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Development of a product lifecycle management model based on the fuzzy analytic hierarchy process

Marko Paavel*, Kristo Karjust, and Jüri Majak

Department of Machinery, Tallinn University of Technology, Ehitajate tee 5, 19086 Tallinn, Estonia

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Abstract. PLM and PDM are important tools in decision-making and management. This article suggests a way how to optimize and simplify the PLM or PDM implementation process with the PLM Maturity Model. It is shown how different benefits are linked with business dimensions and their sub-categories to get a better overview of the current situation. An expert group was involved in the evaluation process of the input and questions. The introduced maturity model is based on the FAHP method. The impact factors of the business dimensions are pointed out.

Key words: product lifecycle management, PLM maturity model, PLM functionalities, FAHP.

1. INTRODUCTION

Increasing competition is forcing companies to enhance their information systems, decision-making techniques, and processes. Small and medium-sized enterprises (SMEs) are forced to meet new challenges. One of the opportunities is to seek help from product lifecycle management (PLM). As defined by Stark, 'PLM is the business activity of managing, in the most effective way, a company's products all the way across their lifecycles; from the very first idea for a product all the way through until it's retired and disposed of' [1].

There are a number of different options how to simplify PLM or product data management (PDM) deployment. The PLM maturity model is one of the tools that help to evaluate the current situation in a company. The maturity model considered is based on the fuzzy analytic hierarchy process (FAHP). The FAHP is implemented by using the multi-criteria decision-making method.

* Corresponding author, Marko.Paavel@gmail.com

2. PLM IMPLEMENTATION

Implementing PLM does not mean only software implementation, but it also means a new way of thinking for all persons in an enterprise, i.e. new know-how. It might be necessary to change current activities and processes to support effective implementation of PLM [2–7].

PLM is a huge bundle of complex IT tools and applications that support digital design and manufacturing [8]. This means that during the integration phase a large number of important decisions have to be made to ensure successful implementation. After PLM implementation companies usually hope to get cost reduction, quality improvement, time saving, and better business decisions [9].

PLM implementation has to start with overall business vision description of the company. If the company's overall business vision objectives are described and a PLM vision is created, the next step is to describe and specify the PLM strategy and the PLM implementation strategy [1]. Even if the company does not create a

relevant document, for successful implementation it is necessary to think through the connected activities.

There are many ways how to simplify the implementation process. According to Stark [10], numerous objectives and strategies have to be formulated before implementation; these include

- the company's objectives, strategy, success factors, key issues;
- the PLM initiative;
- description of the PLM vision;
- next steps: PLM strategy, PLM implementation strategy, PLM roadmap, PLM plan, schedules, resources, value, cost, return on investment.

For a successful implementation process it is important to establish objectives and goals for the enterprise's PLM strategy, review all processes and data, and also train personnel for new processes [11].

The PLM Maturity Scorecard lists certain activities such as Mechanical Design Maturity, Electrical Design Maturity, and Software Design Maturity to the PLM maturity model, which support easier PLM implementation [12]. These give information about the current situation in a company.

3. BACKGROUND OF THE PLM MATURITY MODEL

There are three different approaches how to handle the current PLM maturity situation: (1) self-assessment means that company gathers information about its own capabilities and level of maturity; (2) third-party assisted assessment, where external specialists support the expertise; and (3) certified practitioners are used when the company's organization and technology are complex [13].

In the maturity model development six major phases can be distinguished (Fig. 1). In the first phase it is necessary to fix the scope and focus of the model. This will influence all the remaining phases in the model development and will show the focus of the model and how it differs from the other models. In the design phase

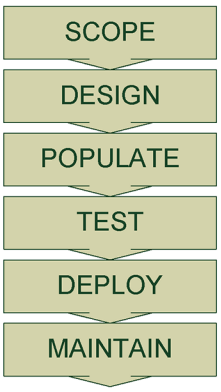

Fig. 1. Model development phases [14].

it is necessary to determine the design and architecture of the model and specify to whom it is addressed, what the application methods are, who will perform these actions, and whether it is required to specify the target group. In the populate phase it is decided what is measured and how it is done. In the test phase confirmation of relevance and reliability is to be acquired. During deployment the model is made available for use to verify the extent of its generalizability, and by maintenance continued relevance of the model has to be achieved [14].

