methods for application integration aim to share information. Therefore, methods for defining and managing interfaces between PLM and different authoring applications like CAD, CAM, CAE and integrated enterprise software such as ERP, SCM or CRM systems can be classified into information sharing group. Table 7 lists main functionalities and related technologies reported in the existing product information management literatures.

Table 8 Business process management

Functionality	*Issues & Technologies*
product development	collaborative conceptual design[88] collaborative product design [38, 89-92] collaborative visualization [93] collaborative product innovation[77] open standard, source, tools and methods[94] engineering change management [82] a distributed change control workflow[90] design process design [95] Design chain management: DCOR [96] selecting partners decision model [97, 98] performance measures and metrics[99] collaborative design chain model[100, 101] supplier involvement[35] supplier integration [93, 102, 103] design chain management solution[19] Project management: Project scheduling using Design Structure Matrix (DSM) [38]
process planning	process selection process sequencing[104, 105]: Genetic algorithms (GAs) Artificial neural network (ANN) Analytical hierarchical process (AHP) particle swarm optimization approach
Manufacturing	CAM/CAPP Collaboration[33]
inventory	decision-making framework [106]
Maintenance management	E-maintenance [31, 107] predictive algorithm [108] condition monitoring maintenance [109]: ICT
End of life	Decision making based on RFID [51]
Process modelling	Product lifecycle modeling: Unified Markup Language (UML) [32, 110]

As for the information tracking and tracing, Auto-ID technologies including barcode, RFID, smart card, and biometric systems, are commonly used to identify products or delivery units. In addition to automatic identification, there are product information tracking and tracing systems such as EPC

Network, The Dialog platform, World Wide Article Information.

Product information management also entails product information representation, modeling, exchanging, and sharing, with technologies and standards such as feature recognition, Unified Markup Language (UML), STEP, etc.

The ultimate aim of informational product management is to support stakeholders at different stages of the product lifecycle in rapidly browsing, retrieving and manipulating product information.

Such category is divided on our own showing, with addressing the interchangeable items, such as collaboration and integration, configuration management and change management.

Current researches on the business process management address issues such as collaborative product development, process modeling, process planning, manufacturing, maintenance, change control, etc. (see Table 8). Product development phase attracts lots of attention, including design chain management, conceptual design, innovation, project management. Meanwhile, other authors are devoted to the integration of CAD, CAPP and CAM, as well as optimizing inventory levels and improving the efficiency of scheduled or unscheduled maintenance.

3.4. Product Lifecycle Management: Roadmap

Based on the above analysis, more and more fundamental components in the product lifecycle management have been figured out, which fall into seven categories including product, stakeholder, lifecycle phase, business process, data, technology and function. Components within each category can be decomposed into subcomponents. For example, for the informational product in the product category, there are four sub-components like product structure, attribute, properties, status and simulation data (as we mentioned in section 3.2). Furthermore, the relationships between those components need to be clarified. The relationships can be also classified into various types. A dependency relationship may exist between two business processes; an include relationship may exist between two functionalities; a usage relationship may exist between a stakeholder and a technical tool; and an association relationship may exist between two kinds of data. In Figure 3, a PLM roadmap breakout structure is given based on those extracted components and their relationships. With this roadmap all related issues and literatures can be systematically organized. Conversely, it can also be extended and refined with the advent of new components and by creating new connections between components. Thus, PLM concept, scope and features will become richer and more mature through recursive evolvement of the roadmap. Such roadmap is a hierarchical structure that can be decomposed step by step from top to down. Figure 4 and 5 present a detailed map of the relations between functionalities and technologies associated with specific components.

4 RESEARCH GROUPS AND APPLICATIONS

4.1 Current research groups and issues

Following the proposed PLM roadmap, we classify current research issues in active academic groups, as shown in Table 9. Advanced Design and Modeling Laboratory of Nanyang Technological University are trying to achieve a universal product and process model. Their efforts advance the attractiveness of PLM by bridging declarative decision making modules and product/process oriented engineering applications[111]. Auto-ID Labs and Laboratory of Computer-Aided Design and Production are mainly focusing on the research of information tracking and tracing by developing and applying RFID technology to realize close-loop PLM. The National Institute of Standards and Technology (NIST) gains sight into the standardized representation of manufacturing, called Process Specification Language (PSL)[80]. University of Bath, Purdue University and University of Michigan, and others are working on various components in the PLM, such as product development, information searching information modeling, process modeling, knowledge management, configuration management, application integration.

