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# Practitioner requirements for integrated Knowledge Based Engineering in PLM

**Abstract.** The effective management of knowledge as capital is considered essential to the success of engineering product/service systems. As Knowledge Management and Product Lifecycle Management (PLM) practice gain industrial adoption the question of functional overlaps between both approaches becomes evident. This paper explores the interoperability between PLM and Knowledge Based Engineering (KBE) as a strategy for engineering KM. The opinion of key KBE/PLM practitioners are systematically captured and analysed. A set of ranked business functionalities to be fulfilled by the KBE/PLM systems integration is elicited. The paper provides insights for researchers and practitioners playing both user and development roles on the future needs for knowledge systems based on PLM.

**Keywords**: Product Lifecycle Management, Knowledge Based Engineering, Engineering Design, Computer Aided Design, Engineering Knowledge Management.

## 1 Introduction

The recognition that engineering design practice is the means to deliver product/service systems rather than just artefact descriptions matures alongside the development of engineering oriented IT systems. The current PLM vision evolved through several generations of computer aided design tools including early geometric modelling, solid modelling and Product Data Management (PDM). This evolution has seen the increasing role of computer mediated design work coordination integrated with engineering problem solving technologies that support the analysis, synthesis and evaluation of product solutions. The combination of different schools of thought in engineering design research and practice has contributed to this progressive contextualisation of the product engineering function as part of a larger socio-technical system, (Figure 1).

Modern engineering design practice needs to pay special attention to the socio-technical context in which it happens. This means that in addition to technical challenges, soft organisational constraints affect the performance of the design process, (O´Donell and Duffy 2005). The work of (Hobday 1998, Eckert and Clarkson 2003) highlight the difficulties in managing large scale design projects in which socio-technical issues appear. In these situations, the deterministic design process models tend to fail and mechanisms to manage its complexity are needed, (Eckert and Clarkson 2005). The research community has proposed frameworks like the Design Structure Matrix to manage this complexity from different viewpoints, (Steward 1981, Eppinger et al. 1990, Kusiak and Wang 1993, Sharman and Yassine 2004). However, engineering projects go though various series of iterations not only to execute the design work but also to find and exchange information, to consolidate agreements, to select suppliers and other non-purely technical decisions and tasks. It has been quantified by (Hales 1993, Crabtree et al. 1997) that these activities are 50% of the workload of engineering design teams. Human factors play an important role as it has been described by Siemieniuch and Sinclair (2006). This would explain some research results highlighting that engineering organisations are paying increasing attention to the soft skills of their engineering designers (Hong et al. 2005, Robinson et al. 2005). These skills include: “personal attributes”, “project management skills”, “clarity of project targets” and “shared knowledge about customers”.

Another socio-technical issue affecting engineering operations is the geographical dispersion of teams in global projects. In these conditions, networked enterprise systems like PLM are becoming the only option to coordinate geographically dispersed engineering activities. They also provide an infrastructure for data storage, distribution and management. Until recently, PLM is primarily seen as the technology to provide a repository for intellectual capital for the Knowledge Management practice, (Str.Direction 2005b). A practical question is how to retain and capitalise the large amounts of engineering information stored in PLM repositories as intellectual property assets. McMahon et al. 2005 proposes the use of formal knowledge representation approaches for:

- Enriching the semantics of engineering data entities such as Computer Aided Design (CAD) files.
- Supporting the capture of engineering decision making processes as well as the information sources that trigger them.

The rest of the paper explores these issues and is structured as follows. Section 2 gives a background on KBE. KBE can be used as a KM tool to support the codification and personalisation of knowledge. Section 3 presents the integration of KBE and PLM for Knowledge Management. Section 4 describes the methodology used for research with industrial practitioners. Section 5 reports the interview results and discusses the relevant findings in respect to the KBE/PLM integration. Section 6 draws conclusions from the research.

## 2 KBE as a Knowledge Management instrument

In the 1980s, the integration of Artificial Intelligence (AI) techniques in CAD tools created the early of KBE systems. The first commercial success of the technology was *The ICAD System*. The software uses a LISP-based language closely integrated with a geometric modeller so engineers can encode engineering knowledge and run data generation programs. In the early 1990s KBE technology was used primarily by the aerospace and automotive industries. In the late 90s CAE vendors at the high end of the market (i.e. *Catia* and *Unigraphics*) started to include KBE functionalities in their CAD suites, (McMahon 2004). Following *Dassault Systems'* acquisition of the company that owed *ICAD*, *Autodesk* acquired the company responsible for *Intent!* with the aim of offering KBE functionalities on its products, (Dassault-Systems 2002, CimDATA 2005). Similarly, the *Unigraphics' Knowledge Fusion* software product offering KBE functionality has its origins in a strategic partnership in which *Intent!* technology was transferred to the system, (Li et al. 2000b). As KBE becomes part of the CAD systems, Str.Direction (2005a) reports that medium size engineering firms are increasing the uptake of KBE technology. In essence, KBE enables the semantic enrichment of Computer Aided Design (CAD) models so explicit engineering knowledge can be embedded. More importantly, KBE technology supports Knowledge Management by the systematic retention of engineering problem solving procedures, (Cooper et al. 1999).

It is widely recognised that Knowledge Management is a key practice for 21st century organisations to capitalise their expertise and know-how. Various sources of literature acknowledge the current debate on the role of computing technology in KM, (Call 2005, Tsui 2005). The inseparability of KM from computer-based support has been discussed by Holsapple (2005). His research acknowledges the importance of Information and Communication Technologies (ICTs) to speed up knowledge intensive work carried out by individuals, groups and systems. In the engineering domain, McMahon (2004) distinguishes between ICTs is used to personalise and codify knowledge. Personalization refers to computer tools that support the management of human resources and communication. Codification is the use of ICTs for collecting and organising knowledge. According to the author, examples of codification tools are KBE systems and ontology editors. Computer supported collaborative work (CSCW) and web-based communities of practice are personalisation tools.

