Knowledge enabled engineering

M. Bertoni, C. Johansson, A. Bertoni
Department of Mechanical Engineering, Blekinge Institute of Technology, Sweden.

Abstract

The development of complex product-service combinations challenges the existing practices for engineering knowledge management. The objective of the paper is to highlight how such practices need to change to meet the engineers' demand for knowledge when developing "functions" instead of merely hardware. It further proposes Knowledge Enabled Engineering (KEE) as an umbrella term that collects engineering knowledge management methods and tools inspired by the *second wave of knowledge management,* and that are aimed to meet needs of today's modern knowledge workers in engineering organizations. The current state of readiness of these approaches is eventually described together with results from verification and validation activities.

Keywords: Knowledge Enabled Engineering, Knowledge Based System, Knowledge Management, Product Development, Engineering Design.

1 Introduction

Product-oriented organizations are increasingly shifting their scope from selling 'hardware' to providing 'functions' with the purpose of delivering added value to customers [1]. Aerospace companies, for instance, have started to take on lifecycle responsibilities by extending their traditional hardware-centered offers with different combinations of services and software. When developing such offers, engineers are no longer solving merely the hardware problems [2], because maintenance, repair, and overhaul become a cost for the provider instead of a source of profit [3]. The incentive to reduce operational costs turns into the need of simulating a range of usage scenarios early in the design process, to make the offer profitable from a business point of view [1].

One aspect of this transition is concurrent engineering [4]: design activities become more overlapping, information sharing across company functions more frequent and bilateral, and engineers have to pay attention to business/service considerations in addition to more traditional product properties [5].

Available engineering knowledge management support is today closely coupled to the knowledge for solving engineering-specific problems, and is bound to geometry modeling. This fits with hardware-focused projects [5] where the innovation strategy is relatively incremental and methods for solving the problems are available, but does not address the problem of capturing a broader spectrum of knowledge to enable early multi-disciplinary simulations to be populated and executed [6]. Hence, the objective of the paper is to highlight how engineering knowledge management practices need to change to meet the engineers' demand for knowledge when developing "functions" instead of merely hardware. It proposes Knowledge Enabled Engineering (KEE) as an umbrella term that collects engineering knowledge management approaches, inspired by the *second wave of knowledge management* [7], and meets the need of modern knowledge workers in engineering organizations.

The findings of this research have been collected from empirical work mainly conducted within two research projects in the European Commission's FP6 and FP7 programs, and within a Swedish Research profile on *Model Driven Development and Decision Support*. The research can be methodologically likened to action research [8]. It has featured close industry-academia partnerships, with numerous multi-day workshops, virtual meetings and company site visits. The discussion with the manufacturing companies in the diagnosis stage has contributed to the definition of the problem area chosen to investigate. Invention and reflective learning have been aided by the continuous participation in debriefing activities by the research team in relation to the work-meetings.

2 Engineering knowledge support: a literature review

Since the introduction of computers, knowledge has been used to automate engineering chains in a computer-based environment. The objective of Knowledge Based Systems (KBS) is to attain knowledge related to a specific task from expert people, and to transform it into *if-then* rules [9]. Rule Based Systems [10] are an instantiation of KBS that uses rules to make deductions or choices. Case Based Reasoning (CBR) evolved from Rule-Based systems [11]: it resembles human reasoning when looking for design solutions, and was initially used to capture and automate engineering and design in the aircraft industry. KBE has evolved from CBR to include facts and rules in a defined product model, to help engineers in the process of understanding and reasoning about the behaviour of a product.

The basic assumption of KBS is that both knowledge and experience can be captured and archived in textual or rule-based form, using formalization methods such as MOKA or CommonKADS, to automate the generation of solution concepts. This approach is acknowledged (e.g., in [7]) as the *first wave of knowledge management*, and concerns the formalization of individuals' tacit knowledge and its distribution to other individuals in the organization.

According to Mourtisen and Larsen [7] a major problem with this approach is that knowledge, as opposed to data or information, is always found with the employees directly involved in the company's environment. A *second wave of knowledge management* is then proposed: it considers social capital, and not only human capital, as core component of a knowledge management strategy. This wave emerges from observing the growing virtualization of partnerships and consortia, which makes individuals increasingly loosely coupled [12]. This challenges the informal, spontaneous and relatively unstructured interactions considered natural in co-located teams [6]. Engineers are working together with more people than ever before, but often with very limited knowledge of whom they are actually working with, what their collaborators know, and to what extent they can be trusted [6]. This implies a different set of knowledge sharing queries when addressing the problem of developing knowledge support tools for engineering designers in the new context (Table 1).