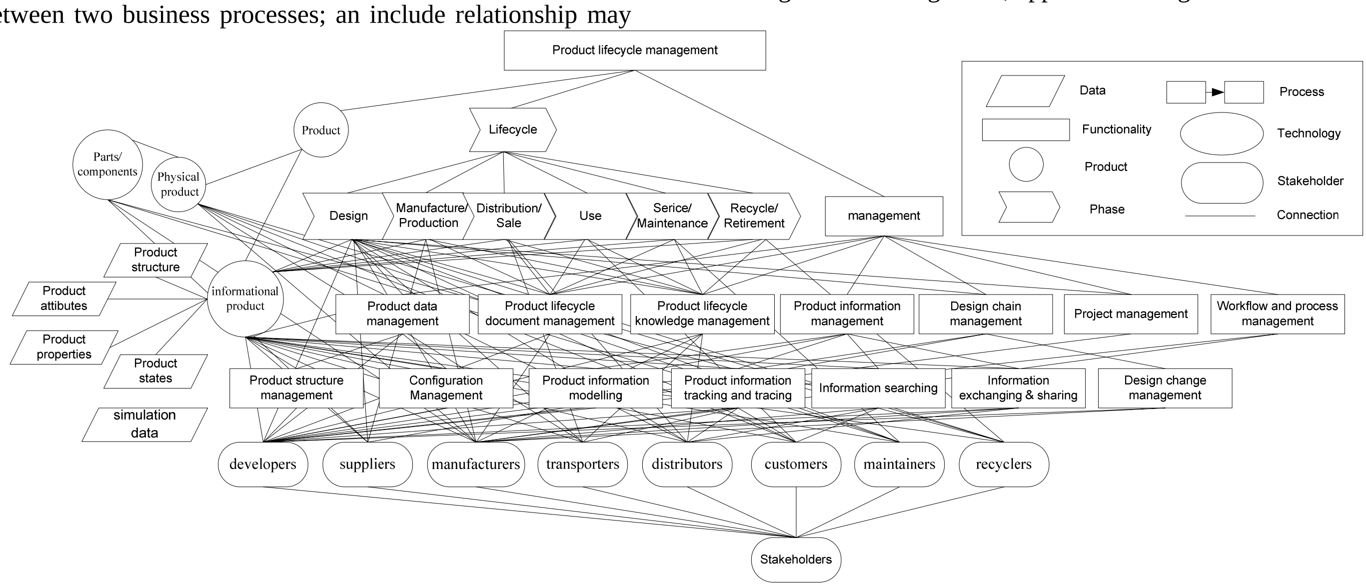

Figure 3 PLM roadmap

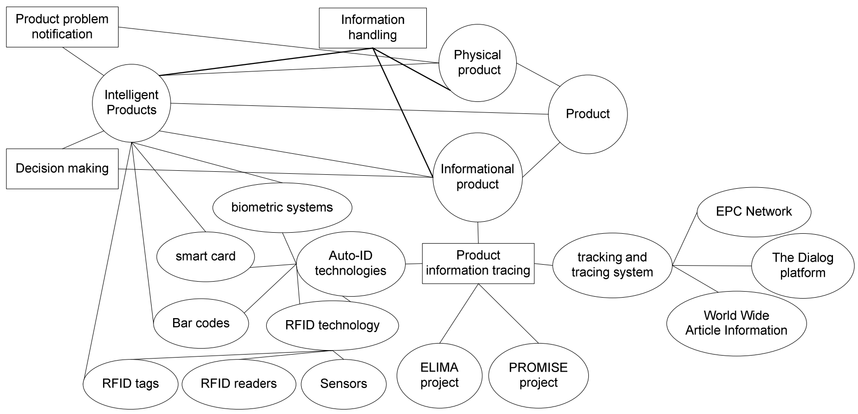

Figure 4 PLM roadmap_ product information tracing layer

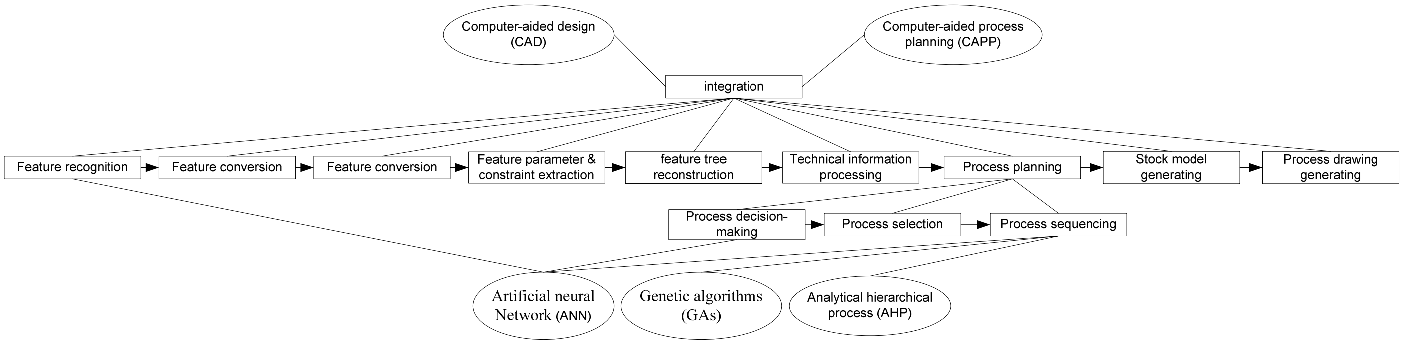

Figure 5 PLM roadmap_ CAD and CAPP Integration layer

Table 9. Recent active academic group in PLM.

Active universities and research institute	Main Research Issue
Auto-ID Lab MIT[112]/ Cambridge [113]	Information tracking and tracing: Physical Mark-up Language[114] Networked Radio frequency identification[115], EPCglobal Network [62]
Swiss Federal Institute of Technology in Lausanne (EPFL): Laboratory of Computer-Aided Design and Production (STI-IPR-LICP)	Information tracking and tracing: system architecture, issues of closed-loop PLM [17, 116] predictive algorithm for maintenance [108] PROMISE: PROduct lifecycle Management and Information tracking using Smart Embedded systems [31]
University of Bath: The Innovative Design & Manufacturing Research Centre[117]	Information representation & product design: product information lightweight representation[66] Graphical representation of key iterations during the design process[118] Information searching: structured document retrieval [69, 119] Process planning: operation sequencing optimisation [105]
The National Institute of Standards and Technology (NIST): Manufacturing Engineering Laboratory (MEL) [120]	Information modeling: Core Product Model [121] product information modeling framework [12] Information representation: an adaptive XML based information representation [122] Standards: role of standards [123], Process Specification Language[124]
Purdue University: Purdue Research and Education Center for Information Sciences in Engineering(PRECISE)[125] Product Lifecycle Management Center of Excellence	Information searching: shaped-based searching for PLM systems[126] representation and Matching for Engineering Shapes[127] information retrieval [128] Information Mirror Model[4, 129]
University of Michigan: PLM Alliance [130]	Knowledge management: Ameri et al. [18] defined knowledge management processes in each lifecycle of PLM.