A survey of maturity model business dimensions is given in Table 1.

The Batenburg PLM framework for the assessment and guidance of PLM implementation consists of five business dimensions: Strategy & Policy, Management & Control, Organization & Processes, People & Culture, and Information technology (Table 1). All dimensions are evaluated as Ad Hoc, Departmental, Organizational, or Inter-organizational [15]. PLM Strategy & Policy includes information acquisition about the company's PLM strategy, description of alignment with corporate strategy and evaluation, and PLM strategy incorporation into an action plan. The PLM strategy changes communication at all levels of the company [16].

Table 1. Maturity model business dimensions [17]

Batenburg [16]	Schuh [18]	Saaksvuori [9]	Stark [10]	Kärkkäinen [19,20]
1. Strategy & Policy	1. PLM definition	1. Process	1. Company	1. Strategy & Policy
2. Management & Control	2. PLM foundation	2. Structures	2. Product development	2. Management & Control
3. Organization & Processes	3. The set of processes reference models	3. IT systems	3. PDM	3. Organization & Processes
4. People & Culture	4. Vendor natural software description	4. PLM strategy		4. People & Culture
5. Information technology	5. PLM software support	5. People in PLM change management		5. Information Technology
	6. PLM knowledge base			6. Customer orientation
	7. PLM benefits			

In the Management & Control process working responsibilities for the time schedule, product delivery, and explicit processes are defined. There also time-to-market of new products and product quality after market introduction are monitored. Metrics for product quality are defined and it is known how to manage a product through its whole lifecycle. The statuses of the lifecycles of products are known and the rules of cost allocation are set during the product development phase [16].

Organization & Processes describes PLM processes and implemented procedures to support the PLM system. PLM process descriptions are standardized and maintained. Product lifecycle teams are organized. PLM leads the product release process including document revision and change management [16].

People & Culture demonstrates how tasks and job descriptions contain references to PLM processes and procedures. The concept and strategy are clearly understood and employees support these. Employees are actively participating in the implementation process and make suggestions how to influence product lifecycle decisions. It is shown how PLM training is valuable for the organization [16].

The Information technology dimension reflects how PLM software is used and integrated with other systems in the company and whether it is based on compatible industry and technology standards. All the processes are automated and document management works with product changes [16].

The Schuh framework involves seven maturity elements of PLM: PLM definition, PLM foundation, the set of processes reference models, vendor natural software description, PLM software support, PLM knowledge base, and PLM benefits (Table 1). The Schuh framework is based on process orientation in PLM. This is applied to guide implementation in industry. Companies can rely on a provided conceptual framework to establish their own framework linking the company element to the PLM environment [18].

The Saaksvuori framework gives a rough overview of how companies and their management teams can develop processes and information systems to get to a higher level. The model describes what phases a company usually goes through as it adapts itself to new cultural issues, processes, management practices, business concepts, and models of operation [9].

Stark described the maturity model for product data management (PDM) [1]. The company can be evaluated according to six different maturity stages: Traditional, Archipelago of PLM Islands, Frontier-crossing PLM, Enterprise-wide, Patchwork and Enterprise-wide, and Enterprise-deep. Assessable topics are Company, Product development, and PDM (Table 1) [1].

Kärkkäinen et al. [19] and Silventoinen et al. [20] included an extra business dimension – customer orientation. They claim that PLM implementation affects and causes changes in partners' processes. Maturity levels are divided into Chaotic, Conscientious, Managed, Advanced, and Integration [19,20].

Basically all evaluations in the maturity model start from the low level of knowledge and proceed up to a well integrated system where everyone is aware of PLM needs. Also PLM is deeply integrated into activities and processes.