*2.1 Codification and personalisation aspects of KBE*

KBE tools encode the engineering data generation processes using specialised languages to control the instantiation of software objects in CAD systems. Using the generative modelling capabilities, engineers can model the creation of a wide range of engineering data elements (geometry, bills of material, etc.). KBE runs explicitly defined engineering rules to control the instantiation of the data. Engineering rules enrich CAD data from multiple engineering viewpoints including that of manufacturing, ergonomics, and many others.

. KBE software tools "out of the box" are just codification Knowledge Management instruments(Bates et al. 1997, Chapman and Pinfold 1999, Lovett et al. 2000, Kulon et al. 2006). However, much of the value of KBE as part of a Knowledge Management strategy is its role as a personalisation KM instrument. Gaining the benefits of KBE as a personalisation instrument requires methodological support and organisational endorsement rather than just software. The implementation of KBE encourages the following beneficial KM practices:

- **Analysis of engineering activities**. KBE projects usually start with the identification of a routine or variant engineering task suitable to be automated. Identifying a business case for KBE is in itself a continuous improvement engineering practice. Furthermore, deploying KBE has other beneficial side effects like standardising terminologies, clarifying procedures and identifying engineering decisions.
- **Identification of multidisciplinary knowledge areas necessary to solve engineering problems**. KBE implementations usually integrate engineering rules from different knowledge domains. Their elicitation is an interdisciplinary exchange of information, knowledge sharing and the establishment of collaboration networks.
- **Documentation of engineering best practices**. Either by using structured KBE codes or more informal descriptions, the knowledge about engineering procedures is explicitly retained in a way that otherwise would remain tacit.
- **Making more efficient the work that is not fully supported by software systems**. Bespoke software could be developed to automated any engineering tasks. However, software development usually involves high costs not only to code the engineering activities but to capture knowledge . KBE is a cost-effective computational solution for engineering jobs in which automation is needed and bespoke software development is expensive.

A unique approach to realise both the codification and personalisation KM capabilities of KBE is the Methodology and Tools for Knowledge Based Engineering (MOKA), reported by Stokes (2001). Using MOKA, major aerospace and automotive companies have deployed KBE as an enterprise best practice rather than just as a solution for automating certain engineering tasks. In addition to KBE codification tools, MOKA´s methodological support includes procedures to interview experts, ontological schemas to organise the knowledge and tools for representing and publishing the knowledge across the organisation. However, MOKA makes no specific commitments to the management of knowledge. Observations from industrial MOKA implementations have revealed the use of extensions of the methodology to support the management of changes in knowledge repositories.

## 3 Towards integrated KBE in PLM

This paper identifies the potential of the integration between KBE and PLM. KBE systems can be used as knowledge authoring tools to model engineering tasks. Their use as a codification instrument can be complemented by PLM as the personalisation instrument. This approach allows the use of ICT mediated mechanism to share, reuse and maintain KBE resources across PLM connected engineering teams. The functional interoperability between both technologies brings the opportunity to realise "out of the box" KM solutions. This would significantly reduce the investments in KM technology and culture change for large as well as small organisations. End user acceptance of KM using the well known tools of KBE and PLM technologies shall be easier compared with the introduction of disruptive systems and frameworks.

The integration of KBE within product lifecycle systems is discussed by Penoyer et al. (2000) as a need for future engineering support tools. Subrahmanian et al. (2005) suggests that a possible path to realise the PLM concept as a strategy for knowledge capitalisation is by leveraging the integration between existing standards related to PLM. This includes not only product engineering data schemas but also other standards for structured information modelling and knowledge representation. Similarly, a KBE/PLM integration roadmap has been proposed by the Prostep-iViP association in the context of a study on strategic product engineering areas subject up to the year 2010. According to this work, a combination of different standards on information and data modelling like STEP, UML, XML and others shall contribute to realise the integration, (Lukas et al. 2005). It is expected that standard based semantic modelling will play a significant role in these initiatives. Examples of these standard modelling frameworks are the Semantic Web for e-business and web based systems supported by the W3 Concsortium, (Daconta et al. 2003) and the Model Driven Architecture framework (MDA) for interoperability between IT systems, owned by the Object Management Group (OMG), (Mellor et al. 2004). In particular, the OMG plays a proactive role in establishing standards to achieve software interoperability in a variety of strategic application domains. Domain Task Forces (DTFs) cover areas in Business Modelling & Integration, C4I, Finance, Government, Healthcare, Life Sciences Research, Robotics, Software-Based Communications, and Manufacturing Technology & Industrial Systems (MANTIS). DTFs are composed of representatives from industry, academia and government agencies. In 2004, the MANTIS Task Force identified that KBE is maturing to become a significant software application for the manufacturing industry. The interests of OMG members in KBE are related to the prediction of the kind of software applications needed to support product/service systems in the knowledge economy, and the associated interoperability issues, OMG (2005).

### *3.1 Challenges for the KBE/PLM integration*

A major factor to achieve success in KBE/PLM interoperability is the expectations from end users of the technology. Both technologies have a certain level of maturity on large aerospace and automotive companies. The expertise gained by engineering teams in these organisations forms an important input to clarify the business functionalities of the integration. While the use of 3D and CAD was a relatively mature reality when the ISO-STEP initiative was launched, systematic enterprise management of engineering knowledge to support product/service systems is still an emerging concept. The major aerospace and automotive OEMs are still exploring the product/service business concepts. Investment in the software technology to deliver the vision is seen as a cost and the responsibility of the vendors who shall benefit from cross selling the technology to a wider user space. Two major challenges for the KBE/PLM interoperability are identified in the research:

- The ability to unlock engineering knowledge from proprietary representations.
- The ability to manage the lifecycle of KBE models.