Nanyang Technological University: Advanced Design and Modelling Laboratory[132]	Product data exchange &CAD/CAM integration Patil et al. [75, 131] proposed product semantics representation language (PSRL) for semantic interoperability of product information. Configuration management: Engineering change evaluation process [83]. Process modeling & application integration: Thimm et al. [32] proposed a semantically and graphically explicit description of product lifecycle stages using the Unified Markup Language (UML). Ma et al. [133] introduced the concept of associative feature for applications integration. Chen et al. [38, 134]enhanced their interaction mechanisms through associative features, which are modeled based on intelligent design patterns. Chen et al. [76] unified different application feature types are with a generic definition.

4.2 Application Areas and Commercial Tools

There are many companies that supply software to support the PLM process. Table 10 summarizes the recent industrial status of PLM solutions from worldwide leading vendors. The fast growing market for product life cycle management software is becoming more complex. Dassault Systemes (DS) acquired MatrixOne in 2006, Siemens' Automation and Drives group acquired UGS in 2007, Oracle acquired Agile Software in 2007, and PTC acquired CoCreate in 2007 [135]. So far these four vendors plus SAP and Autodesk are current leading global providers of PLM software, which have annual revenue close to or exceeding $1 billion. The galaxy of PLM "solution-providers" comes mainly from the digital engineering(CAD, CAE, CAPP, CAPE, …), ERP and I&CT collaborative three different backgrounds[136]. The main functionalities offered are generally realized integrating diverse tools, including authoring and simulation tools (for CAx applications), product structure management tools (for product data management), data vault and document management tools (for a secure storage and retrieval of product definition information) and program management tools (for resource scheduling and project tracking) [136].

Table 10. Recent industrial status of PLM solutions

Leading/Sample vendors	*Features & functions*
Siemens PLM Software (UGS) [137]	Collaboration Platform, Collaborative Project Management, PDM (Workflow & Lifecycle Management, Change Management, Doc Management, Product Structure Management), CAD/CAM, e-Manufacturing, e-Vis Advantage : CAD, PDM, Design Collaboration, Project/Portfolio Weakness: MPM
Dassault system [138] / IBM-Dassault system[139]	CATIA, ENOVIA, SMARTTEAM: Planning, Implementation, Design, Engineering & Analysis, Manufacturing, Service after sales, PDM & Collaboration Advantage : CAD, PDM, MPM, Design Collaboration Weakness: Project/Portfolio
Oracle/AgileSoft[140]	Product Collaboration, Product Governance and Compliance, Product Cost Management, Product Quality Management, Product Portfolio Management, Engineering Data Management, Collaboration , Engineering Collaboration, Variant Management, AutoVue Electro-Mechanical Professional Advantage : PDM, Design Collaboration, Project/Portfolio Weakness: CAD, MPM
PTC/ Windchill[141]	PDM (Workflow & Lifecycle Management, Change Management, Doc Management, Product Structure Management), ProjectLink, CAD/CAM Advantage : PDM, Design Collaboration, CAD Weakness: MPM, Project/Portfolio
SAP/mySAP PLM[142]	Life-cycle data management, Program and project management, Life-cycle collaboration, Quality management Enterprise asset, Environment, health, and safety management Advantage : Project/Portfolio, Design Collaboration Weakness: MPM, CAD

5. FUTURE TRENDS

In line with the proposed roadmap, we can find that existing researches are still more focused on the PDM, the management of BOL and MOL, while there are other areas and novel features that need to be paid more attention in the future when establishing new connections, especially

- Intelligent management: an intelligent product self-management concept can be generated by linking product with management. Such self-management not only stays in the information handling level, but also makes decision throughout the whole product lifecycle.
- Total process management: to establish connections between businesses processes not only those in BOL and MOL, but also including product maintenance, reuse, recycle, and disposal in the end of life management.
- Lean management: linking data, management, and parts/components implies that the management to the product data can go deeper from product type, as typically in PDM, to item, even to component/part,

realizing item lifecycle management, and component/part lifecycle management.

- Knowledge management: although researchers have pay many efforts on it, extensive unstructured data during the whole product lifecycle are still need to be explored, elicited, stored, linked, thus used in a larger area for effective management and product innovation. It also strengthen the link between
- Simulation lifecycle management (SLM): SLM interfaces was developed by Dassault/SIMULIA recently which links simulation data, processes, stakeholders, management, and etc., to allow for many, previously excluded, downstream elements of product development projects to be engaged with the upstream elements as early as the concept creation stage.
- Collaborative management: to a certain extent, collaboration is not only the issue on the process but involves in all levels (tool, method, process – in house or 3rd party originating, standard or customized solution). A collaboration hierarchy model is derived, as shown in Figure 6.

