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Review of information and the state of the art of knowledge management practices in the construction industry*

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Abstract

This paper focuses upon the contribution which adequate use of the latest development in IT can make to the enhancement, development and improvement of professional expertise in the construction domain. The paper is based on the author's personal expertise and involvement in several UK- and European-funded research projects. First, the paper gives an overview of the benefits that can be gained from improved information and knowledge management in the construction industry. The latest developments in information and communication technologies are then described and presented as an enabler for effective knowledge management. Finally, the paper reviews the most promising techniques for information and knowledge management in the construction domain, highlighting the advantages and disadvantages of each of them, as well as future directions for knowledge management in construction.

1 Introduction

Over the last decade, construction companies have invested heavily in the improvement of their business processes. New forms of innovative project management, supported by IT, appeared as a response to the ever-growing pressure from clients to deliver high-quality facilities on time and on budget. While the construction area is becoming an information-intensive industry, a new activity emerged from the process of managing projects and established itself as a discipline in its own right: that of information and knowledge management.

Despite the interest and the effort put into knowledge management by many leading companies, the discipline is still in its infancy. Many practitioners and researchers have acknowledged the limitations of current approaches to managing the information and knowledge relating to and arising from a project (Choi & Ibbs, 1995). Among the key reasons for these limitations are given below.

- Much construction knowledge, of necessity, resides in the minds of the individuals working within the domain.
- The intent behind decisions is often not recorded or documented. It requires complex processes to track and record the thousands of ad hoc messages, phone calls, memos, and conversations that comprise much project-related information.

* The paper is based on work carried out in several research projects including COMMIT – information management in collaborative environments (EPSRC); CONDOR – technology and processes for integrated construction document production and management (ESPRIT Framework 4 – Ep 23105), and OSMOS – Open System for inter-enterprise information Management in dynamic virtual envirOnmentS (IST 1999-10491).

- People responsible for collecting and archiving project data may not necessarily understand the specific needs of the actors who will use it, such as those involved in the maintenance of the building(s).
- The data is usually not managed while it is created but is instead captured and archived at the end of the construction stage. People who have knowledge about the project are likely to have left for another project by this time – their input is not captured.
- Lessons learned are not well organised and are buried in details. It is difficult to compile and disseminate useful knowledge to other projects.
- Many companies maintain historical reports of their projects. Since people always move from one company to another, it is difficult to reach the original report authors who understand the hidden meaning of historical project data. This historical data should include a rich representation of data context, so that it can be used with minimum (or no) consultation.
- New approaches to the management of knowledge within and between firms imply major changes in individual roles and organisational processes. While potential gains are desired, the necessary changes are resisted.

Knowledge in the construction domain can be classified into the three following categories.

- *Domain knowledge.* This forms the overall information context. It includes administrative information (e.g. zoning regulations, planning permission), standards, technical rules, product databases and so on. This information is, in principle, available to all companies, and is partly stored in electronic databases.
- *Organisational knowledge.* This is company specific, and is the intellectual capital of the firm. It resides both formally in company records and informally through the skilled processes of the firm. It also comprises knowledge about the personal skills, project experience of the employees and *cross-organisational knowledge.* The latter covers knowledge involved in business relationships with other partners, including clients, architects, engineering companies and contractors.
- *Project knowledge.* This is the potential for usable knowledge and is at the source of much of the knowledge identified above. It is both knowledge each company has about the project and the knowledge that is created by the interaction between firms. It is not held in a form that promotes reuse (e.g. solutions to technical problems, or for avoiding repeated mistakes), thus companies and partnerships are generally unable to capitalise on this potential for creating knowledge. It includes both project records and the recorded and unrecorded memory of processes, problems and solutions.

The Latham Report (Latham, 1994) identified lack of integration across partners as a major issue affecting the performance of the UK construction industry, and puts forward the use of IT to facilitate the sharing of information and knowledge as a major factor in securing improved performance in the future. In addition, the Latham Report reveals that construction industry practitioners believe that approaches promoting knowledge management would help to overcome many of the constraints inherent in their sector. These approaches are expected to contribute to improving working conditions, health and safety; to providing methods and tools to improve learning from experience; to providing a better quality of end-product; and preserving the environment and natural resources. This will lead, in the long term, to the empowerment of the employee by promoting organisational learning through corporate information and knowledge bases making use of the company's "lessons learned".