The need to unlock engineering knowledge representations becomes evident when proprietary KBE models need to be exchanged between two systems. This interoperability problem is illustrated in Figure 2. Using two different KBE platforms and their respective languages, CAD models are "knowledge-enriched" to generate engineering design data. The two KBE applications can have the same engineering abstraction of the entities to be instantiated and the set of rules that govern the data generation. However, using current data exchange standards, it is only possible to transfer an instance of the design and not the knowledge embodied to generate it.

This example points out that being able to produce the same part using different KBE applications implies that there is some semantic equivalency between the knowledge abstraction metamodels in the two systems. The unification of engineering design knowledge models is a subject of intensive research, (Sim and Duffy 2003). Initiatives in this are gaining momentum thanks to the adoption of semantic modelling standards. An early attempt for building engineering semantic models is the EXPRESS language created during the STEP standardisation efforts, (ISO10303-11 1994). Other research efforts are MOKA, the Core Product Model and its extensions, (Rachuri et al. 2005, Sudarsan et al. 2005). These formalisms use the Unified Modelling Language (UML) to define engineering information metamodels independent from particular software platforms. Similarly, the WEBKIDSS approach uses the Semantic Web modelling languages to respond to the same need (Zha and Du 2006a, Zha and Du 2006b). Despite the availability of representation formalisms, interoperability and knowledge exchange between them is a common issue, (Yao and Etzkorn 2006).

In addition to the ability to connect KBE systems, the management of KBE models is perceived by engineering practitioners as a major challenge. It is expected that achieving the interoperability between KBE and PLM enables coordination of KBE development work. In current practice, specialised teams deploy KBE to engineering units across the organisation whenever opportunities to gain benefits from the technology are identified. The KM opportunity is the use of PLM technology to coordinate KBE deployment activities. This implies the definition of KBE models as software services whose lifecycle is managed using existing PLM functionalities (Figure 3).

An example of this is the deployment of KBE application that captures the knowledge about the design of aircraft wing ribs as a software service. The application becomes an “item” that can be retrieved or re-engineered according to users’ needs. T This KBE service could then be used by other designers in other aircraft design programmes or validated by manufacturing and servicing engineers in later stages of the KM lifecycle.

It has been pointed out by Sharma (2005) that KBE design automation models should be driven by PLM for enhanced enterprise visibility and reuse. The benefits for managing knowledge to make KBE codes become more transparent to non-programming experts have been reported in Fan et al. (2002). This include better maintenance of KBE models that otherwise would become difficult to adapt to changes. Finally, managing the lifecycle of KBE models involves the continuous improvement through validation and feedback from the users. Industrial KBE practitioners participating in this research recognise this as a bottleneck that could be supported with PLM mediated service management.

## 4 Research methodology

The objective of the research is to elicit strategic requirements for the KBE/PLM integration from engineering practitioners. A qualitative study has been designed to collect and analyse data from KBE and PLM experts. Interviews and other qualitative research methods are common tools to elicit the needs for future support systems in engineering design research, (Li et al. 2000a, Lowe et al. 2004). The seven practitioners who took part of in this study have been selected to ensure that they meet the following key features:

- They have responsibilities closely related to KBE and PLM implementation. In particular, all the interviewees hold leading positions in their organisations related to KBE technology. The only exception is one participant who recently retired from his position after more than 20 years of KBE development activity in a large aerospace Original Equipment Manufacturing (OEM) organisation.
- They have significant experience on the deployment of KBE technology and exposure to KM and PLM practice. All the participants have been users of the first KBE system in the market (ICAD) and have seen the evolution of the technology since then. All of them have more than 10 years experience in KBE.
- They belong to engineering organisations large enough to have a corporate strategy for KBE implementation and PLM interoperability. This includes one member of an academic institution. She has been in charge of KBE in several research programmes in the aerospace domain. All the participants declared in the study that the integration of KBE and PLM is part of their vision of future product realisation technologies.

Table 1 gives information about the participants in terms of the organisations to which they belong and their roles in to KBE and PLM technologies. An initial data collection and analysis to elicit the business functions to be fulfilled by the KBE/PLM integration was carried out through a literature survey. This has been reported in Sections 1 to 3. Further data gathering uses unstructured interviews with some of the selected practitioners and other KBE/PLM technologists. In these sessions, the challenges described in Section 3.1 guided the discussion. The analysis of interview transcripts and meeting notes helps to narrow down a definitive set of 10 business functionalities.

The final set of data for the research has been gathered from the selected practitioners with the aim to rank the importance of the elicited business functions. This part of the research was carried out through interviews guided by a structured questionnaire, (see Appendix A). The final outcome of the study is a ranked set of business functionalities that the interviewed participants expect to be fulfilled from the KBE/PLM integration. The criteria for ranking the business functionalities is based on the relevance that participants assign to each of them according to its alignment to their short and long term KBE/PLM integration strategies. Values from 1 to 5 are assigned to each of the business functions in order to weight their importance, with 1 and 5 represent the minimum and the maximum relevance respectively.

## 5 Results and discussion

The results from the research are a set of business functionalities expressing the practitioners' requirements for integrated KBE systems in PLM. The quantitative significance of the ranking results is limited due to the small data sample. However, a qualitative analysis of the data considering the background of the participants and the value of their inputs provides useful insights. There are only a small number of KBE teams in large organisations. It is difficult to know accurately the total number of KBE team leaders in industry and consequently estimate the size of a relevant research sample. On the other hand, the participant's selected is representative of the distribution of KBE experts across the engineering community. Most KBE technology users are in large OEM organisations (4 representatives in the study). The second most common type of KBE users are in consultancy services. The study includes two representatives from this group: one form a large international engineering consultancy firm; and another one from a leading PLM/KBE software vendor. The last participant represents the academic/research community.

Table 2 illustrates the elicited business functions ranked by the average of the importance assigned by the participants. An example of application for each business function is also given. In general, there is consensus on the importance of the business functions presented and on their relevance distribution.

