Systems Engineering meets Knowledge Management: Introducing a 'System of Knowledge Management Approaches'

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Abstract

This paper highlights the complementarity between systems engineering (SE) and knowledge management (KM); in doing so, it offers a platform from which the development of both disciplines could be accelerated. By drawing attention to some of the challenges in the practice of SE and, in keeping with Martin (2002), the authors suggest that embedding relevant KM practice within SE practice may assist 'traditional' SE in meeting the demands of engineering current and future systems. Specific attention is paid to the importance of creating a knowledge sharing culture in SE practice and guidance is offered as to knowledge sharing methods which might be used effectively in particular SE settings.

The paper begins by identifying some of the challenges that SE faces in contemporary practice. The focus then moves on to knowledge and its management. After an introduction to the distinctions between data, information and knowledge, and to a representative cycle of KM, emphasis is placed on the process of knowledge sharing and the characteristics of a knowledge sharing culture. Discussion moves on from the cultural dimension of knowledge sharing and into the contexts and environments of SE practice. Jackson and Keys' (1984) System of Systems Methodologies (SofSM) is introduced to trigger a taxonomical theme for the rest of the paper. In a similar way that Flood and Jackson (1991) link the SofSM to problem contexts, the authors overlay their taxonomy of SE contexts with knowledge sharing methods so as to guide the SE practitioner in an effective matching of method with context. The paper closes with reflections on the potential reciprocal relationship between SE and KM.

Introduction

Organisations that have traditionally practised systems engineering (SE), are facing many challenges; those in sectors such as aerospace and defence are using SE in project environments that are far removed from the ones in which SE originated. Projects have increased in size and involve additional layers of complexity. For instance, the recognition of a wider range of stakeholders (sponsors, users, contractors, and so on) complicates the lines of accountability and introduces expectations from a wider range of perspectives. In addition, the 'softer' and cultural aspects of projects have come to the fore and demand new skills for their effective management. Mindful of such changes in the project environment, there is a growing necessity to learn lessons from a diverse range of past projects and other domains to ensure project success. In parallel, there is a continuing need to justify the value of a SE approach since the application of 'approved' SE processes still does not appear to prevent project problems, and 'poor SE' often takes the blame for failures which may be attributable to causes outside its normal remit. It is not surprising therefore that, in those organisations where SE forms the backbone of company processes, there is an ongoing search for an additional 'catalyst' that will ensure predictable delivery of complex projects.

Looking for answers in an adjacent discipline

The actions of many such organisations indicate a belief that accessing their internal body of experience and 'lessons learned' may be the catalyst that is needed. However, the search for a way to embed such experience from the past into current projects takes us out of the SE domain and into the domain of KM. Whilst KM initiatives are not new to these organisations, there is somehow a sense that most are less complete or less successful than was hoped for at the outset. For example, many such organisations access the knowledge carried in the heads of senior and long standing members by encouraging them to lead design and project reviews, using experience from the past and from other projects to highlight and avert potential problems in the early stages of a project. However, for three reasons, this is a partial solution. Firstly, these people can only access a fraction of the collective organisational memory via their own experiences and personal networks. Secondly, inevitably, not every issue is identified at review stage and, even then, rework is needed. Finally, these organisations face the additional challenge of an aging workforce, where retirement of this pool of expertise is just a matter of time. Other attempts at KM take a more technology-focused approach, gathering codified project expertise to share via company intranets using comprehensive databases. Typically, these too struggle – either through the lack of time or motivation to populate and retrieve the content from them, or simply by the fact that they may be shut down when the project is complete or because the 'golden nugget' has not been surfaced through such formal approaches.

Accepting that KM has a part to play within SE practice *per se* moves discussion into focussing on the need to improve the effectiveness of KM in contemporary SE practice. This paper addresses that challenge and starts to address the question of how the knowledge of experienced project members can be embedded into SE projects of the next generation (Meakin & Wilkinson 2002) by highlighting the role of one of the processes of KM, that of knowledge sharing, in SE projects.