Several projects and initiatives have been and are being pursued in order to address this problem of information-sharing, including projects such as ATLAS (Bohms *et al.*, 1994), COMBINE (Dubois, 1995), CIMSteel (1995), ICON (Cooper *et al.*, 1994) and OSCON (Marir *et al.*, 1998). A number of these (e.g. ICON and OSCON at Salford University) have tried to address the problem in a manner that allows different participants to carry on working with their own perspectives on the information. Initiatives such as ISO STEP (ISO/TC184/SC4, 1994) and EDIFACT have attempted to improve the portability of information across different applications and participants. More recently, the International Alliance for Interoperability (IAI) has been working towards the development of standards for inter-working between object based systems in construction in the form of its Industry Foundation Classes (IAI, 1997). Other research has tackled various aspects that fall within the scope of information management, including change notification and propagation (Khedro, 1996), and versioning support (Katz, 1990; Law *et al.*, 1996; Talens *et al.*, 1993). Several other projects, including the UK Link/IDAC funded B-Hive project, have looked at how processes which promote critical reflection to create knowledge can be introduced into the construction domain and sustained, drawing on work in organisational learning and knowledge creation (Argyris & Schon, 1978; Nonaka, 1995).

This paper is based on work and research undertaken within several past and ongoing research projects aiming at improving information-sharing and knowledge reuse within the construction industry. Parts of these projects have separately investigated IT and organisational process-led solutions to the crucial information- and knowledge-management issues mentioned above. First, the paper gives an overview of the benefits that can be gained from improved information and knowledge management in the construction industry. The latest developments in information and communication technologies are then described and presented as an enabler for effective knowledge management. Finally, the paper reviews the most promising techniques for information and knowledge management in the construction domain, highlighting the advantages and disadvantages of each of them, as well as future directions for knowledge management in construction.

2 Information technology and knowledge management

Advances in personal computer technology, along with the rapid evolution of graphical user interfaces, networking and communications, have had a substantial impact on industry business processes. The emergence of client/server applications (ranging from file server to database server applications), at the end of the 1980s, have offered a first promising answer to the problems of flexibility, scalability (the ability to upgrade a system without having to redesign it), and extensibility (the ability to extend the underlying data structures of applications without losing the data) of modern businesses. Software applications were downsized from expensive mainframes to networked personal computers and workstations that are often more user-friendly and cost-effective. The introduction of the Internet, along with advances in three-tier architectures and middleware technologies, have brought new challenges and competitive advantages that the industry is now trying to comprehend and exploit. On the other hand, new techniques have been developed to integrate legacy and proprietary systems with new upcoming component-based applications. These legacy, proprietary and commercial applications, widely used by the industry, range from low-cost document-management systems to high-cost groupware applications.

However, recent surveys (Vakola, 1999; Zarli *et al.*, 1998) reveal that current technology solutions in use in the building and construction domain present one or more of the following characteristics.

- *Homogeneity.* Despite recent evolutions, mainly due to the impact of the Internet, existing solutions are still often fixed and not open, with a lack of support for legacy, as well as new, upcoming systems in terms of hardware, software, databases and networks.
- *High entry level.* IT solutions are still often expensive to buy for SMEs. More entry levels should be provided, e.g. from personal (low-cost) to enterprise (high-cost) editions.
- *Lack of scalability.* Most available proprietary and commercial solutions offer limited growth path in terms of hardware and software.
- *Application-centric and lacking support for business processes.* There is often a requirement to organise the enterprise around the adopted IT solution.

State-of-the-art research in computer-integrated construction reveals that integration has been achieved, mostly, on static models that define the structure of shared information in the form of files or databases. Many researchers (e.g. Zarli *et al.*, 1998; Brown *et al.*, 1996) advocate that integration should be made through frameworks which define semantic relationships between the interfaces of separate distributed components. This is an area where construction needs advances that can, ultimately, benefit knowledge management within companies. These frameworks are already under development, within the Object Management Group, through business object facilities, based on the Common Object Request Broker Architecture (CORBA). There is, however, a need to extend these existing services and propose new ones for the benefit of the construction industry in order to provide effective IT-based distributed information and knowledge-management solutions in an environment where industry-standard software, groupware tools and distributed three-tiered architectures are expected to be predominant.