4. PLM ELEMENTS IN THE MATURITY MODEL

There is also another approach to evaluating companies' PLM maturity. This consists in going deeper into PLM functionalities and using different PLM elements. Usually it is divided into three bigger categories: (1) PLM Organization examines how well the organization is structured, trained, operated, and managed to apply a PLM strategy and to work with PLM processes and tools. (2) PLM Processes explores the processes used to support PLM including communication, change control, collaboration both inside and outside of the organization, use of defined product development processes, management disciplines, etc. (3) PLM Technology determines the level of IT infrastructure and solution deployment available to support a PLM strategy including consistency of tool use, how data is maintained, maturity of tools, tool and information integration, etc. [21].

Tata Technologies, a company providing engineering services and product development IT, has brought out 17 important PLM elements that should be evaluated: Portfolio Management, Quality/Compliance Management, Requirements Management, Supplier Collaboration, Project/Resource Management, Manufacturing Process Workflow/Process Management, Maintenance, Repair, and Operations (MRO), Configuration/BOM Management, Reporting & Analytics, Classification Management, Collaboration, Component Management, Computer Aided (CAX) Integration, Document Management, Visualization, Change Management [21].

Zhang et. al. [22] proposed 15 PLM components based on the PLM functionalities. These 15 PLM components are maturity dimensions: techniques & practices, PLM software & applications, strategy & supervision, quality management, business management, maintenance management, bill of materials (BOM) management, PDM, financial management, people, distributed collaboration management, workflow & process management, eco-friendly & innovation, life cycle assessment, and green conception.

In addition, the essential elements of PLM should be used. These include Management of product data, product information, product design, process documents, product structure (bill of material); Central data vault (electronic file repository); Part and document classification and metadata ('attribute') management; Materials content identification for environmental compliance; Product-focused project task assignment; Workflow and process management for approving changes; Multi-user secured access, including 'electronic signature'; Data export for loading downstream enterprise resource planning (ERP) systems; and Requirements (functional, performance, quality, cost, physical factors, interoperability, time, etc.) [23,24].

Cholewa suggested the following classification of PLM fundamentals with the relevant percentages [25]:

- Product data management (20%)
- Product and process definition (15%)
- Configuration management (10%)
- Collaboration software (10%)
- Customer-oriented applications (10%)
- Visualization/Viewing (5%)
- Data exchange (5%)
- Supplier-oriented applications (5%)
- Definition and management of product lifecycle processes (5%)
- Project management (5%)
- Portfolio management (5%)
- Integration (5%).

Herein only a small number of different PLM elements, fundamentals, and functionalities were listed.

5. MATURITY MODEL COMPONENTS FOCUSING ON PLM ELEMENTS

The aim of the maturity model is to give information about the current situation. Usually companies start implementing a PLM system to get some kind of benefits. In this model benefits are divided into the following four larger categories that cover the majority of the expected benefits (Fig. 2):