The focus now moves on to knowledge and its management. After an introduction to the concepts of data, information and knowledge, emphasis is placed on the process of sharing knowledge and a culture that will support it.

Introducing Knowledge Management

In order to develop a better understanding of how KM can improve the effectiveness of SE, it is useful to appreciate what knowledge is. Everyday use of terms such as 'data', 'information' and 'knowledge' can cause confusion as they are often used interchangeably and the distinction between the terms can be lost.

Data is considered to comprise the raw facts and figures, numbers, and descriptions of things that are not ordered or placed into context. As Styhre (2003, p57) states, "data is merely observation of events or entities". Data is the starting point from which information is derived. For example, data may be a series of numbers – 20, 21, 19, 20 – which, without placing them in a context, offer very little meaning. **Information,** then**,** is data that is accessible and useable, organised and interpreted. A database of the aforementioned sets of statistics might provide information that can be utilised to aid decision-making. As a string of numbers, they have little to offer but as a set of temperature readings, for example, they may inform the forecasting of weather and subsequent decisions that are weather dependent. And so the transformation from data to information is evident. **Knowledge** is the culmination of codified data, which has been organised into coherent information and which can be utilised to enable users to perform some task or duty that is reliant on access to that information. In other words, "knowledge builds on information that is extracted from data" (Boisot, 1999, p12) and can be used effectively by those with the skills and experience that are not necessarily codified within the information itself. And, according to Styhre (2003, p38), knowledge "should be managed as an organisational resource". However, "knowledge is much more complex and elusive than almost any other organizational resources" (Styhre, 2003, p24), and is reliant on the ability of people to fully grasp the meaning of the information, so that "information becomes knowledge once it is processed in the mind of an individual" (Alavi and Leidner, 2002, p17). This cannot be guaranteed and hence the need to actively manage knowledge in organisations.

A summary of the concepts of data, information and knowledge are indicated in Table 1 below that has been adapted from Bierly, Kessler and Christensen, (2000, p598) in Styhre, 2003, p59.

Level	**Definition**	**Learning Process**	**Outcome**
Data	Raw facts	Accumulating truths	Memorization (databank)
Information	Meaningful, useful data	Giving them form and functionality	Comprehension (information bank)
Knowledge	Clear understanding of information	Analysis and synthesis	Understanding and context (knowledge bank)

Table 1. Distinctions between data, information and knowledge

Jashapara (2004) uses a familiar pyramid format to illustrate the development of one concept into another and the increasing contribution that they make to purposeful action as shown in Figure 1.