The remaining sections will describe the state-of-the-art information- and knowledge-management practices and technologies (along with their constituents) in use in the construction sector. It will try then to analyse each of them and identify their potential contribution to knowledge capitalisation.

3 Document management systems

Most information used during the design-and-build process of a construction project is conveyed using documents. These are most of the time exchanged, for contractual and legal reasons, on a paper-based medium, even when produced using computers. The challenge that the industry is facing today is the reuse of the knowledge and lessons stored within these documents. The latter are unstructured, poorly organised and embedded within the "black-box" that constitutes the document.

Document management has become a crucial issue within modern construction companies. The various solutions proposed by some software vendors have been revealed to be unsatisfactory, to a point where many leading construction organisations, with an advanced IT department, have undertaken the development of their own tools and solutions to support the production and maintenance of project documents. Even though such proprietary tools provide many helpful facilities, including support for document storage, retrieval, versioning and approval, they do not handle any semantics of the information being processed and therefore remain limited in their support of the end-user. In fact, construction project data and documentation (including full specification documents) constitute two fragmented information sectors where compatibility and interoperability are most needed. Moving these pseudo-sectors closer together to support construction-project documentation as part of the life cycle of the building product is becoming an actual and urgent topic for standard bodies and the industry alike.

A survey undertaken within the ESPRIT Framework 4 Condor project (Rezgui & Karstila, 1998) reveals the following limitations of existing proprietary Electronic Document Management (EDM) systems used within the construction industry:

- every partner within the project must use the same EDM system on a project in order to be able to access and share documents;
- the document's semantics and internal structuring is not controlled by the EDM system; documents are handled as "black-boxes";
- the EDM system does not support document cross-referencing or semantic linking;
- security is always an issue – it is not as easy to implement as for printed documents; EDM systems require improved user authentication and document protection;
- the EDM system is not integrated with proprietary and commercial applications used within the company (e.g. CAD applications and word processors);
- most end-users in the construction industry are not computer-literate. EDM systems lacking user-friendliness, or used in a maladapted environment (e.g. with network-communication problems), discourage the user from using the EDM system.

Several projects have tackled the crucial problem of document management, including RATAS (Bjork, 1993), ATLAS (Bohm *et al.*, 1994), DOCCIME (Rezgui & Debras, 1995), and CONDOR (Rezgui *et al.*, 1999). In addition, many commercial web-based EDM systems are now available. These include