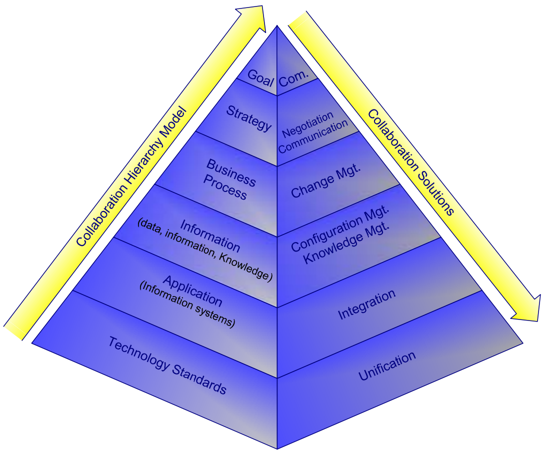

Figure 6 Collaboration Hierarchy Model

There are six levels implied in the collaboration: technology standards, applications, information, processes, strategies, and goals. The collaboration in the product lifecycle management can be established from top to bottom, and realized from bottom to top. The solution to the collaboration of goals and strategies would be communication and negotiation among stakeholders, while the collaboration of business processes, product data, and knowledge can be supported through functionalities such as collaborative project management, collaborative product data management, change management, configuration management, document management, and knowledge management. The applications integration and technology standards unification form the basis of information processing and exchange.

Therein, the integreation is always the keyword in today's PLM context. This will not change within the next few years. The increasing importance and complexity of supply chain management (SCM) as well as customer relationship management (CRM) are examples of future PLM integration aspects.

6. CONCLUDING REMARKS

PLM is widely recognized as a business necessity in current time. PLM enables companies to leverage their investments in product related intellectual and physical assets and is the vehicles to reduce cost, provide solid return on investment, and enable product and process innovation. PLM vendors are trying to provide solutions that help more users from more organizations, across more functions to easily create, capture, access, share, and use their extended enterprise's intellectual assets, and enabled businesses in multiple industry sectors to respond to market pressures in new and innovative ways. Thus, those requirements force PLM become broader in scope, functionality, and technology, as well as in academic literature and industry application. This paper decomposes the product lifecycle management structure step by step from top to down and derives a hierarchical roadmap for PLM, based on which current literature and issues are organized. Furthermore, most active industrial PLM solutions are presented and analyzed in terms of their advantages and weaknesses. Future trends of PLM are suggested.

Due to the increasing areas that PLM involves, its roadmap is recursively evolving. Additionally, the proposed roadmap can be extended and detailed along with the forthcoming literature and applications in the future.

ACKNOWLEDGMENT

The research in this paper is supported by NSERC-CRD (PJ 350114-06). We are grateful to the financial support from NSERC, CRIAQ, Pratt & Whitney Canada Corp, Bombardier Inc., CAE Inc., CMC Electronics Inc., and Rolls-Royce Canada Limited. The first author is partially supported by CSC (The China Scholarship Council).

REFERENCES

[1] Amann, K., *Product lifecycle management: empowering the future of business*. 2002, CIM Data, Inc.

[2] Sääksvuori, A. and A. Immonen, *Product lifecycle management*. 2nd ed ed. 2005, Berlin, London: Springer.

[3] Abramovici, M. and O.C. Sieg, 2002, "Status and Development Trends of Product Lifecycle Management System", *Proceedings of IPPD 2002*, Wroclaw, Poland.

[4] Grieves, M., *Product Lifecycle Management: Driving the Next Generation of Lean Thinking* 2006, New York: McGraw-Hill.

[5] Fathi, M., et al., 2007, "Advanced Condition Monitoring Services in Product Lifecycle Management", *Information Reuse and Integration, 2007. IRI 2007. IEEE International Conference on*.

[6] Staresinic, D.J. *Product Lifecycle Management (PLM)*. 2007 [cited 02/02/2008]; Available from: www.gmaonline.org/events/2007/isld/presentations/product.pdf.

[7] Ameri, F. and D. Dutta, *Product Lifecycle Management Needs, Concepts and Components*. 2004, University of Michigan, Ann Arbor, MI. p. p. 2.

[8] Stark, J., *Product lifecycle management, in: 21st Century Paradigm for Product Realisation*. Decision Engineering Series. 2005, London: Springer-Verlag 441.