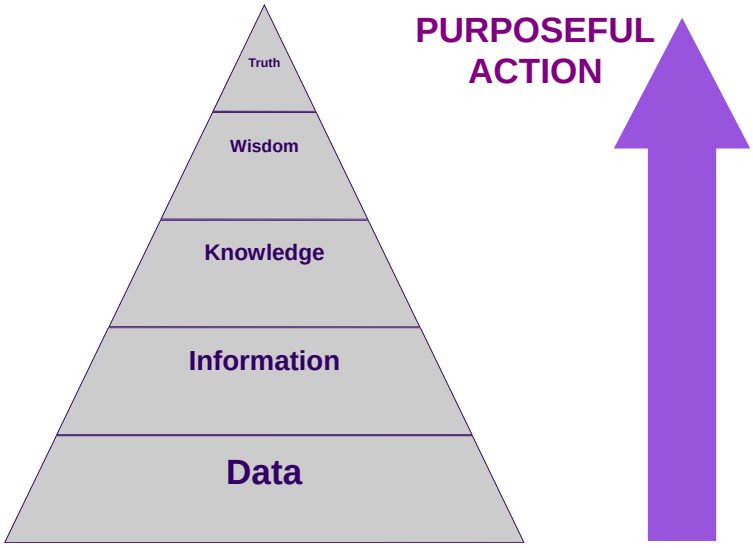

Figure 1. Jashapara's Knowledge Pyramid

Knowledge types

There is general acknowledgement of two forms of knowledge. Nonaka and Takeuchi (1995), for example, consider that it is important to identify and acknowledge not only **explicit** knowledge, but also the **tacit** knowledge that can be accessed in organisations. As Kermally (2002, p58) states, "explicit knowledge is the knowledge that has been articulated, coded and recorded" and, as such, is in a format that is relatively easy to disseminate. Such knowledge may, for example, include the adherence to rules and regulations, and recognised organisational practices. On the other hand, tacit knowledge is more difficult to identify and thus harder to capture and to share. "Tacit knowledge is personal knowledge and in practice it is very difficult to communicate fully to others" (Kermally, 2002, p58). Polanyi's (1966, p18) well used expression of "We can know more than we can tell" highlights the difficulty of identifying and accessing tacit knowledge. This type of knowledge is internal to the individual, and may be a gut feeling or something that has been learned so well that such processes are not thought about, but are merely acted upon instinctively. So, whilst explicit knowledge can be identified, shared and explained, and is therefore available as a resource to organisations, tacit knowledge is not so easily managed. The technological route may be effective in enabling the capture and sharing of explicit knowledge but an emphasis on social interactions is suggested by the less tangible nature of tacit knowledge.

A Model of Knowledge Management

Having defined the terms 'data', 'information' and 'knowledge' and introduced the notion of two types of knowledge - tacit and explicit – attention now turns to the activities associated with managing knowledge. An adaptation of Abou-Zeid's (2002, p490-491) and Liebowitz's (1999, p37) models is used in Figure 2 to embrace a stance that aligns with the harder nature of SE. Discussion of KM related processes moves in a clockwise direction.

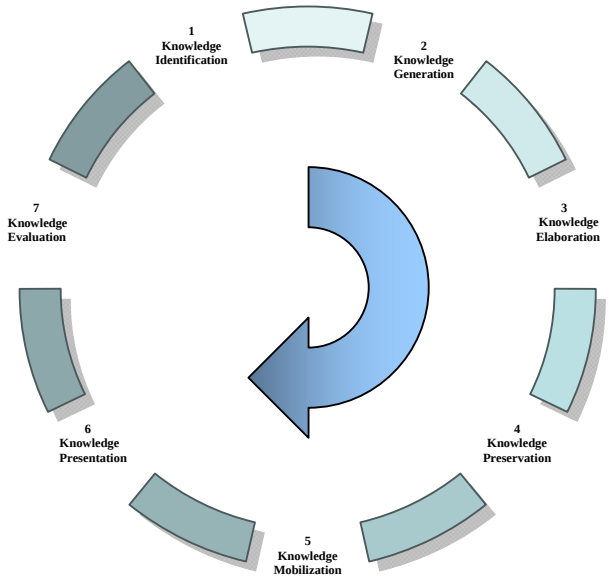

Figure 2: Model of Knowledge Management

1. Knowledge Identification.
This involves identifying three aspects of an organisation - gaps in knowledge, areas in need of updating or change and the sources of knowledge, both internal and external, to the organisation.

2. Knowledge Generation
At this stage, information is gathered together and collated in order that knowledge is created within an organisation. The required knowledge is generated by gathering together documents, people, resources and previous knowledge that may be needed to create a KM system.

3. Knowledge Elaboration
This is a sub-process in which the existing and newly acquired knowledge is ordered and refined by testing, analysis and indexing so that the knowledge is contextualised and brought into focus for the needs of the organisation. In other words, this is a stage to "assess knowledge relevance, value and accuracy" (Liebowitz, 1999, p37).

4. Knowledge Preservation
Next the knowledge needs to be stored in such a way that it is available to those who need it, and can be referred to in the future. In the case of explicit knowledge, this may include documentation, manuals, and the storage of such knowledge in different formats including computerised data and textual articles. Where tacit knowledge is to be preserved, this may require the passing on of such information through mentoring or apprenticeships and through socialisation.