The high relevance perceived regarding the modularity and easiness to develop KBE models (top business function) confirms the evolution and the market trends discussed in Section 2. As KBE becomes a mainstream practice users demand more user friendly modelling functions so non-specialised engineers can benefit from the technology. In particular, the aerospace interviewees recognise the need of making the technology more modular and reducing the entry skills to gain its benefits. However, they acknowledged that they frequently operate complex KBE applications involving hundreds of software objects and thousands of code lines. The development of this kind of KBE software services are likely to be commissioned to specialised teams using a traditional hard-coding KBE approach like in the ICAD system or other alternatives in the market.

The second most appreciated business function is aligned with the challenge to manage KBE services within a PLM environment. It can be noticed that the coordination of KBE development work is more appreciated than the KBE interoperability challenge (5th business function). 5 out of the 7 interviewed experts consider the use of PLM to coordinate KBE work as "highly relevant" and 3 of them identify the issue as part of their short term strategy. Aligned to this view, (Siemieniuch and Sinclair 1999) recognise that in competitive environments knowledge has a lifecycle that includes its creation, propagation and retirement across the organisation. A representative from a major PLM and KBE software vendor summarises these ideas as follows:

> Definitely, exposing the components of a KBE solution in PLM has the same power as exposing the component artefacts of an engineering design in PLM. You can search and re-use at a much finer level of granularity, and you can approach the problems of versioning, maturity, release management and configuration management methodically and in a unified manner. Note that mature users of KBE now realize that the second-tier problem with KBE is solution management, configuration and reuse.

The transparency of KBE is appreciated by the participants as a socio-technical barrier for the effective deployment of the technology (4th business function). Making more transparent the functionality of KBE models reduces the fears to take up into KBE as it is no longer perceived as a "black art". Moreover, model transparency also correlates with the ability to manage KBE deployment work. The knowledge embedded in KBE models can not be validated if it is not visible to the users. This issue is pointed out in the following quotation from a participant:

> Transparency is critical for the success of KBE within the traditional enterprises. If it is perceived as a "club" or only for "elite" engineers, it will not succeed. It must become "democratized". But transparency, as well as interoperability, will require the development of strong and relevant standards.

The concern on formal knowledge representation (3rd business function) expresses the willingness of KBE users to exploit fundamental innovation like structured knowledge representation. This aspect is emphasised by the presence of semantic web services and service oriented architectures as business functions (9th and 10th business functions). It is also remarkable that the KBE/PLM integration raises expectations on traditional KM best practices. Knowledge reuse, sharing and maintenance are acknowledged by KBE users in the 6th, the 7th and the 8th business functions respectively. Such business functions seem to be associated to the analogy made on the use of PLM technology to distribute manage and store product data. These perceptions can be summarised with the following question: why not use PLM to manage the lifecycle of engineering knowledge in a similar way as it is done with engineering data “items”?

Discussions during the interviews confirmed the consensus on the importance for all the elicited business cases. This suggests that the elicited business cases are positively correlated. Improvement on one of them is likely to impact positively on the others. Apart from the 10 elicited business functionalities, two additional concerns are identified as a common pattern across the different interviewed practitioners:

- The prevention of possible “knowledge leaks” when KBE services become items on a PLM infrastructure. This raises the question beyond the generic 7th business function on how KBE services integrated in PLM will protect the intellectual property embedded in engineering rules and other knowledge models.
- The role of ISO 10303 and related standards in the KBE/PLM integration. There is common agreement among the practitioners on the need of additional information modelling infrastructure to capture the semantics of engineering processes encoded in KBE. However, it is considered that the KBE/PLM integration shall use STEP data models in combination with semantic modelling approaches.

## 6 Concluding remarks

The research reported here illustrates the consensus in the engineering community to strive towards interoperability between KBE and PLM systems. The participation by the community of engineering software users and vendors identified the major challenges to be addressed in KBE/PLM system integration. Concrete business functionalities for the KBE/PLM interoperability are elicited and ranked.

This research contributes to the understanding of the needs for future PLM-based KM systems and their associated interoperability issues. The integration of KBE/PLM systems plays two valuable business roles for product engineering tool users and vendors:

A) As a knowledge retention strategy adapted to the socio-technical reality of product engineering practice.

The capture of knowledge about an engineering product or process at certain point in time is only short term knowledge retention. Making KBE and PLM interoperable fulfils the business functionality of managing the lifecycle of engineering knowledge to sustain a KBE infrastructure in the long term. PLM can be used to coordinate the knowledge capture and encoding processes to consolidate enterprise knowledge retention and the deployment of KBE services. In addition, global competition in the product/service engineering practice will become unaffordable for unnetworked teams and undistributed innovation chains. The exchange of data, information and knowledge (and the control to stop so) will increasingly need to be carried out through the use of ICTs. PLM is the emerging paradigm for supporting these activities as connectivity and coordination framework.

B) As a Potential framework for "out of the box" engineering KM toolsets.

It is widely accepted that enterprise culture and readiness to adapt is a crucial factor for the success of KM initiatives, (Choi and Lee 2002, Siemieniuch and Sinclair 2002). For instance, the MOKA methodology was built upon extensive KBE practice at large automotive and aerospace manufacturers. However, it is difficult for smaller organisations to appreciate a Knowledge Management approach to KBE like MOKA. In these cases, built-in PLM functionalities such as file change management can be used to update and approve KBE applications. In this approach, knowledge reuse and sharing is enforced through the use of the PLM system as a repository for existing KBE enriched CAD or KBE code files embedding best practices into engineering rules. Similarly, knowledge maintenance is supported by a managed way of deploying KBE applications through a PLM networked organisation.