[9] Kiritsis, D., 2004, "Ubiquitous product lifecycle management using product embedded information devices", *Proceedings of IMIS'04*.
[10] Ming, X.G., et al., "Technology solutions for collaborative product lifecycle management - Status review and future trend", *Concurrent Engineering-Research and Applications*, 2005. Vol.**13**(4), pp. 311-319.
[11] Hartmann, G., *Product lifecycle management with SAP: The complete guide to my SAP PLM strategy, Technology and best practices*. 2005: SAP Press.
[12] Sudarsan, R., et al., "A product information modeling framework for product lifecycle management", *Computer-Aided Design*, 2005. Vol.**37**(13), pp. 1399-1411.
[13] Lee, Y.-C., L.-C. Sheu, and Y.-G. Tsou, "Quality function deployment implementation based on Fuzzy Kano model: An application in PLM system", *Computers & Industrial Engineering*, 2008. Vol.**55**(1), pp. 48-63.
[14] IBM, "Dassault aviation revolutionizes aircraft development with the Virtual Platform and PLM", 2004.
[15] Hung, S. and Y. Fan, "Overview of product lifecycle management", *Computer Integrated Manufacturing Systems*, 2004. Vol.**10**(1), pp. 1-9.
[16] Ravi, M.R., et al., "Streamlining Product Lifecycle Processes: A Survey of Product Lifecycle Management Implementations, Directions, and Challenges", *Journal of Computing and Information Science in Engineering*, 2005. Vol.**5**(3), pp. 227-237.
[17] Jun, H.B., D. Kiritsis, and P. Xirouchakis, "Research issues on closed-loop PLM", *Computers in Industry*, 2007. Vol.**58**(8-9), pp. 855-868.
[18] Ameri, F. and D. Dutta, "Product Lifecycle Management: Closing the Knowledge Loops", *Computer Aided Design & Applications*, 2005. Vol.**2**(5), pp. 577-590.
[19] CIMdata, *Product lifecycle management: empowering the future of business*. 2002.
[20] Edwards, J.D., "Product Life Cycle Mangement: A White Paper", 2002.
[21] TERZI, S., *Elements of Product Lifecycle Management: Definitions, Open Issues and Reference Models*. 2005, l'Université Henri Poincaré Nancy I en cotutelle avec le Politecnico di Milano (en Italie).
[22] Gretti, M. and S. Terzi, 2004, "Product Lifecycle Management: definition, trends and open issues", *International Conference on Advances in Production Engineering*, Warsaw, Poland.
[23] Kotler, P., *Marketing Management: Analysis, Planning, Implementation and Control*. 1988, Englewood Cliffs: Prentice-Hall International.
[24] Khosrowpour, M., *Managing information technology resources in organizations in the next millennium*. 1999, Hershey, PA, USA: Information Resources Management Association International Conference.
[25] Baïna, S., H. Panetto, and G. Morel, "New paradigms for a product oriented modelling: Case study for traceability", *Computers in Industry*, 2009. Vol.**60**(3), pp. 172-183.
[26] Schedit, L.G. and S. Zong, 1994, "An approach to achieve reusability of electronic modules", *Procedings of the IEEE International Symposium on Electronics & the Environment*, San Francisco, USA: IEEE.
[27] Ullman, D.G., *The Mechanical Design Process*. 1997, New York: McGraw-Hill.
[28] Anderson, C. and C. Zeithaml, "Stage of the product life cycle, business strategy, and business performance", *Academy of Management Journal*, 1984. Vol.**27**(1), pp. 5-24.
[29] Alting, L., *Life-cycle design of products: a new opportunity for manufacturing enterprises*, ed. A. Kusiak. Vol. In Concurrent Engineering: Automation, Tools, and Techniques. 1993: New York: Wiley. 1-17.
[30] Kriwet, A., E. Zussman, and G. Seliger, "Systematic integration of design-for-recycling into product design", *International Journal of Production Economics*, 1995. Vol.**38**(1), pp. 15-22.
[31] Kiritsis, D., A. Bufardi, and P. Xirouchakis, "Research issues on product lifecycle management and information tracking using smart embedded systems", *Advanced Engineering Informatics*, 2003. Vol.**17**(3-4), pp. 189-202.
[32] Thimm, G., S.G. Lee, and Y.S. Ma, "Towards unified modelling of product life-cycles", *Computers in Industry*, 2006. Vol.**57**(4), pp. 331-341.
[33] Ming, X.G., et al., "Collaborative process planning and manufacturing in product lifecycle management", *Computers in Industry*, 2008. Vol.**59**(2-3), pp. 154-166.
[34] Smirnov, A., et al., "Ontology-based support for semantic interoperability between SCM and PLM", *International Journal of Product Lifecycle Management*, 2006. Vol.**1**(3), pp. pp.289-302.
[35] Akira, T., "Bridging inter- and intra-firm boundaries: management of supplier involvement in automobile product development", *Strategic Management Journal*, 2001. Vol.**22**(5), pp. 403-433.
[36] Dowlatshahi, S., "Implementing early supplier involvement: a conceptual framework", *International Journal of Operations & Production Management*, 1998. Vol.**18**(2), pp. 143 - 167.
[37] Clark, K.B., "Project Scope and Project Performance: The Effect of Parts Strategy and Supplier Involvement on Product Development", *Management Science*, 1989. Vol.**35**(10), pp. 1247-1263.
[38] Chen, Z.Y. and Y. Zeng, "Classification of product requirements based on product environment", *Concurrent Engineering: Research and Applications, An International Journal*, 2006. Vol.**14**(3), pp. 219-230.
[39] Oracle. [cited 02/26/2009]; Available from: http://www.oracle.com/global/kr/download/seminar/2008/mrd/s03.pdf.
[40] Garetti, M. and E.b.S. Terzi, *A new point of view on Product Lifecycle Management*, University of Bergamo: Italy.
[41] Kärkkäinen, M., et al., "Intelligent products--a step towards a more effective project delivery chain", *Computers in Industry*, 2003. Vol.**50**(2), pp. 141-151.
[42] Oaks, S. and H. Wong, *Jini in a nutshell: a desktop quick reference*. 2000, Sebastopol, CA: O'Reilly and Associates.