5. Knowledge Mobilization/Sharing
To enable knowledge to be identified and utilised, it needs to be accessible, and therefore the mobilization of knowledge ensures that it is made available in various forms and shared across an organisation to enable collaboration. Again, tacit knowledge mobilization requires that socialisation is facilitated through the encouragement of interpersonal relationships which involve the passing on of knowledge, perhaps, within "communities of practice" and through professional training and "social learning systems" (Wenger, 2000, p225).

6. Knowledge Presentation
This involves the knowledge generated and stored in the previous steps not only being available to those who need it, but also to be understood and utilised. This means that the knowledge may be used in training or to support others within their work. The knowledge at this stage may also be used to develop new products or to assist in generating new ideas.

7. Knowledge Evaluation
The final step to the KM model presented here is the evaluation of the effectiveness of the knowledge generated. At this stage, the use, organisational value and personal value of the knowledge is assessed and the processes of the KM model are restarted with the identification of ways in which the knowledge can be improved and become more effective.

While attention to any, or indeed all, of the above processes of the KM cycle holds potential for improving SE practice, contemporary literature emphasises knowledge sharing as a key feature of successful KM: knowledge sharing, and characteristics of organisational culture that support and enhance knowledge sharing, are therefore the focus of the rest of this paper.

Organisational Culture and Knowledge Sharing

"In many organizations, especially bureaucratic ones, employees and managers are discouraged from sharing knowledge and expertise" (Liebowitz, 1999, p40). In such organisational cultures, knowledge is seen as power, and protectionist practices may be expected. Where there is a culture of competitiveness between employees, strict hierarchies and adherence to rules and formal procedures, knowledge sharing may be difficult to initiate and support. As Swan et al (2002, p185) stress, "people-management issues do indeed pose critical constraints on knowledge-sharing across projects". Further, since the radical downsizing of commercial organisations and move towards outsourcing, the resultant lack of job security felt by some employees means that it is difficult to overcome the perceived risks associated with sharing any of their unique knowledge to enable others to copy and to learn. In such organisations there is a need to undertake considerable cultural change. An organisational culture that encourages individual learning, growth and change and which actively seeks improvement will have a greater chance of developing a successful KM strategy. Building up trust, recognising that knowledge sharing is an integral part of everyone's job and overcoming the inherent difficulties of 'unlearning' in order to accept new learning are part of that strategy. Much of the recent KM literature stresses the importance of developing an organisational culture that is rooted in a sense of community and that encourages social interaction in order to enable knowledge sharing between individuals. An organisational understanding that people will get together for meetings and brainstorming sessions, and that people will be brought into projects who have worked on similar or related projects before is important. This is key to accessing the tacit knowledge of experienced individuals, and "may facilitate the efficient exploitation of knowledge, and reduce the amount of re-invention that occurs" (Swan, et al, 2002, p192). Utilising individuals' previous experience and judgement can prevent costly mistakes. Methods such as storytelling, knowledge fairs, open forums, knowledge cafes, job rotation, secondment and mentoring, along with organisational structures such as communities of practice and cross functional teams offer possibilities for supporting a knowledge sharing culture.

Organisational Culture and Systems Engineering

Instead of the culture expounded by KM texts where the ability to interact freely seems to underpin the concept of a learning organisation, the traditional SE organisation is built on foundations of structure and formalism. Information (which is often commercially or nationally sensitive) is not displayed on walls, but stored in locked cabinets. Sharing of information between organisations is covered by confidentiality agreements, and copies of the most sensitive documents are individually registered and tracked. Projects themselves may require huge, complex management activities to engage thousands of people in a multi-year, multi-million pound effort to deliver tens of thousands of components from hundreds of suppliers and to integrate them successfully. Typically funded with public money, structure and culture are driven by the demands of accountability, auditability and control. Intellectual curiosity and free exploration are not naturally at home in an organisation which is set up to predictably develop and deliver a complex product in this very formalised way.