Table 1: Differences between First and Second Wave of knowledge [7]

Research question	**First wave**	**Second wave**
Why is knowledge shared?	Managerial needs	Part of daily work: as a routine
When is knowledge shared?	When there is an opportunity to do so	When there is a need to do so
Where is knowledge shared?	Operational level	Organisation-wide
Whose knowledge is managed?	Individual: human capital	Collective: social capital
What knowledge is shared?	Codified	Tacit and codified
How is knowledge shared?	Repository systems and electronic networks	Via personal and electronic networks

3 Expanding KBS: needfinding from the empirical study

3.1 Need #1: Creating and exploiting social connections

Developing *functions* instead of *hardware* means being able, early on, to use simulation models to verify whether the physical product will be exposed to conditions that will affect its function along the lifecycle. This knowledge is found to be dispersed across a wide range of individuals: looking, for instance, to an aero-engine, maintenance experts, technicians, sales people, airport technical service personnel, and even cabin crew may provide useful tips on how to operate, service or maintain the hardware at best [13]. The new problem context emphasizes the need to assist knowledge workers in more exploratory activities [6], which are *"…more concerned with recall (maximizing the number of possibly relevant objects that are retrieved) than precision (minimizing the number of possibly irrelevant objects that are retrieved)* [14]."

While KBS focus on formalizing design and manufacturing knowledge into rules, they are not suited to capture knowledge about usage processes [15]. Also, their focus on *codification* [15] contrasts with the stakeholder´s motivation to share what they know. As shown by the resistance to first wave initiatives, knowledge sharing cannot be forced: people will only share knowledge if there is a personal reason to do so, and if the trade-off between perceived benefit and sharing effort is kept below a given threshold [16]. Furthermore, KBS accessibility is often limited to groups and functions [17]. This is problematic for designers, because facts and experiences normally recorded in local databases are not visible early in the design process [13].

The empirical study stresses the need for an environment where opportunities for innovation can be discovered outside the designers' usual network of connections [6]. This means supporting more explorative search activities than the ones enabled by KBS systems. The final aim is to make knowledge from the later system lifecycle phases more visible, to model and simulate the behaviour of a system earlier in the design process than what happens today. This is achieved by developing knowledge support tools that facilitate users in "stumbling upon" relevant knowledge, in browsing a wide variety of topics that makes sense to others, and in gaining a deeper understanding of what knowledge other people find useful and how they choose to deploy that knowledge.

3.2 Need #2: Capturing working information and contextual knowledge

Understanding is a complex but essential issue within concurrent product development. For instance, aero-engines can be maintained in service for more than 40 years: if problems arise, engineers have to understand the issue by tracing it back to its roots. The information created along the course of the work - lessons learned, rationale and arguments related to choices made by the team - is crucial to avoid pitfalls in future development projects. The empirical study showed that such *working information* is seldom preserved in the same way as more formal project documentation. Lessons learned, rationale and arguments cannot simply be extracted from the latter: a richer description of the situation/context in which they were generated is needed to be correctly understood. Such contextual knowledge is normally spread across emails, phone calls, telephone/personal meetings, workshops and lunch talks. Eventually, *working information* is poorly traceable and difficult to apply in new projects.

3.3 Need #3: Retrieving applicable knowledge

The empirical study showed that the organizational memory literally grows by the hour, making it progressively difficult to retrieve information and knowledge applicable to the task at hand. A design specialist referred to the usage of traditional knowledge engineering tools as "go fish", making reference to the classic card game. Designers' reuse intention is perceived as the key element to successful knowledge retrieval. This emphasizes the role of context-based filtering within the domain of engineering design: if the context for the search query is known, in fact, it is possible to anticipate the type of result that will be useful, and refine the query accordingly, providing more tailored knowledge to people with similar profiles [18].

3.4 Need #4: Managing uncertainty in the knowledge base

Decision makers need to know, when analysing a trade-off, to what extent the figures related to a given design parameter (e.g., the results of the simulation) are reliable, or if they are based on flawed, uncertain or missing information, lacking of completeness, trustworthiness or accuracy [19]. This is particularly true when the knowledge foundation for decisions encompasses a wide range of disciplines and is built on the input of a wide network of peers. The empirical study shows that raising the awareness of what these flaws entail is a first step towards increasing decision makers confidence in the trade-offs they need to make. A strategy to deal with these issues is perhaps not to directly focus on reducing the uncertainty, rather to assist the decision makers in achieving a better understanding of what those ambiguities and assumptions actually involve [20]. In some areas engineers might be able to "live with" a certain degree of uncertainty, whereas in other areas it is crucial that you have complete certainty.

A major finding is that engineers need methods and tools that raise awareness on uncertainties in the decision, and that display assumptions, ingrained views, and provisional results in a way they are not mistaken for verified facts.