[43] Sun. *RMI Specification*. 1998 [cited 06/28/2001]; Available from: http://java.sun.com/products/jdk/1.2/docs/guide/rmi/spec/rmiTOC.doc.html
[44] Orfali, R., D. Harkey, and J. Edwards, *Instant CORBA*. 1997, New York: Wiley.
[45] Boxall, G., 2000, "The use of RFID for retail supply chain logistics", *Tag 2000, Baltic Conventions*, The Commonwealth Conference & Events Centre, London.
[46] Zhekun, L., R. Gadh, and B.S. Prabhu, 2004, "Applications of rfid technology and smart parts in manufacturing", *Proceedings of DETC'04*.
[47] PROMISE. [cited 02/25/2009]; Available from: http://www.promise.no/.
[48] Srivastava, B., "Radio frequency id technology: the next revolution in scm", *Business Horizons*, 2004. Vol.**47**(6), pp. 60-68.
[49] Kahn, O., et al., 2006, "Rfid in automotive: a closed-loop approach", *Proceedings of ICE'06*.
[50] Anke, J. and K. Främling, 2005, "Distributed decision support in a plm scenario", *Proceedings of Product Data Technology Europe 14th Symposium*.
[51] Parlikad, A.K. and D. McFarlane, "RFID-based product information in end-of-life decision making", *Control Engineering Practice*, 2007. Vol.**15**(11), pp. 1348-1363.
[52] Meyer, G.G., K. Främling, and J. Holmström, "Intelligent Products: A survey", *Computers in Industry*, 2009. Vol.**60**(3), pp. 137-148.
[53] Rankl, W. and W. Effing, *Smart Card Handbook*. 3 ed. 2004: Wiley.
[54] Collins, D.J. and N.N. Whipple, *Using Bar Code - why its taking over*. 2 ed. 1994: Data Capture Press.
[55] UPnP. [cited 02/26/2009]; Available from: http://www.upnp.org/.
[56] Jain, A.K., A. Ross, and S. Prabhakar, "An introduction to biometric recognition", *Circuits and Systems for Video Technology, IEEE Transactions on*, 2004. Vol.**14**(1), pp. 4-20.
[57] PROMISE. [cited 02/26/2009]; Available from: http://www.promise-plm.com/.
[58] Cassina, J., et al., 2006, "Development of the semantic object model for a pdkm system", *Proceedings of ICE 2006*.
[59] Simon, M., et al., 2004, "Product design informed by life cycle information: initial results from ELIMA", *Proceedings of the 2nd International Conference on Manufacturing Research (ICMR2004)* Sheffield Hallam University, UK.
[60] Bodenhoefer, K., et al., 2004, "Environmental life cycle information management and acquisition: first experiences and results from field trials", *Proceedings of the Conference on Electronics Goes Green 2004*, Berlin, Germany.
[61] Sarma, S., D.L. Brock, and K. Ashton, *The networked physical world*. 2000, MIT Auto-ID Center.
[62] Auto-ID-Labs. [cited 02/26/2009]; Available from: http://www.autoidlabs.org/.
[63] Dialog. [cited 02/26/2009]; Available from: http://dialog.hut_/.
[64] Främling, K., et al., *Product agents for handling information about physical objects*. 2003, Helsinki University of Technology.
[65] WWAI. *World wide article information*. [cited 02/26/2009]; Available from: http://www.wwai.org/.
[66] Ding, L., et al., 2007, "Product representation in lightweight format for product lifecycle management (PLM)", *Digital Enterprize Technologies (DET)*, Bath.
[67] Antonio, C., K.G. Satyandra, and K. Mukul, "A Survey of Shape Similarity Assessment Algorithms for Product Design and Manufacturing Applications", *Journal of Computing and Information Science in Engineering*, 2003. Vol.**3**(2), pp. 109-118.
[68] Iyer, N., et al., "Three dimensional shape searching: state-of-the-art review and future trends", *Comput Aided Design*, 2005. Vol.**37**(5), pp. 509-530.
[69] Liu, S., C.A. McMahon, and S.J. Culley, "A review of structured document retrieval (SDR) technology to improve information access performance in engineering document management", *Computers in Industry*, 2008. Vol.**59**(1), pp. 3-16.
[70] McKay, A., A. de Pennington, and J. Baxter, "Requirements management: a representation scheme for product specifications", *Computer-Aided Design*, 2001. Vol.**33**(7), pp. 511-520.
[71] Eynard, B., et al., "UML based specifications of PDM product structure and workflow", *Computers in Industry*, 2004. Vol.**55**(3), pp. 301-316.
[72] Dixon, J.R., 1988, "Designing with features for component design", *Wkshp. Features & Manufacturing National Science Foundation*, University of California at Los Angeles, USA.
[73] Shah, J.J., "Assessment of features technology", *Computer Aided Design*, 1991. Vol.**23**(5), pp. 58-66.
[74] Balakrishna, A., et al., "Integration of CAD/CAM/CAE in Product Development System Using STEP/XML", *Concurrent Engineering*, 2006. Vol.**14**(2), pp. 121-128.
[75] Patil, L., D. Dutta, and R. Sriram, "Ontology-based exchange of product data semantics", *Automation Science and Engineering, IEEE Transactions on*, 2005. Vol.**2**(3), pp. 213-225.
[76] Chen, G., et al., "Unified feature modelling scheme for the integration of CAD and CAx", *Computer Aided Design & Applications*, 2004. Vol.**1**(1-4), pp. 595-601.
[77] Sharma, A., "Collaborative product innovation: integrating elements of CPI via PLM framework", *Computer-Aided Design*, 2005. Vol.**37**(13), pp. 1425-1434.
[78] Pratt, M.J., "the STEP standard for product data exchange, and its PLM capabilities", *International Journal of Product Lifecycle Management*, 2005. Vol.**1**(1), pp. 89-94.
[79] Zhang, Y., C. Zhang, and H.P. Wang, "Interoperation of STEP application protocols for product data management", *Concurrent Engineering-Research and Applications*, 1998. Vol.**6**(2), pp. 161-169.
[80] Sudarsan, R., et al., "Information sharing and exchange in the context of product lifecycle management: Role of standards", *Computer-Aided Design*, 2008. Vol.**40**(7), pp. 789-800.