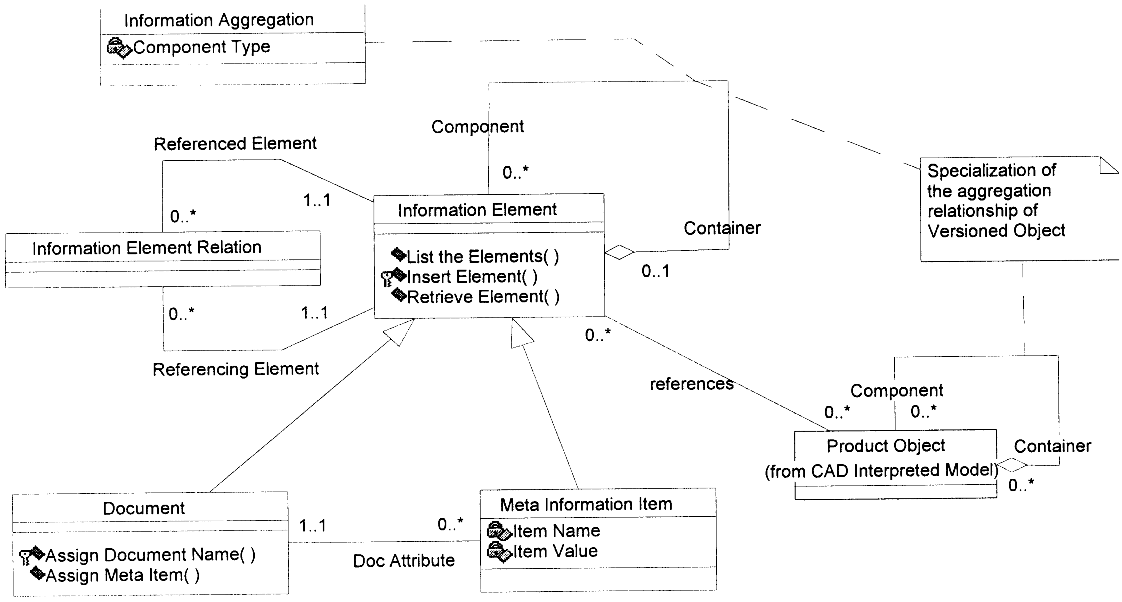

Figure 1 Condor generic document model

ProjectNet,[1] BidCom,[2] Evolv,[3] and Buzzsaw.[4] These systems provide document and workflow management services across the Internet. The Condor project differs from these commercial systems and other companion projects in that it provides a framework for managing the internal semantics of documents in a way that promotes reuse of knowledge. The Condor project has produced models that describe the logical structuring and semantic linking between the various forms of information used in the industry. These include written documents, drawings and multimedia objects. A detailed description of the models can be found in (Rezgui *et al.*, 1998). A simplified version of the model is presented in Figure 1. A Condor API (Application Programming Interface) has also been developed. This supports various services, including document-based information cross-referencing.

The implementation of the cross-referencing functionality enables an end-user through his favourite EDM system to

- add a reference to a document part,
- link a document to a referenced part of another document,
- retrieve a referenced part of a document, and
- list the referenced parts in a document.

It is worth mentioning that document parts are treated as documents and can be physically located on any server. This was made possible thanks to the use of the CORBA 2.0 standard (OMG, 1997). In particular, a CORBA name server is used to store the CORBA references of all Condor-distributed objects. When an EDM system needs to connect to other EDM systems (for instance to get the list of all documents located on these remote servers), it first connects to the name server in order to retrieve the CORBA references of these remote EDM systems. Then it connects in sequence to each identified EDM system, using a CORBA-based protocol.

Condor provides a framework that allows users to produce documents structured in the form of a tree at the desired level of granularity. Each node of the tree constitutes a document part. The semantics of these nodes is summarised in an abstract along with Metadata attached to it, and is made accessible to other users provided that this information is registered with the system via the implementation of

[1] ProjectNet: `http://www.bluelineonline.com/program/prducts/projnet.html`
[2] BidCom: `http://www.bidcom.com/html/overview.html`
[3] Evolv: `http://www.bricsnet.com`
[4] Buzzsaw: `http://www.buzzsaw.com/content/services/main.html`

a dedicated function of the Condor API. All these document nodes constitute a network of document-based knowledge made persistent through an object-oriented database, and available for potential cross-referencing and reuse.

4 Product data technology

Product modelling is an important step towards the integration of information across the various disciplines of an industry, including construction. A comprehensive description of ongoing effort in the area of product-modelling can be found in Eastman and Augenbroe (1998). However, after over ten years of product-model development through STEP (ISO 1996) and more recently the IFC (IAI 1994), the industry has not yet reached its promised “Nirvana”.

Several critical limitations of STEP have been identified. These limitations should not necessarily be addressed by STEP, they are, however, essential for the effective sharing of integrated construction-project information and knowledge. The following issues, and others, are under discussion within the STEP community and need to be properly addressed:

- support for the behavioural aspects of products,
- support for flexible-form models (architects need flexible methods to define the shape of their project),
- support for different views by different actors,
- the life-cycle positioning and functional objectives of application protocols,
- support for object states, versioning and ownership, and
- support for project history and intent behind decision, etc.

The question of whether STEP’s remit will be widened beyond “product data” in the future remains open. A section of the STEP community feels that, due to the dynamic nature of the building design-and-construction process and continued change in available materials and products, schema evolution is a prerequisite for the complete support of product description throughout its life cycle.

In fact, standards like STEP or the IFC normalise product data entities at an appropriate level for data exchange and sharing, but not for interoperable product components. Nor do they specify a framework supporting component interoperability. These standards have to focus on the interfaces (APIs) which define the communication layer, whilst the communication mechanisms (including transactional behaviour) themselves will be implemented by a tier middleware such as CORBA. The author believes that product components (referred to, more generally, as business objects) can provide an opportunity to structure knowledge in the construction domain. This approach has already been adopted by several software vendors, including Bentley Systems through their Engineering Component Model (ECM).