Further architectural integration of the technologies shall support the exchange of knowledge between highly structured KBE codes and other unstructured representations available in the PLM databases. As PLM technology becomes a repository for engineering data, domain specific metadata models are progressively emerging to annotate many forms of semi-structured information available in engineering environments such as drawings, pictures and many others. More structured knowledge models may also be populated within PLM databases to accurately classify and map the relationships between more abstract engineering concepts such as product functions and specifications. In the former case, flat metadata models in combination with searching tools will suffice to classify knowledge and make it available to end users. In the latter, the need to add formal semantics to the models will require the use of more advanced information modelling such as ontologies. In the journey to KBE integrated in PLM the use of semantic modelling standards will play a significant role in the management of engineering knowledge. The achievement of this vision will require the participation of specialist teams responsible not only to administer PLM systems but also to act as curators of the engineering knowledge. The end users of these enterprise knowledge infrastructures shall benefit from the ability to have up to date knowledge at the right time and the right place.

Finally, the findings help to create a research agenda leading to further stages of KM/PLM integration research and standardisation. Two areas are suggested for future research action:

- The study of socio-technical issues in the coordination of engineering KM activities through networked enterprise systems. On one hand, the building of trust through IT systems in distributed teams needs to be investigated in order to enable PLM-based KM operations. On the other hand, the understanding of collaborative learning processes in distributed engineering teams is a key input to develop knowledge lifecycle management strategies.
- The exploration of emergent IT technologies to become engineering Knowledge Management infrastructures. This includes strategies to support the interoperability between different enterprise domains. A promising concept in this direction is the MDA approach supported by the OMG. Although the concept it is on its early stage, results from using the approach for model-based IT system development are starting to be delivered. The spreading out of MDA into engineering environments raises expectations.

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## References

Bates, J. P., Morris, A. J. and Payne, P. N. (1997). 'Knowledge-based geometric modelling of aircraft structures'. *Proceedings of the Institution of Mechanical Engineers - Part G.* Vol. 211, pp. 273-284.

Call, D. (2005). 'Knowledge management - not rocket science'. *Journal of Knowledge Management.* Vol. 9, No. 2, pp. 19-30.

Chapman, C. B. and Pinfold, M. (1999). 'Design engineering - a need to rethink the solution using knowledge based engineering'. *Knowledge-Based Systems.* Vol. 12, pp. 257-267.

Choi, B. and Lee, H. (2002). 'Knowledge management and its link to knowledge creation process'. *Expert Systems with Applications.* Vol. 23, pp. 173-187.

CimDATA (2005). 'Autodesk acquires Engineering Intent Corporation'. *CimDATA PLM Industry Summary Online Archive.* WWW document: http://cimdata.com/newsletter/2005/42/03/42.03.01.htm (accessed 16th August 2006).

Cooper, S., Fan, I.-S. and Li, G. (1999). 'A Best Practice Guide – Achieving Competitive Advantage through Knowledge-Based Engineering'. *British Department of Trade and Industry (DTI).* WWW document: http://www.ds-kti.com/pdf/kti_dti.pdf (accessed 18th May 2006).

Crabtree, R. A., Fox, M. S. and Baid, M. K. (1997). 'Case studies of coordination activities and problems in collaborative design'. *Research in Engineering Design.* Vol. 9, pp. 70-84.

Daconta, M. C., Obrst, L. J. and Smith, K. T. (2003). *The semantic web: A guide to the future of XML, web services, and knowledge management.* John Willey & Sons. ISBN: 0471432571.

Dassault-Systems (2002). 'Dassault Systems acquires Knowledge Technologies International'. *Dassault Systems Press Room*. WWW document: http://www.3ds.com/se/news-events/press-room/release/796/1/ (accessed 16 August 2006).

Eckert, C. M. and Clarkson, P. J. (2003). The reality of design process planning. In: *Research for Practice - Innovation in Products and Processes. International Conference on Engineering Design. ICED'03*. edited by: Folkeson, A., Gralen, K., Norell, M. and Sellgren, U. The Design Society.ISBN: 1904670008.

Eckert, C. M. and Clarkson, P. J. (2005). The reality of design. In: *Design process improvement. A review of current practice*. edited by: Eckert, C. M. and Clarkson, P. J. Springer-Verlag.ISBN: 185233701X.

Eppinger, S. D., Whitney, D. E. and Smith, R. P. (1990). Organizing the Tasks in Complex Design Projects. In: ASME Conference on Design Theory and Methodology, Chicago, Illinois, American Society of Mechanical Engineers.

Fan, I.-S., Li, G., Lagos-Hernández, M. and Bermell-Garcia, P. (2002). A rule-level knowledge management system for knowledge-based engineering applications. In: Proceedings of DETC’02, ASME International 22nd Computers and Information in Engineering, (CIE) Conference, Montreal, Canada, 29 September – 2 October, American Society of Mechanical Engineers.

Hales, C. (1993). *Managing engineering design*. Longman/John Wiley & Sons Harlow/New york. ISBN: 0582039339.

Hobday, M. (1998). 'Product complexity, innovation and industrial organisation'. *Research Policy.* Vol. 26, No. 6,April 1998, pp. 689-710.

Holsapple, C. W. (2005). 'The inseparability of modern knowledge management and computer-based technology'. *Journal of Knowledge Management.* Vol. 9, No. 1, pp. 42-52.

Hong, P., Vonderembse, M. A., Doll, W. J. and Nahm, A. Y. (2005). 'Role change of design engineers in product development'. *Journal of Operations Management.* Vol. 24, pp. 63-79.

ISO10303-11 (1994). 'Industrial automation systems and integration -- Product data representation and exchange -- Part 11: Description methods: The EXPRESS language reference manual'. *International Organization for Standardization, ISO.*

Kulon, J., Mynors, D. J. and Broomhead, P. (2006). 'A knowledge-based engineering design tool for metal forging'. *Journal of Materials Processing Technology.* Vol. 177, pp. 331-335.

Kusiak, A. and Wang, J. (1993). 'Decomposition of the design process'. *Journal of Mechanical Design.* Vol. 115, No. 4,pp. 687-695.

Li, G., Bracewell, R. H. and Wallace, K. M. (2000a). A knowledge framework to support engineering design. In: 7th ISPE International Conference on Concurrent Engineering, Lyon, France, 17-20 July 2000, International Society for Productivity Enhancement.