With this in mind, it is not surprising that writers on KM from traditional SE organisations highlight the need for cultural change at the very foundation of a KM programme (Call, 2005). They see the descriptions of successful KM organisations and, unable to equate the suggested freedom with their own experiences, call for cultural change. However, given the widespread acceptance that cultural change is the most difficult to achieve (see, for example, Davenport & Prusak, 2000, p160), this tends to suggest that KM projects in traditional SE organisations are immediately doomed to failure. Clearly this need not be the case: in fact, given the variety of contexts in which SE is being practised, it is highly likely that some of them will support a culture conducive to knowledge sharing. In the next section, attention is drawn to the contexts in which SE is being applied, viewed from two different levels of detail – with respect to the problem situation and with respect to the wider environment. The System of Systems Methodologies (Jackson and Keys, 1984) aids with the former and an original framework for KM approaches addresses the latter.

Building on the 'System of Systems Methodologies'

Twenty five years ago, Jackson and Keys (1984) published their system of systems methodologies (SofSM). Since then, Flood and Jackson (1991) incorporated it into their problem solving framework of Total Systems Intervention (TSI) wherein it plays a significant role in TSI's phase of choosing an appropriate systems methodology (or methodologies) for a particular problem situation. The essence of the SofSM lies in Jackson and Keys' (1984) rigorous work in making explicit the basic assumptions that underpin different systems approaches and the differing views of problem contexts that they adopt. The SofSM takes the form of a 3 x 2 matrix. The x-axis represents the participant dimension and "refers to the relationship (of agreement or disagreement) between the individuals or parties who stand to gain (or lose) from a systems intervention" (Flood and Jackson, 1991, p33), with three relationship types defined as unitary, pluralist and coercive. The y-axis represents the systems dimension and indicates the relative complexity of the systems that make up the problem situation.

SE is associated with the simple-unitary problem context within the SofSM. This means that there is an assumption "that the 'problem solver' can easily establish objectives in terms of a system(s) in which it is assumed a problem resides" (Flood and Jackson, 1991, p37) and that there is no significant dispute about these objectives.[1] So, the SofSM provides a new mindset through which to articulate the local context in which SE is considered to be most effective and the contexts in which it may be being applied. Taking this theme a little further, the wider context for the application of SE is now explored using a related taxonomy.

A System of Knowledge Management Approaches

Building on Jackson and Keys' (1984) taxonomy, the six-box model for a 'system of KM approaches (SoKMA)' is shown in Figure 3. Although the model is drawn with distinct boxes, both axes represent a continuum, and the boxes provide an indication of problem types rather than creating artificial barriers between them. The horizontal axis represents the participants through the dimension of organisational culture (identifying the nature of the business that is mirrored in the need for predictability) and the vertical axis expresses the nature of the knowledge management system.

[1] Whilst beyond the scope of this paper, it is notable that SE is now applied beyond the simple-unitary position. It would be worthwhile to consider what has changed in the past 25 years, and explore the evidence relating to the effectiveness of SE in these broader applications.