5 Groupware systems

A great deal of research has been done in the field of computer support for cooperative work (CSCW). CSCW is more generally concerned with the introduction and use of groupware systems to enable and support teamwork. Groupware deals with highly unstructured data, including text, images, graphics, faxes, mail and bulletin boards. Groupware solutions include, traditionally, a subset of the following system components: workflow (task scheduling), multimedia document management, email, conferencing and shared scheduling of appointments. A recent survey of groupware constituent technologies (Zarli *et al.*, 1998) reveals a lack of homogeneity, and a diversity of applicable de facto standards and APIs from the leading groupware vendors.

Groupware has the potential to flatten organisations and remove layers of bureaucracy. Groupware helps manage and track the project lifecycle throughout its various stages. It also allows the actors collaborating on specific tasks to exchange ideas and synchronise their work. It offers the potential to keep track of the project memory and record all its “learned lessons” in a way that promotes reuse.

One of the important constituent of groupware is workflow. According to the WfMC (Workflow Management Coalition), a workflow process consists of a collection of activities. An activity is a logical step that contributes towards the completion of a workflow process. It is executed by an application software outside the workflow system. Workflow helps bring the information to the people who can act on it. It coordinates existing software and tracks the processes and helps to ensure that activities are performed by the right application undertaken by the right actors that have the right skills.

However, it is well acknowledged in the construction industry that many enterprises, taking part in collaborative work involving several non co-located actors, are often reluctant to join and adopt a workflow-based process, or to fully use a groupware solution. There is still a strong requirement to ensure the availability of up-to-date, accurate and relevant information, while at the same time providing access control (based on actors' rights and role in the project) and concurrent business transaction support. In fact, the peculiarities of the construction sector suggest that equal consideration should be given to technical as well as social, contractual and legal aspects (including responsibilities) relating to projects.

This is the aim of the IST (Information Society and Technology) Framework 5-funded OSMOS project (Rezgui *et al.*, 1999). The overall aim of the OSMOS project is to enhance the capabilities of construction enterprises to act and collaborate effectively on projects by setting up and promoting value-added Internet-based flexible services that support teamwork in the dynamic networks of the construction industry. These services will provide means by which proprietary and commercial building and construction applications can inter-work by enabling the sharing and cross-referencing of information in a Virtual Enterprise (VE) environment (Figure 2). This is based on existing standards, including CORBA services developed by OMG; the (XML) DOM standard object API (W3C), which is being managed as part of the W3C's user interface domain; and existing leading groupware vendors' APIs, including the Workflow Client API from the Workflow Management Coalition (WfMC), mail APIs (e.g. VIM, MAPI, CMC and X400), and the Calendaring and Scheduling API (CSA) from the XAPIA standards association.

The OSMOS project concentrates on two fundamental technologies that are very promising: on the one hand, the XML specification and all its related current developments; on the other hand, the cataloguing, indexing, archiving and retrieval of this information using proven techniques, including agent-based technology.

XML can be viewed as a standard way of passing data between many heterogeneous distributed application servers, as well as across multiple operating systems, and as a basic model for data interchange at the level of middleware and client-server connections. XML provides concise searching