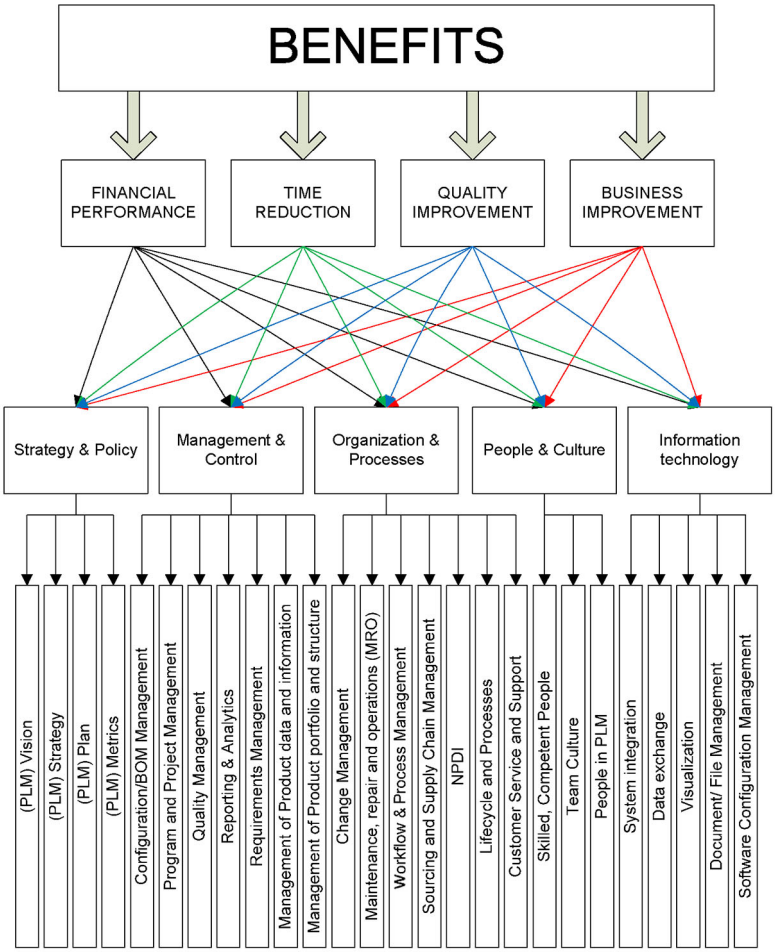

Fig. 2. Description of the PLM maturity model. NPDI – New Product Development and Introduction.

- Financial Performance
- Time Reduction
- Quality Improvement
- Business Improvement.

In the current study it is proposed that an extended PLM maturity model should be used so that PLM maturity could be valued in more specific fields. Batenburg's five business dimensions have subcategories, where main PLM functionalities, fundamentals, and elements are taken together and divided into smaller groups. These business dimensions with elements focused on subcategories would give a more exact overview and the company would have a better understanding of the current situation [10,26–28]. Figure 2 shows how these elements are combined together for a PLM maturity model. Based on benefits the expert group evaluated the readiness for different business dimensions.

6. MATURITY LEVELS OF THE ANALYSIS MODEL

Each business dimension and sub-dimension is evaluated according to Saaksvuori and Immonen PLM maturity model levels [9] as shown in Table 2, which gives an overview of the current situation. The same maturity levels are used to describe companies' expectations of their achievements.

7. FAHP METHOD FOR EVALUATING BUSINESS DIMENSIONS

In the PLM maturity model all five business dimensions are compared with one another according to their main benefits. Comparison is made based on expert group knowledge. The expert group consisted of Estonian specialists in academic and industrial fields.

The Analytic Hierarchy Process (AHP), proposed by Saaty [29], is a widely used method in multiple-attribute decision making [30]. It structures the alternatives into a hierarchical framework. Fuzzy Analytic Hierarchy Process (FAHP) is an extension of the AHP method, which uses fuzzy logic and also fuzzy sets and fuzzy numbers for determining the ranking of certain criteria [31].

Fuzzy Set Theory (FST) was introduced by Zadeh in 1965 to deal with uncertainty and vagueness [32]. A tilde (~) placed above a symbol refers to FST. A Triangular Fuzzy Number (TFN) is defined as a triplet (l, m, u) and the membership function can be defined by equation (1) [33].

Table 2. PLM maturity levels [9]