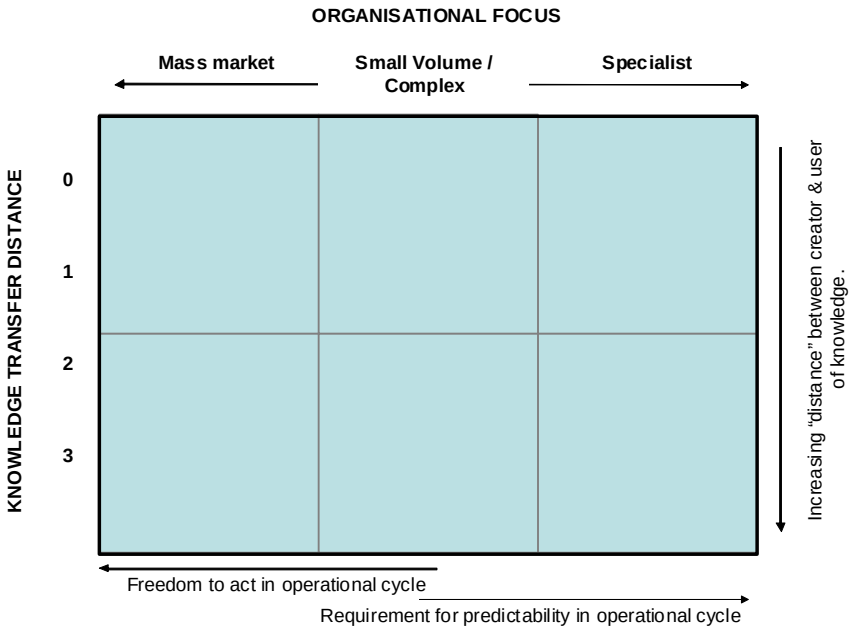

Figure 3: System of Knowledge Management Approaches (SoKMA) model

The horizontal axis reflects the organisation's need for predictability of outcome, with an increasing requirement for predictability towards the right hand side. The impact of this environmental factor may be made explicit in the organisational culture by differences in the level of control imposed on day-to-day activities, with the left-hand side representing minimum control and a freedom to explore, and the right-hand side representing tight control and limited scope to explore. At the left-hand side, the organisational driver is innovation. The KM focus is to leverage ideas to shape the market, develop "solutions looking for problems" and "think out of the box" – in effect, to create and exploit opportunities, and to deliver business gain and competitive advantage in a fast-moving market. This extreme is exemplified by consultancies and high-tech companies such as HP, Sony, etc – typically held up as examples of excellent KM. In contrast, the driver at the right-hand side of this model is learning lessons from past, recreating success, and preventing repeated mistakes. The emphasis is on risk mitigation and the avoidance of loss. At the extreme, armed forces or space exploration exemplify this focus, and the objective is achieving the aim whilst minimising high-impact risks such as loss of life.

Classic SE organisations (typically established to deliver defence or aerospace products) are positioned in the centre of the horizontal axis. Their drivers are typically to ensure that lessons are learned from previous projects and across related projects (e.g. with similar customers or technologies). Some degree of innovation has its place in the development of solutions to well-specified technical problems, but innovation which might disrupt the predictability of the overall process outcomes is actively discouraged. Lack of knowledge is a barrier to entry for competitors and protection of company knowledge offers some degree of competitive advantage.

The vertical axis of the SoKMA model replaces the relative complexity of the systems project used by Jackson and Keys (1984) with a measure of the difficulty of the KM project,

represented by a concept known as "Knowledge Transfer Distance (KTD)". 'Distance' here may be physical distance, but might also be related to factors such as time, organisational structure, language and culture. It represents the organisational difficulty of sharing knowledge, through from knowledge capture in a form that enables sharing, through analysis, classification and appropriate storage to enable retrieval, and reflects the issues of sense-reading and sense-giving addressed by Walsham (2001). Table 2 provides definitions of the four KTD levels.

KTD '0'	relates to knowledge management within the current "project" and therefore implies the flow of knowledge within and between teams in order to deliver the current tasks to achieve a shared objective.
KTD '1'	relates to knowledge management with an adjacent project. Adjacency may occur in space, time, organisation, domain etc. Examples of adjacent projects include a follow-on contract, concurrent implementation of a project in more than one division of the same organisation, or the handover of a military task from one force unit to another. In all cases, there is potential for real-time communication between adjacent project teams but day-to-day objectives for the two teams are different.
KTD '2'	relates to knowledge management with related projects. Related projects will share some commonality in terms of people, processes, technology or location. Examples of related projects include the application of the same technologies in other divisions of the same organisation, delivering otherwise unrelated contracts to the same customer, and fighting a military campaign in the same geographic region.
KTD '3'	relates to knowledge management with apparently unrelated projects. Unrelated projects share little obvious "common ground" and therefore pose the greatest challenge for KM. Knowledge management between unrelated projects is often driven by either lateral thinking or by fortuitous coincidence.