Li, G., Cooper, S. and Fan, I.-S. (2000b). KBE application and research in the UK. In: Proceedings of the International Conference on Advanced Manufacturing Systems and Manufacturing Automation, AMSMA 2000, Guangzhou, China, 19-21 June.

Lovett, P. J., Ingram, A. and Bancroft, C. (2000). 'Knowledge-based engineering for SMEs - a methodology'. *Journal of materials processing technology.* pp. 384-389.

Lowe, A., Chris, M. and Culley, S. (2004). 'Characterising the requirements of engineering information systems'. *International Journal of Information Management.* Vol. 24, pp. 401-422.

Lukas, U. v., Krause, F.-L., Rothenburg, U., Wöhler, T., Romahn, A., Anderl, R., Melk, K., Awiszus, B., Ufer, R., Binotsch, C., Schützer, K. and Gemignani, B. H. (2005). Engineering 2010: Setting the course for innovative engineering. VMM Wirtschaftsverlag.

McMahon, C. (2004). 'Knowledge management in engineering design: personalization and codification'. *Journal of Engineering Design.* Vol. 15, No. 4,pp. 307-325.

**Formatted:** German (Germany)

McMahon, C., Giess, M. and Culley, S. (2005). 'Information management for through life product support: the curation of digital engineering data'. *International Journal of Product Lifecycle Management.* Vol. 1, No. 1,pp. 26-42.

Mellor, S. J., Scott, K., Uhl, A. and Weise, D. (2004). *MDA distilled: principles of model-driven architecture*. Addison Wesley. ISBN: 0201788918.

O´Donell, F. J. and Duffy, A. H. B. (2005). *Design performance*. Springer-Verlag London. ISBN: 185233889X.

OMG (2005). '"KBE services for PLM" Request for Proposal. OMG document: dtc/05-09-11'. *The Object Managment Group*. WWW document: http://www.omg.org/cgi-bin/doc?dtc/2005-9-11 (accessed 16th August 2006).

Penoyer, J. A., Burnett, G., Fawcet, D. J. and Liou, S.-Y. (2000). 'Knowledge based product life cycle systems: principles of integration of KBE and C3P'. *Computer aided design.* Vol. 32, pp. 311-320.

Rachuri, S., Baysal, M., Roy, U., Foufou, S., Bock, C., Fenves, S. J., Subrahmanian, E., Lyons, K. and Sriram, R. D. (2005). 'Information models for product representation: core and assembly models'. *International Journal of Product Development.* Vol. 2, No. 3, pp. 207-235.

Robinson, M. A., Sparrow, P. R., Clegg, C. and Birdi, K. (2005). 'Design engineering competencies: future requirements and predicted changes in the forthcoming decade'. *Design Studies.* Vol. 26, pp. 123-153.

Sharma, A. (2005). 'Collaborative product innovation: integrating elements of CPI via PLM framework'. *Computer aided design.* Vol. 37, No. 13, pp. 1425-1434.

Sharman, D. and Yassine, A. (2004). 'Characterizing Complex Product Architectures'. *Systems Engineering.* Vol. 7, No. 1, pp. 35-60.

Siemieniuch, C. E. and Sinclair, M. A. (1999). 'Organizational aspects of knowledge lifecycle management in manufacturing'. *International Journal on Human-Computer Studies.* Vol. 51, pp. 517-547.

Siemieniuch, C. E. and Sinclair, M. A. (2002). 'On complexity, process ownership and organisational learning in manufacturing organisations, from an ergonomics perspective'. *Applied Ergonomics.* Vol. 33, pp. 449-462.

Siemieniuch, C. E. and Sinclair, M. A. (2006). 'Systems Integration'. *Applied Ergonomics.* Vol. 37, No. 1, pp. 91-110.

Sim, S. K. and Duffy, A. H. B. (2003). 'Towards an ontology of generic engineering design activities'. *Research in Engineering Design.* Vol. 14, pp. 200-223.

Steward, D. V. (1981). 'The design structure system: a method for managing the design of complex systems'. *IEEE Transactions on Engineering Management.* Vol. 28, No. 3, August 1981, pp. 71-74.

Stokes, M. (2001). *Managing engineering knowledge: MOKA methodology for knowledge based engineering applications*. Professional Engineering Publishing London. ISBN: 1860582958.

Str.Direction (2005a). 'Engineering automation for the SME: a viable tool for "mass" customisation'. *Strategic Direction.* Vol. 21, No. 1, pp. 1-35.

Str.Direction (2005b). 'Widening appreciation of PLM. Investing in delivering innovation'. *Strategic Direction.* Vol. 21, No. 9, pp. 35-37.

Subrahmanian, E., Rachuri, S., Fenves, S. J. and Foufou, S. (2005). 'Product lifecycle management support: a challenge in supporting product design and manufacturing in a networked economy'. *International Journal of Product Lifecycle Management.* Vol. 1, No. 1, pp. 4-25.

Sudarsan, R., Fenves, S. J., Sriram, R. D. and Wang, F. (2005). 'A product information modelling framework for product lifecycle management'. *Computer aided design.* Vol. 37, No. 13, pp. 1399-1411.

Tsui, E. (2005). 'The role of IT in KM: where are we now and where are we heading?' *Journal of Knowledge Management.* Vol. 9, No. 1, pp. 3-6.

Yao, H. and Etzkorn, L. (2006). 'Automated conversion between different knowledge representation formats'. *Knowledge-Based Systems.* Vol. 19, No. 6, pp. 404-412.

Zha, X. F. and Du, H. (2006a). 'Knowledge-intensive collaborative design modelling and support. Part I: Review, distributed models and framework'. *Computers in Industry.* Vol. 57, pp. 39-55.

Zha, X. F. and Du, H. (2006b). 'Knowledge-intensive collaborative design modelling and support. Part II: System implementation and application'. *Computers in Industry.* Vol. 57, pp. 56-71.