[81] Rouibah, K. and K.R. Caskey, "Change management in concurrent engineering from a parameter perspective", *Computers in Industry*, 2003. Vol.**50**(1), pp. 15-34.
[82] Huang, G.Q., W.Y. Yee, and K.L. Mak, "Development of a web-based system for engineering change management", *Robotics and Computer-Integrated Manufacturing*, 2001. Vol.**17**(3), pp. 255-267.
[83] Joshi, N., F. Ameri, and D. Dutta, 2005, "Systematic Decision Support for Engineering Change Management in PLM", *ASME 2005 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Long Beach, California USA.
[84] Chen, H.H., et al., "Developing new products with knowledge management methods and process development management in a network", *Computers in Industry*, 2008. Vol.**59**(2-3), pp. 242-253.
[85] Mocko, G., et al., 2004, "Towards Reusable Knowledge-Based Idealizations for Rapid Design and Analysis", *45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics & Materials Conference* Palm Springs, California.
[86] Young, R.I.M., et al., "Manufacturing knowledge sharing in PLM: a progression towards the use of heavy weight ontologies", *International Journal of Production Research*, 2007. Vol.**45**(7), pp. 1505-1519.
[87] Abramovici, M., *Digital Engineering und PLM - Zwei unterschiedliche Ansätze?*, in *Digital Engineering Magazin*. 2005.
[88] Wang, L., et al., "Collaborative conceptual design--state of the art and future trends", *Computer-Aided Design*, 2002. Vol.**34**(13), pp. 981-996.
[89] Huang, G.Q., "Web-based support for collaborative product design review", *Computers in Industry*, 2002. Vol.**48**(1), pp. 71-88.
[90] Shiau, J.-Y. and H.M. Wee, "A distributed change control workflow for collaborative design network", *Computers in Industry*, 2008. Vol.**59**(2-3), pp. 119-127.
[91] Case, M.P. and S.C.Y. Lu, "Discourse model for collaborative design", *Computer-Aided Design*, 1996. Vol.**28**(5), pp. 333-345.
[92] Littler, D., F. Leverick, and M. Bruce, "Factors Affecting the Process of Collaborative Product Development: A Study of UK Manufacturers of Information and Communications Technology Products", *Journal of Product Innovation Management*, 1995. Vol.**12**(1), pp. 16-32.
[93] Tang, D., W. Eversheim, and G.G. Schuh, "A new generation of cooperative development paradigm in the tool and die making branch: strategy and technology", *Robotics and Computer-Integrated Manufacturing*, 2004. Vol.**20**(4), pp. 301-311.
[94] Aziz, H., et al., "Open standard, open source and peer-to-peer tools and methods for collaborative product development", *Computers in Industry*, 2005. Vol.**56**(3), pp. 260-271.
[95] Panchal, J.H., et al., 2004, "Designing design processes in product lifecycle management: Research issues and strategies", Salt Lake City, UT, United States: American Society of Mechanical Engineers, New York, NY 10016-5990, United States.
[96] Nyere, J., *The Design-Chain Operations Reference-Model*, Supply Chain Council (SCC).
[97] Lin, H.-Y., *A Robust Decision Model for Selecting Partners in Design Chain Management*, in *Graduate Institute of Industrial Engineering*. 2003, Feng Chia University.
[98] Wang, J. and H.Y. Lin, "A fuzzy hybrid decision-aid model for selecting partners in the design chain", *International Journal of Production Research*, 2006. Vol.**44**(10), pp. 2047 - 2069.
[99] Nagarajan, R.P., et al., 2004, "Performance Measures and Metrics for Collaborative Design Chain Management", *10th International Conference on Concurrent Enterprising*, Escuela Superior de Ingenieros, Seville, Spain.
[100] Teresa, W., X. Nan, and B. Jennifer, "Design and Implementation of a Distributed Information System for Collaborative Product Development", *Journal of Computing and Information Science in Engineering*, 2004. Vol.**4**(4), pp. 281-293.
[101] Chuang, W.-C. and H.-H. Yang, "Design Chain Collaboration– A Strategic View", *International. Journal of Electronic Business Management*, 2004. Vol.**2**(2), pp. 117-121.
[102] Huang, G.Q. and K.L. Mak, "WeBid: A web-based framework to support early supplier involvement in new product development", *Robotics and Computer-Integrated Manufacturing*, 2000. Vol.**16**(2-3), pp. 169-179.
[103] Tang, D. and X. Qian, "Product lifecycle management for automotive development focusing on supplier integration", *Computers in Industry*, 2008. Vol.**59**(2-3), pp. 288-295.
[104] Ding, L., et al., "Global optimization of a feature-based process sequence using GA and ANN techniques", *International Journal of Production Research*, 2005. Vol.**43**(15), pp. 3247 - 3272.
[105] Guo, Y., et al., 2007, "Operation sequencing optimisation for 5-axis prismatic parts using a particle swarm optimisation approach", *Proceedings of the 4th Int. Conference on Digital Enterprise Technology*, Bath, UK.
[106] Cavalieri, S., et al., "A decision-making framework for managing maintenance spare parts", *Production Planning and Control*, 2008. Vol.**19**(4), pp. 379-396.
[107] Macchi, M. and M. Garetti, "Information requirements for e-maintenance strategic planning: A benchmark study in complex production systems", *Computers in Industry*, 2006. Vol.**57**(6), pp. 581-594.
[108] Jun, H.-B., et al., "Predictive algorithm to determine the suitable time to change automotive engine oil", *Computers & Industrial Engineering*, 2006. Vol.**51**(4), pp. 671-683.
[109] Campos, J., "Development in the application of ICT in condition monitoring and maintenance", *Computers in Industry*, 2009. Vol.**60**(1), pp. 1-20.
[110] Zhang, W. and Y. Fan, *A Conceptual Framework for Product Lifecycle Modeling*, in *Proceedings of the First International Conference on Innovative Computing, Information and Control - Volume 2*. 2006, IEEE Computer Society.