Table 2: Knowledge Transfer Distance Definitions

The KTD concept applies across the breadth of the SoKMA model. At the left-hand side, it could relate to knowledge management within and across different divisions of a global organisation; at the right-hand side this might include knowledge sharing in the armed forces between discrete force units, across different services (land, sea, air) or between campaigns. Figure 4 provides further visualisation of this concept and the implications for knowledge sharing.

At this stage of development of the SoKMA model, KTD '0' and '1' share a box, as do KTD '2' and '3'. Taking secondary information from published studies, it is apparent that one significant distinction can be made: whether or not real-time communication is available as a mechanism for knowledge management, and specifically to enable sharing of tacit knowledge. This single factor is used to differentiate between the upper and lower boxes of the SoKMA model. Further work is needed to confirm whether the level of definition within the available secondary information is adequate to support a 12-box model.

The SoKMA model and the concept of KTDs therefore provide a framework for mapping successful KM approaches to the environment in which they are used. A sample mapping is offered in Table 3 to give an indication of approaches which are drawn from the published literature and are said to have worked in certain cultural environments. Further research is needed to test the generic validity of the data points presented and to identify other approaches to further populate the framework.

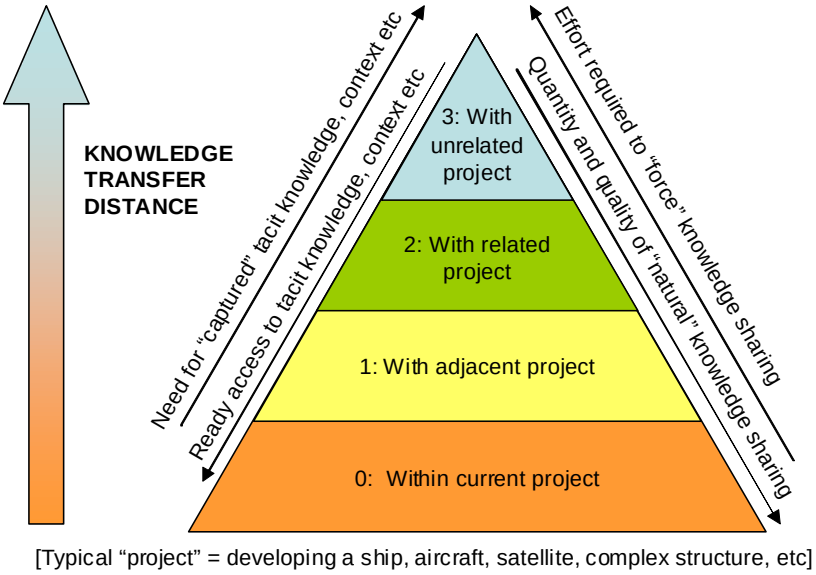

Figure 4: Knowledge Transfer Distance

	Mass Market	***Small volume/Complex***	***Specialist***
KTD 0 **KTD 1**		Knowledge Enabled Engineering environment (Sellini et al, 2006) Learning Histories (Meakin and Wilkinson, 2002)	Iterative Development (Larman, 2004)
KTD 2 **KTD 3**		Process Backbone (Martin and Oddie, 2007) Communities of Practice, Knowledge Portals (Decamps & Galinier, 2004)	Video Database (Wilke et al, 2003)