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## Appendix A. Questionnaire on KBE/PLM integration issues

The following questions describe 10 issues to be supported by the integration of PLM and KBE technology. The text between the parentheses is aimed to clarify each issue description. We ask you to evaluate their relevance in your domain.

- Support the interoperability between KBE systems. (KBE application from KBE system “a” can be used in KBE system “b”)
- Support for increasing the transparency of KBE application functionalities and data processing. (Information processing of KBE applications can be visualised by non KBE experts)
- Support for increasing the reuse of existing KBE applications across domains and projects. (KBE applications can be more easily retrieved and re-engineered to be usable on more situations)
- Support for increasing the efficiency in maintaining and updating KBE applications. (KBE applications can be more efficiently adapted to the changes of the knowledge)
- Support for modularity and easier development of KBE applications. (KBE applications can be more easily created by assembling existing documented components)
- Support for the management of service-oriented KBE infrastructure. (KBE applications can be deployed as services across the network to be discovered and reused more intensively)
- Support for the KBE generation of engineering data through semantic web services. (KBE applications can be deployed as semantic web services that users discover and access in order to generate engineering data)
- Support for the management of intellectual property stored in PLM. (Engineering knowledge stored in the PLM infrastructure is used as an input for KBE applications and vice-versa)
- Support for engineering change management of KBE applications in PLM. (KBE application engineering change requests can be supported by PLM ECM infrastructure)
- Support for more formal knowledge representation methods both in KBE. (KBE systems and PLM solutions allow the deployment of formal conceptual models and advanced inference/reasoning mechanisms)

The possible answers to each of these questions are:

a. Not a relevant issue

b. Some relevance but not in my domain

c. Some relevance in my domain. Part of a long-term strategy

d. Highly relevant issue in my domain. Not in my short term strategy

e. Highly relevant issue in my domain. Part of my short term strategy.

Additional space is provided in the questionnaire to add comments.

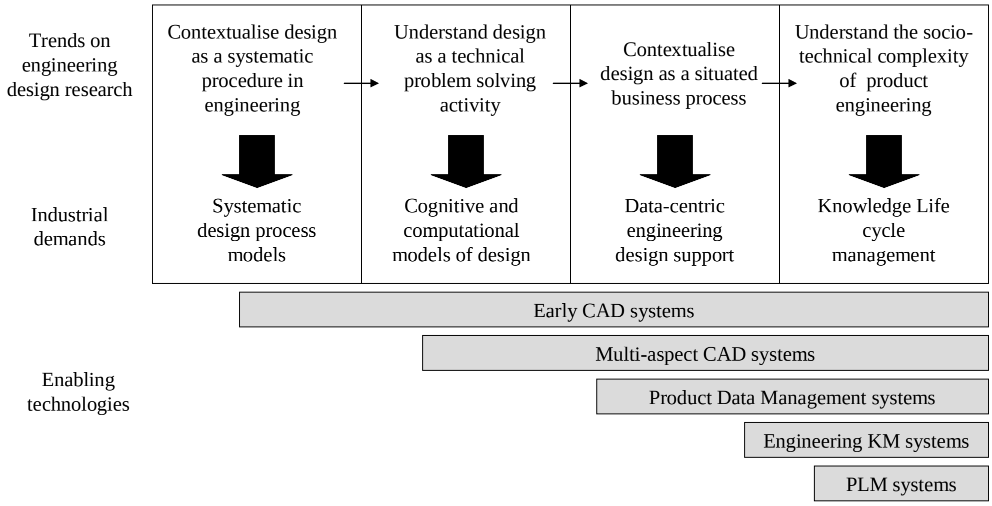


Figure 1. Engineering design practice evolution.