4 What's new in KEE? Technologies and applications

Social media are strong candidate technologies to cope with the needs presented above. They can create connections among individuals, escalate conversations and build more trustworthy relationships between engineering designers and other individuals across functions and companies.

Blogs have emerged as a platform for early feedback from external stakeholders and employees, allowing them to engage in discussions on product and service offers. Wikis provide a space to define (and refine) best practices from the different lifecycle phases: in this way ideas for future products can be collaboratively grown on a day-to-day basis, instead that at the decision gate as it happens today. Forums are intended to scale up internal conversations to experts in the network, managing heavily moderated topical conversations over a prolonged period. Microblogs are seen as a tool to spread innovative ideas, quotes, or links that may allow others to give real-time and focused feedback on technical or service matters, fostering professional connections.

Engineering specialists acknowledge that social media, by gathering information about what people consider relevant in a given role or discipline (such as the most viewed, commented, recommended, tagged or best-rated documents) can complement a search query to provide more tailored knowledge for the task at hand. An example of how these social mechanisms can be translated in an engineering environment is the Knowledge-Enabled Solution Platform (KESP) [21]. The KESP is a context-based application, and self-learning software system, that provides a way to learn the relationship between knowledge elements and the description of the context in which they have been applied. The engineers' profile is firstly described by using six contextual dimensions, which are: Product, Process, Project, Gate, Role, and Discipline. Then, the KESP filters knowledge elements in a query on the basis of what other users with a similar profile have found to be relevant for them. Eventually, the system asks every user to assess the applicability of what retrieved, to refine future searches.

Knowledge Maturity [22] has further been proposed as an enabler for Knowledge Enabled Engineering. It uses three dimensions - Input, Method and Expertise - to assess the level of readiness and confidence of a knowledge item in a given design task. The initial *generic* knowledge maturity scale, going from 5 (*excellent)* to 1 (*inferior)*, is cascaded down to *contextualized* scales, adapted to a specific task. *The latter* make it easier to assess what methods are specifically mature in the working context, what competences are needed, and what input data quality is requested in the task.

Table 2 summarizes the outcomes of the empirical study, outlining the difference between KBS and KEE. While KBS target traditional engineering situations, focusing on the technical verification of the product requirements, KEE addresses the exploration of different combinations of hardware, software and services to deliver the highest possible value along the lifecycle of the system.

Table 2: The KEE framework

	KBS	**KEE**
Output of the development process	Products + service add-ons	Systems of hardware/software/services
Composition of the development team	Mainly engineers	Cross-functional team members
Purpose of the development process	Requirements fulfillment	Value fulfillment
Focus of development activities	Validation/verification	Exploration
Type of knowledge supported	Mainly design and manufacturing knowledge	Knowledge related to the entire lifecycle
Methods and tools for knowledge sharing	Comparably heavyweight	Comparably lightweight
Strategy for knowledge sharing	Codification	Personalization
Approach to decision making	Eliminating ambiguity	Raising awareness about ambiguity

5 Conclusions

The paper proposes the KEE framework, with associated methods and tools, to facilitate the work of the *knowledge engineer*, the person in a company who is responsible for 'engineering' knowledge bases, and of the *knowledge worker*, who use such knowledge for accomplishing his/her everyday tasks.

The KEE enablers presented here feature different levels of readiness: while some are at a proof-of-concept stage, others are more mature and thoughtfully validated in an industrial environment. The use of social media to support engineering design decisions was verified in design sessions with students and in an industrial setting, in collaboration with an aero-engine sub-systems manufacturer [23]. The KESP was successfully experimented in a laboratory environment, with regards to the development of a turbine rotor [21]. A contextualized Knowledge Maturity scale for market assessment was created to assist in decisions concerning an offer development process [22], and to support the design of an aero-engine turbine compressor case [24]. A target for KEE research is to demonstrate the applicability of the above technologies in the engineers' operational environment. A step in this direction is the recent experimental activities that have aimed at generating experimental predictions about the use of KEE tools within design episodes [25].

6 Acknowledgments

Financial support from the EU FP6 VIVACE project (grant agreement n° 502917), EU FP7 CRESCENDO project (grant agreement n° 234344) and the Swedish Knowledge and Competence Development Foundation (through the MD3S research profile at Blekinge Institute of Technology) is acknowledged.