Table 3: Sample mapping of KM approaches to SoKMA framework

Embedding KM into the SE culture

Although it has been proposed that the implementation of KM first requires a significant change in culture (Call, 2005) this is likely to be unachievable in most organisations. Imposing this as a requirement risks either rejection of KM as inappropriate for the organisation, or the implementation of some superficial cultural adjustments which are inadequate and lead to both cultural stress and KM system failure. Account needs to be taken of the local culture. For example, 'a modicum of process orientation' (Davenport and Prusak, 2000, p157) in the process-rich environment of a traditional SE organisation is likely to mean considerably more process than in a more flexible and process-light environment. The same applies to the language that is used, the way that value is measured, the way that knowledge is structured and the way that participants are motivated. All must be culturally consistent if KM is to become embedded in SE project life, rather than remaining a project in itself. To be successful, the complete KM strategy must be therefore complimentary to organisational

culture, not the other way around. Although perhaps counter-intuitive to those within a more open and innovative culture, formality and structure in the KM approach has been shown to work in the armed forces where formality and structure are the cultural norms, for example through the US Army's 'After Action Review' (AAR) program (Davenport and Prusak, 2000).

However, cultural compliance is not an excuse for an incomplete KM strategy, or an over-reliance on information technology (in effect an IM strategy). Recording 'lessons learned' into a database at the end of a project will not prevent the same 'lessons' from being 'learned' again the next time. Rather than lessons 'learned', this is an example of lessons 'observed but *not* learned' unless the broader strategy is in place to both make those lessons accessible (both physically and intellectually) to others, *and* to embed the search for relevant lessons into the culture of future projects from the start. Waiting for the first problem to strike before looking to see if it has been encountered before is not a sound KM approach.

Embedding SE into the KM culture

One approach which may assist the acceptance of KM within SE is to impose the same structures and processes on the KM project itself. Herald et al (2004) proposed a structured approach to KM projects, which introduced the systems engineering standard ISO15288 to provide a framework and set of guidelines for the project. Whilst this should provide significant benefit for the development and implementation process, it does not address two critical areas:

1. Soft requirements capture – i.e. the identification and articulation of all stakeholder requirements, including those which derive from political and cultural considerations.
2. KM system architecture – i.e. selecting an appropriate KM solution to meet complex stakeholder needs.

Whilst these two issues are beyond the scope of ISO15288, they are critical to ensure that a culturally-appropriate solution is selected. The SoKMA model addresses this shortfall by combining learning from the broader SE domain into this process-focused approach, thus helping to ensure the selection and implementation of a better KM solution.

Conclusions

As with SE, some may claim that effective KM is a panacea, the magical solution to the challenges of engineering complex projects. For those who seek that extra 'something' to turn a well-managed project into a successful project, it may well be a tempting concept for the next 'initiative'. But however compelling the idea, for traditional SE organisations the descriptions of a 'necessary KM culture' - which goes beyond technological solutions into the world of free interactions and unconstrained innovation - risk discouraging the most enthusiastic proponent. It is clear that within such organisations there are examples of KM successes. The authors argue that this is attributable not to a change in culture, but to the selection of KM approaches and implementation paths which are compatible with the extant culture in those organisations. By making explicit the cultural environment in which knowledge sharing methods are successful, the SoKMA has been developed to guide the selection of effective methods for particular SE settings.

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Biographies

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Samantha has over 20 years experience in the UK defence industry, working in a wide range of roles before moving into systems engineering. She holds a BSc in Mechanical Engineering, MScs in Gun Systems Design and Engineering Management, is a Chartered Engineer and Fellow of the Institution of Mechanical Engineers. She is based at the Systems Engineering Innovation Centre (SEIC) in Loughborough, UK where she is currently studying for an Engineering Doctorate (EngD) in Systems Engineering.

Dr Gillian Ragsdell is a Lecturer in Knowledge Management in the Department of Information Science at Loughborough University, United Kingdom. She combines her industrial experience with her academic interests to build on the relationship between the theory and practice of knowledge management. Her origins in systems thinking and creative problem solving have proved particularly effective in studying the generation and sharing of knowledge. Action research projects have taken her into various organisations; recent examples include organisations from the voluntary sector, the water industry and the military.