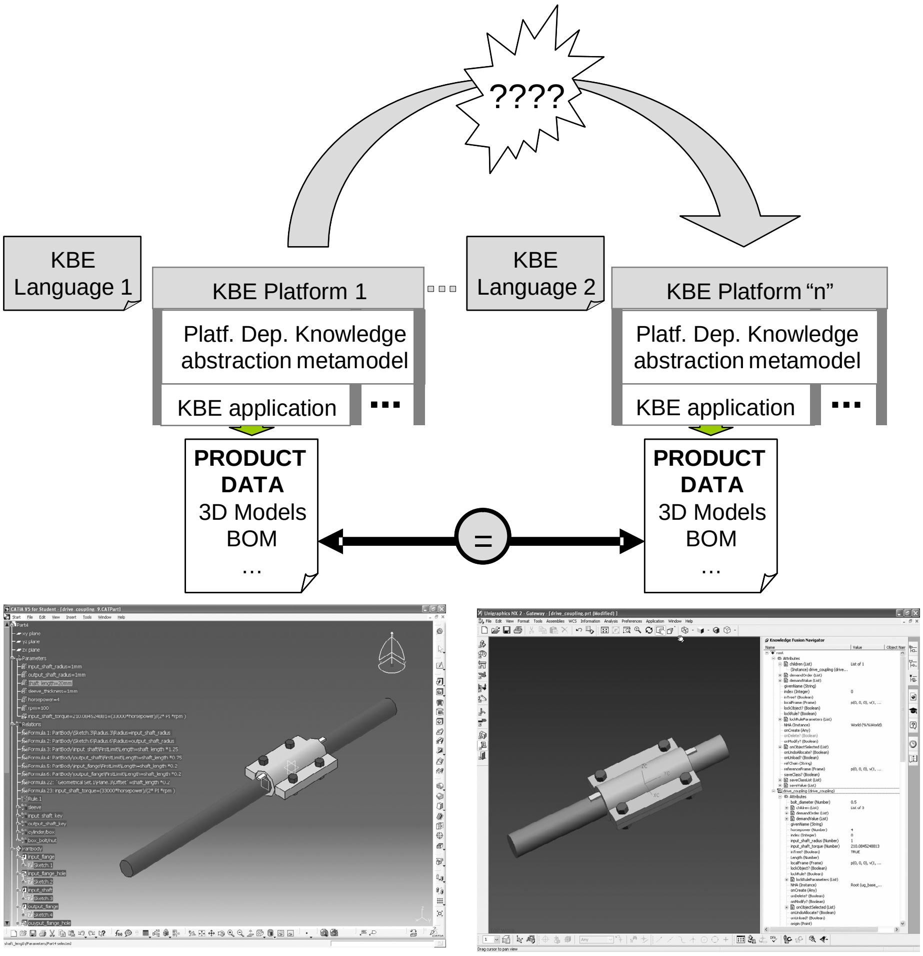


Figure 2. Challenge for KBE interoperability

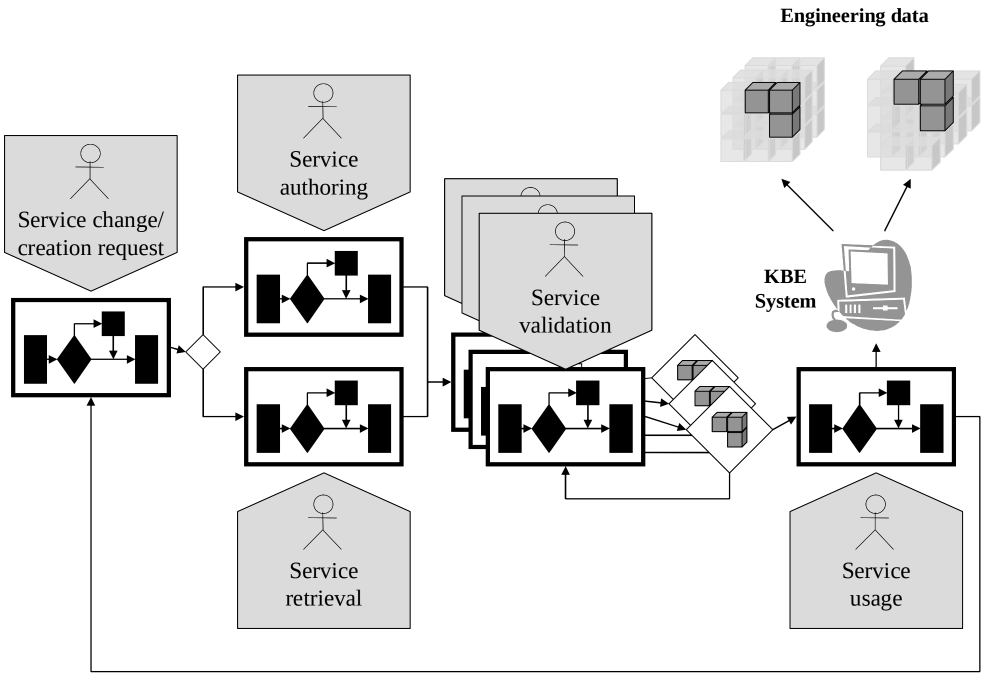


Figure 3. Lifecycle management of KBE software services.

Table 1. Business functions for the KBE/PLM integration

| | *Average perceived importance* | *Business functions to be supported by the KBE/PLM integration* | *Examples of application* |
|---|---|---|---|
| **1** | 4.57 | The modularity and easier development of KBE applications | KBE applications can be more easily created by assembling existing documented components |
| **2** | 4.43 | The increase of efficiency in maintaining and updating KBE applications | KBE applications can be more efficiently adapted to changes in the knowledge |
| **3** | 4.43 | The use of formal knowledge representation methods for both KBE and PLM | KBE systems and PLM solutions enable the deployment of formal conceptual models and advanced inference/reasoning mechanisms |
| **4** | 4.14 | The increase of transparency of KBE application functionalities and data processing | Information processing in KBE applications can be better visualised by non KBE experts |
| **5** | 4 | The interoperability between KBE systems | KBE application from KBE system "A" can be used in KBE system "B" |
| **6** | 4 | The increase of the reuse of existing KBE applications across domains and projects | KBE applications are more easily retrieved and reengineered to be usable in more situations |
| **7** | 4 | The management of in intellectual property stored in PLM | Engineering knowledge stored in PLM repositories is used as an input for KBE applications and vice-versa |
| **8** | 4 | The engineering change management of KBE applications through PLM | The change requests for KBE applications can be supported by the engineering change management functionalities in PLM |
| **9** | 3.71 | The management of service oriented KBE infrastructure | KBE applications can be deployed as services across the network to be discovered and reused |
| **10** | 3.29 | The KBE generation of data through semantic web services | KBE applications are deployed as semantic web services that user discover and access in order to generate engineering data |

Table 2. Information about the participants in the study.

| | Organisation type | Organisation size | Position in the organisation | Role in respect to KBE | | | Role in respect to PLM | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | **D** (1) | **U** (2) | **S** (3) | **IR** (4) | **A** (5) | **U** (6) | **D** (7) |
| **Participant 1** | Consultancy/ Software vendor | Between 1000 and 2000 employees | R&D director | X | | X | | | | X |
| **Participant 2** | OEM aerospace | More than 2000 employees | Senior aerospace engineer | X | X | X | X | X | X | |
| **Participant 3** | OEM aerospace | More than 2000 employees | KBE product line manager | X | | X | X | | | |
| **Participant 4** | OEM aerospace | More than 2000 employees | Associate Technical Fellow | X | | | | | X | |
| **Participant 5** | Consultancy | More than 2000 employees | Engineering automation deputy manager | X | | | | | X | |
| **Participant 6** | OEM aerospace | More than 2000 employees | Knowledge engineering team leader | | | X | X | | | |
| **Participant 7** | Research org. | Between 1000 and 2000 employees | Lecturer and aerospace engineering course director | X | X | | X | X | X | |

(1) Developer of KBE applications; (2) User of KBE applications; (3) Provider of software support for both KBE users and developers; (4) Part of the team responsible for implementing PLM in the organisation; (5) Administrator of a PLM solution in the organisation; (6) User of the PLM solution in the organisation; (7) Part of a PLM software development team.