Level 1: Unstructured
The PLM topic has been recognized and its importance agreed. Work must be done to define and develop the PLM concept and standards. However, at present there are no defined approaches concerning lifecycle management; all lifecycle and product management issues are resolved by individuals on a case-by-case basis.
Level 2: Repeatable but intuitive
Lifecycle and product management processes have developed to the stage where similar procedures are followed by different people undertaking the same task (i.e. the processes function on ad hoc bases). There is no formal development, definition, training, or communication of standard processes; all responsibility is left to individuals. There is a high degree of reliance on individual knowledge and therefore errors occur.
Level 3: Defined
Lifecycle and product management processes have developed to the stage where similar procedures are followed by different people undertaking the same task (i.e. the processes function on ad hoc bases). There is no formal development, definition, training, or communication of standard processes; all responsibility is left to individuals. There is a high degree of reliance on individual knowledge and therefore errors occur.
Level 4: Managed and measurable
It is possible to monitor and measure the compliance between processes and to take action where processes are not functioning well. Processes and concepts are under constant improvement and provide best practices. IT systems support PLM processes well. Process automation is used in a partial or limited way. Processes and concepts are developed through clear vision throughout the corporation. The state of uniformity of processes is clear.
Level 5: Optimal
Processes and concepts have been refined to the level of best practice, based on continuous improvement and benchmarking with other organizations. IT is used in an integrated manner and process automation exists on an end-to-end basis.

$$\mu_A(x) = \begin{cases} 0 & x < 1, \\ \dfrac{x-l}{m-l} & l \le x \le m, \\ \dfrac{m-x}{u-m} & m \le x \le u, \\ 0 & x > u. \end{cases} \quad (1)$$

For evaluation Saaty's 9-point scale with fuzzy logic was used (see Table 3) [34].

The scores given by experts in terms of triangular fuzzy numbers for five decision criteria characterizing financial performance are presented in Table 4. These scores are based on pair-wise comparison of decision criteria considered.

The geometric means of fuzzy comparison values of all criteria are computed by using the following formulas [34]:

$$l_i = \left(\prod_{j=1}^{n} l_{ij} \right)^{\frac{1}{n}}, \quad (2)$$

$$m_i = \left(\prod_{j=1}^{n} m_{ij} \right)^{\frac{1}{n}}, \quad (3)$$

$$u_i = \left(\prod_{j=1}^{n} u_{ij} \right)^{\frac{1}{n}}, \quad (4)$$

where n stands for the number of decision criteria. The i-th triplet corresponding to geometric mean values reads

$$\overline{G_i} = (l_i, m_i, u_i). \quad (5)$$

The numerical values of the l_i, m_i, and u_i and their sums are presented in Table 5.

The eigenvectors of the relative importance in normalized form can be computed with Eq. (6) (see Table 6):

$$\left[\bar{l}_i,\ \overline{m}_i,\ \overline{u}_i\right] = \left[\frac{l_i}{\sum_{j=1}^{n} l_i}, \frac{m_i}{\sum_{j=1}^{n} m_i}, \frac{u_i}{\sum_{j=1}^{n} u_i} \right]. \quad (6)$$

In the following the consistency index CI and consistency ratio CR are calculated for m_i in order to make sure that the judgements remain at the limit of consistency. First the initial matrix of judgements m_{ij} is multiplied by normalized eigenvector $\overline{m}_j$, which results in the vector $\lambda_{\max}\omega$ as in [34].

$$\lambda_{\max\omega} = \sum_{j=1}^{n} m_{ij}\overline{m}_j = \begin{bmatrix} 2.07 \\ 1.43 \\ 0.75 \\ 0.43 \\ 0.40 \end{bmatrix}. \quad (7)$$

Table 3. Linguistic terms and the corresponding triangular fuzzy numbers [34]

Saaty's scale	Definition	Fuzzy Triangular Scale
1	Equally important	(1,1,1)
3	Weakly important	(2,3,4)
5	Fairly important	(4,5,6)
7	Strongly important	(6,7,8)
9	Absolutely important	(9,9,9)
2	Intermittent values	(1,2,3)
4	between two adjacent	(3,4,5)
6	scales	(5,6,7)
8		(7,8,9)

Table 5. Geometric means of fuzzy comparison values

Criterion	l_i	m_i	u_i
Strategy & Policy	1.783	2.491	3.129
Management & Control	1.217	1.719	2.352
Organization & Processes	0.608	0.922	1.351
People & Culture	0.441	0.530	0.699
Information technology	0.407	0.478	0.608
Total	4.456	6.140	8.139