[111]Thimm, G., et al., 2007, "An investigation into the early and retirement life-cycle stages: tools, requirements", *International Conference on Product Lifecycle Management (PLM07)*, Politecnico di Milano.
[112]*MIT, Auto-ID Lab*, *http://autoid.mit.edu/cs/*.
[113]*Cambridge Auto-ID lab*, *http://www.autoidlabs.org.uk/*.
[114]Brock, D.L., *The Physical Markup Language*, MIT AUTO-ID Center.
[115]Harrison, M., et al., 2004, "Information management in the product lifecycle - the role of networked RFID", *Industrial Informatics, 2004. INDIN '04. 2004 2nd IEEE International Conference on*.
[116]Jun, H.B., et al., "System architecture for closed-loop PLM", *International Journal of Computer Integrated Manufacturing*, 2007. Vol.**20**(7), pp. 684 - 698.
[117]*University of Bath, The Innovative Design & Manufacturing Research Centre*, *http://www.bath.ac.uk/idmrc/*.
[118]Daniel, J., A.J. Medland, and L.B. Newnes, 2007, "Graphical representation of key iterations during the design process", *International Conference on Engineerign Design (ICED) 07*, Paris.
[119]Liu, S., *A computational framework for retrieval of document fragments based on decomposition schemes in engineering information management*.
[120]*The National Institute of Standards and Technology (NIST), Manufacturing Engineering Laboratory (MEL)*, *http://www.mel.nist.gov/*.
[121]Foufou, S., et al., 2005, "A Core Product Model for PLM with an illustrative XML implementation", *International Conference on Product Lifecycle Management*.
[122]Qiao, G. and C. McLean, 2004, "Manufacturing Information Integration in Product Lifecycle Management (PLM)", *Proceedings of DETC'04, ASME 2004 Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Salt Lake City, Utah USA.
[123]Rachuri, S., et al., 2006, "The Role of Standards in Product Lifecycle Management Support", *PLM-SP2*
[124]*Process Specification language (PSL)*, *http://www.nist.gov/psl*. 2005.
[125]PRECISE, "https://engineering.purdue.edu/PRECISE/vision_htm".
[126]Iyer, N., et al., "Shape-based searching for product lifecycle applications", *Computer-Aided Design*, 2005. Vol.**37**(13), pp. 1435-1446.
[127]Hou, S., *Structure-oriented contour representation and matching for engineering shapes*.
[128]Li, Z., *Developing engineering ontology for information retrieval*.
[129]Grieves, M., "Back to the Future: Product Lifecycle Management and the Virtualization of Product Information ", in *Product Realization*. 2009, Springer. pp. 1-13.
[130]*University of Michigan, PLM Alliance*, *http://plm.engin.umich.edu/*.
[131]Patil, L., D. Dutta, and R. Sriram, 2005, "Ontology formalization of product semantics for Product Lifecycle Management", *Proceedings of IDETC/CIE 2005 ASME 2005 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference*, Longbeach, CA.
[132]Garetti, M., et al., 1997, "Design issues of an integrated software workbench supporting the manufacturing systems design process", Detroit, MI, USA: Chapman & Hall.
[133]Ma, Y.S. and T. Tong, "Associative feature modeling for concurrent engineering integration", *Computers in Industry*, 2003. Vol.**51**(1), pp. 51-71.
[134]Chen, G., et al., "Knowledge-Based Reasoning in a Unified Feature Modeling Scheme", *Computer Aided Design & Applications*, 2005. Vol.**2**(1–4), pp. 173–182.
[135]Halpern, M. and D. Miklovic. *Magic Quadrant for Manufacturing Product Life Cycle Management, 4Q07*. 2008 [cited; Available from: http://mediaproducts.gartner.com/reprints/oracle/153351.html.
[136]Macchi, M., et al. *The PLM Opportunities to Improve the Collaborative Strategies of Maintenance*. 2005 21-Nov-2005 [cited; Available from: http://www.plmentor.it/index.php?module=subjects&func=viewpage&pageid=20.
[137]*Siement PLM Software*. [cited 02/25/2009]; Available from: http://www.plm.automation.siemens.com/en_us/.
[138]*Dassault system*, *http://www.3ds.com/*.
[139]IBM. [cited 02/027/2009]; Available from: http://www-01.ibm.com/software/plm/.
[140]Oracle, *http://www.oracle.com/applications/agile/index.html*.
[141]PTC, *http://www.ptc.com/products/plm.htm*.
[142]SAP, *http://www.sap.com/solutions/business-suite/plm/index.epx*.