6.1 References

[1] Alonso-Rasgado, T., Thompson G. and Elfström B.-Ö. (2004): The design of functional (total care) products, Journal of Engineering Design, 15:6: 515-540.
[2] Morelli, N. (2002). Product-Service Systems, a Perspective Shift for Designers: A Case Study: the Design of a Telecentre, Design Studies, 24(1): 73–99.
[3] Isaksson, O., Larsson, T.C. and Rönnbäck, A.Ö. (2009). Development of product-Service Systems: Challenges and Opportunities for the manufacturing firm, Journal of Engineering Design, 20(4): 329-348.
[4] Prasad, B. (1996). Concurrent Engineering Fundamentals, Vol.1, Prentice Hall, Upper Suddle River, NJ, 478p.
[5] Baxter, D., Roy, R., Doultsinoua, A., Gaob, J. and Kaltac, M. (2009). A Knowledge Management Framework to Support Product-Service Systems Design, Journal of Computer Integrated Manufacturing, 22(12): 1073-1088,
[6] Larsson, A., Ericson, Å., Larsson, T., Isaksson, O. and Bertoni, M. (2010). Engineering 2.0: Exploring Lightweight Technologies for the Virtual Enterprise, in Randall, D. and Salembier, P. (ed) From CSCW to Web 2.0: European Developments in Collaborative Design, Computer Supported Cooperative Work, Springer-Verlag London,173-191.
[7] Mouritsen, J. and Larsen, H.T. (2005). The 2nd wave of knowledge management: The management control of knowledge resources through intellectual capital information, Management Accounting Research, 16(4): 371-394.
[8] Stringer ET (1999) Action Research, 2nd edn. Sage, Thousand Oaks.
[9] Chapman, C.B. and Pinfold, M. (2001). The application of a knowledge based engineering approach to the rapid design and analysis of an automotive structures, Advances in Engineering Software, 32(12): 903-912.
[10] Gupta, A., Forgy, C., and Newell, A. (1989). High-speed implementations of rule-based Systems, ACM Transactions on Computer Systems, 7: 119-146.

[11]Dixon, J.R. (1995). Knowledge-Based Systems for Design. Special 50th Anniversary Design Issue. Transactions of ASME, 117:11-16.
[12]Davidow, W.H. and Malone, M.S. (1993). The Virtual Corporation: structuring and revitalizing the corporation for the 21st century, Harper Business, New York.
[13]Bertoni, M. and Larsson, A. (2011). Engineering 2.0: an approach to support cross-functional teams in overcoming the knowledge sharing barriers in PSS design. International Journal of Product Development, 15(1/2/3): 115-34.
[14]Marchionini, G. (2006). Exploratory Search: From Finding to Understanding, Communications of the ACM, 49(4): 41-46.
[15]Ammar-Khodja, S., Perry, N. and Bernard, A. (2008). Processing knowledge to support knowledge-based engineering systems specification, Concurrent Engineering: Research and Applications, 16(1): 89–101.
[16]Bertoni, M., Larsson, A., Ericson, Å., Chirumalla K., Larsson T., Isaksson, O. and Randall, D. (2012) The rise of social product development. International Journal of Networking and Virtual Organizations, 11(2):188-207.
[17]Vroom, R.W. and Olieman, A.M. (2011). Sharing relevant knowledge within product development, International Journal of Product Development, 14(1–4): 34-52.
[18]Rehman, F.U. and Yan, X.T. (2011). Application of context knowledge in supporting conceptual design decision-making, International Journal of Product Development, 13(1): 47-66.
[19]Flanagan, T., Eckert, C., and Clarkson, P.J. (2007). Externalizing tacit overview knowledge: A model-based approach to supporting design teams. Artificial Intelligence for Engineering Design, Analysis and Manufacturing, 21: 227–242.
[20]Stacey, M. and Eckert, C. (2003). Against ambiguity, Computer Supported Cooperative Work, 12: 153-183.
[21]Redon, R., Larsson, A., Leblond, R., and Longueville, B. (2007). VIVACE Context Based Search Platform, Proceedings of CONTEXT´07, Roskilde, Denmark, 2007, Springer-Verlag, Berlin, pp. 397–410.
[22]Johansson, C., Hicks, B., Larsson, A. and Bertoni, M. (2011) Knowledge maturity as a means to support decision making during product-service systems development projects in the aerospace sector, Project Management Journal, 42(2): 32-50.
[23]Chirumalla, K., Bertoni, M., and Johansson, C. (2013). Experience feedback using social media: from the product lifecycle phases to the design practices. In Meier, H. (ed), Product-Service Integration for Sustainable Solutions, pp.459-471.
[24]Bertoni, M., Bertoni, A., Broeze, H., Dubourg, G., & Sandhurst, C., (2014). Using 3D CAD models for value visualization: an approach with SIEMENS NX HD3D Visual Reporting, Computer-Aided Design and Applications, 11(3): 284-294.
[25]Bertoni A., Bertoni M., Johansson C. (2015). Analysing the effects of value drivers and knowledge maturity in preliminary design decision-making. 20th International Conference on Engineering Design, in press.