Table 6. Eigenvectors of fuzzy comparison values

Criterion	$\bar{l}_i$	$\overline{m}_i$	$\overline{u}_i$
Strategy & Policy	0.40	0.41	0.38
Management & Control	0.27	0.28	0.29
Organization & Processes	0.14	0.15	0.17
People & Culture	0.10	0.09	0.09
Information technology	0.09	0.08	0.07

Table 4. The scores of experts in terms of triangular fuzzy numbers

Financial Performance	Strategy & Policy	Management & Control	Organization & Processes	People & Culture	Information technology
Strategy & Policy	(1,1,1)	(1,2,3)	(2,3,4)	(3,4,5)	(3,4,5)
Management & Control	(1/3,1/2,1)	(1,1,1)	(1,2,3)	(2,3,4)	(4,5,6)
Organization & Processes	(1/4,1/3,1/2)	(1/3,1/2,1)	(1,1,1)	(1,2,3)	(1,2,3)
People & Culture	(1/5,1/4,1/3)	(1/4,1/3,1/2)	(1/3,1/2,1)	(1,1,1)	(1,1,1)
Information technology	(1/5,1/4,1/3)	(1/6,1/5,1/4)	(1/3,1/2,1)	(1,1,1)	(1,1,1)

Table 7. Eigenvectors according to business dimensions

	Strategy & Policy	Management & Control	Organization & Processes	People & Culture	Information technology
Financial Performance	0.38–0.41	0.27–0.29	0.14–0.17	0.09–0.10	0.07–0.09
Time Reduction	0.07	0.12–0.13	0.25	0.38–0.40	0.16–0.17
Quality Improvement	0.10–0.11	0.14–0.18	0.31–0.35	0.30–0.31	0.10–0.11
Business Improvement	0.38–0.40	0.14–0.15	0.11	0.06–0.07	0.29

Next, the estimate of $\lambda_{\max}$ is obtained by dividing the components of the vector given in Eq. (7) by m_i and computing the average of the resulting vector. The $\lambda_{\max} = 5.07$ is obtained.

Finally, according to the approach proposed by Saaty, the consistency index CI and consistency ratio CR are computed as follows:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n-1} = 0.02, \qquad \mathrm{CR} = \frac{\mathrm{CI}}{1.12} = 0.02. \quad (8)$$

The constant 1.12 in (8) is determined by the dimension of the judgements matrix ($n = 5$). In general, the CR values less than 0.1 indicate that the judgements are at the limit of consistency. Thus, the obtained value of CR = 0.02 means that the results are trustworthy. Table 7 gives an overview how the expert group evaluated different business dimensions in view of different benefit groups.

The FAHP was used to get boundaries for different business dimensions. Eigenvectors reflect the current evaluation by the expert group for different business dimensions according to different benefit groups. Eigenvector boundaries show how much certain dimensions are more important than others. For example, in financial performance dealing with Strategy and Policy has the greatest effect.

8. CONCLUSION

The current paper presents a model for evaluating PLM maturity in SMEs. In the model development an expert group was involved to help to evaluate different business dimensions, questions, and answers. All the evaluation was done by using the FAHP model to get boundary conditions. Boundary conditions were calculated based on each benefit group for each business dimension.

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FAHP-meetodi baasil PLM-küpsusmudeli arendus

Marko Paavel, Kristo Karjust ja Jüri Majak

Tänapäeva keerukas maailmas otsivad ettevõtted konkurentsieelise saavutamiseks erinevaid võimalusi. Üks süsteemidest, mis võib ettevõttele sellise eelise anda, on PLM. Käesolevas artiklis on antud ülevaade, kuidas on toimunud PLM-küpsusmudeli arendus. Küpsusmudeli arendamisel on kasutatud ekspertgruppi ja FAHP-meetodit. Küpsusmudeli eesmärk on anda ülevaade ettevõtte PLM-i hetkevalmidusest ja eesmärkidest, milleni soovitakse jõuda. On välja toodud valdkondade piirid, mis kajastavad ettevõtte ootusi.