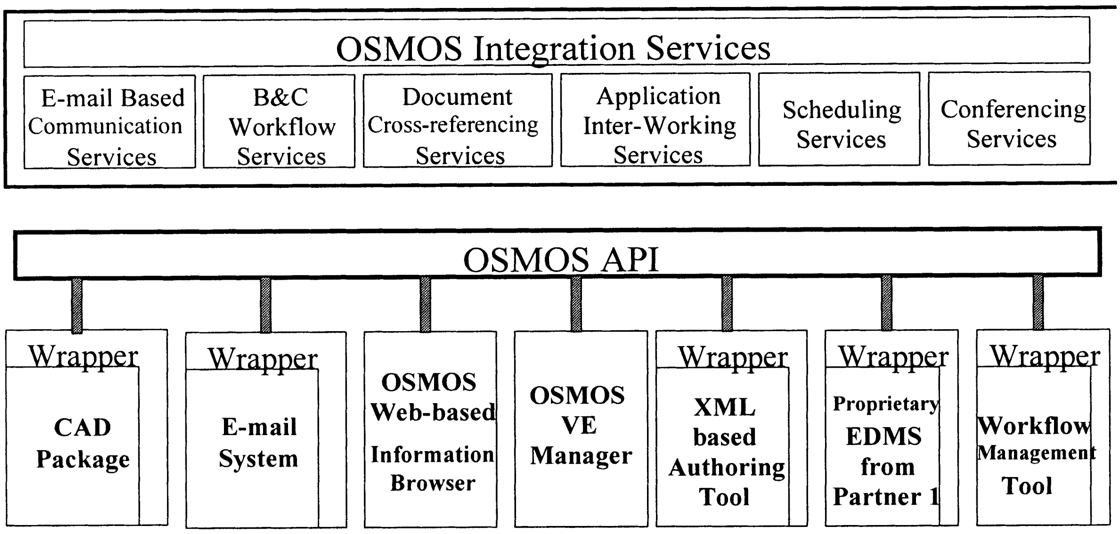

Figure 2 The OSMOS system architecture

capabilities through custom-defined tags, and offers efficient data exchange through XML-based protocols, and this can be tailored for vertical markets. Therefore XML can be used for cataloguing, accessing and distributing information in quite a structured way, and at the level of interchange/interoperability as well. Relying on the work done in the W3C and also around XMI (the XML Metadata Interchange format, defined by the OMG), the OSMOS project is proposing new routes for application interoperability based on XML.

Furthermore, by combining XML with agent-based solutions, OSMOS is expecting to make advances in the area of construction knowledge management by providing models, tools and architectures to support this critical process, and offer new capabilities for semantic information management and workflow management in a dynamic virtual enterprise environment.

6 Advanced information management systems

The author, along with other research colleagues and representatives from the industry, carried out an in-depth analysis in relation to information management. This study (part of the EPSRC-funded COMMIT project) was made in the context of existing and new developments in information technology, including Java and CORBA, and standardisation in the areas of information representation for construction, including STEP (STandard for the Exchange of Product models) and the IAI (International Alliance for Interoperability). In the light of the conclusions of the study, it was agreed with the COMMIT project steering group (comprising representatives from the industry) that the COMMIT technical work should address six “key issues”, which are closely related and are central to information management:

- ownership, rights and responsibilities: each actor is assigned a specific role (or roles) in the project, through which he or she interacts with the project information base;
- versioning of information: a mechanism used to keep track of all the states in which an object has existed, including its current state;
- schema evolution: allowing the underlying conceptual model used by the project actors to be altered, and to evolve over time, without affecting the overall consistency of the project information base;
- recording of intent behind decisions leading to information: providing support for recording the factors that influence decisions, leading to information being produced or changed;
- tracking of dependencies between pieces of information;
- notification and propagation of changes: ensuring that objects and actors are kept informed of relevant changes introduced to the project information base.

In order to address these issues, the system architecture for COMMIT was designed to support information management in a distributed object environment. A COMMIT Information Management Model (CIMM) was developed. A simplified view of the CIMM is given in Figure 3. The latest version of the CIMM can be found in Rezgui *et al.* (1998). The most significant issues arising were concerned with the level of granularity at which various forms of information management should be applied. This issue was addressed by providing sufficient flexibility in the models to allow for variations in granularity, and by introducing a mechanism for aggregating changes for the purpose of notification and recording of intent.

The creation of prototypes for COMMIT consisted of creating concrete implementations of the (information management) classes defined in the CIMM, building a browser to allow objects of those classes to be instantiated and manipulated, integrating the classes into an object-oriented construction object database and incorporating information-management interfaces into the tools providing access to those construction objects.

The majority of the prototypes were created using the C++ language in conjunction with the ObjectStore database. These prototypes were restricted in certain areas of functionality, such as schema evolution and access to class definitions from within the object browser. However, these prototypes have been particularly useful due to the ability to integrate them with integrated databases developed previously in the EPSRC-funded ICON project and the DoE-funded OSCON project. The advantage

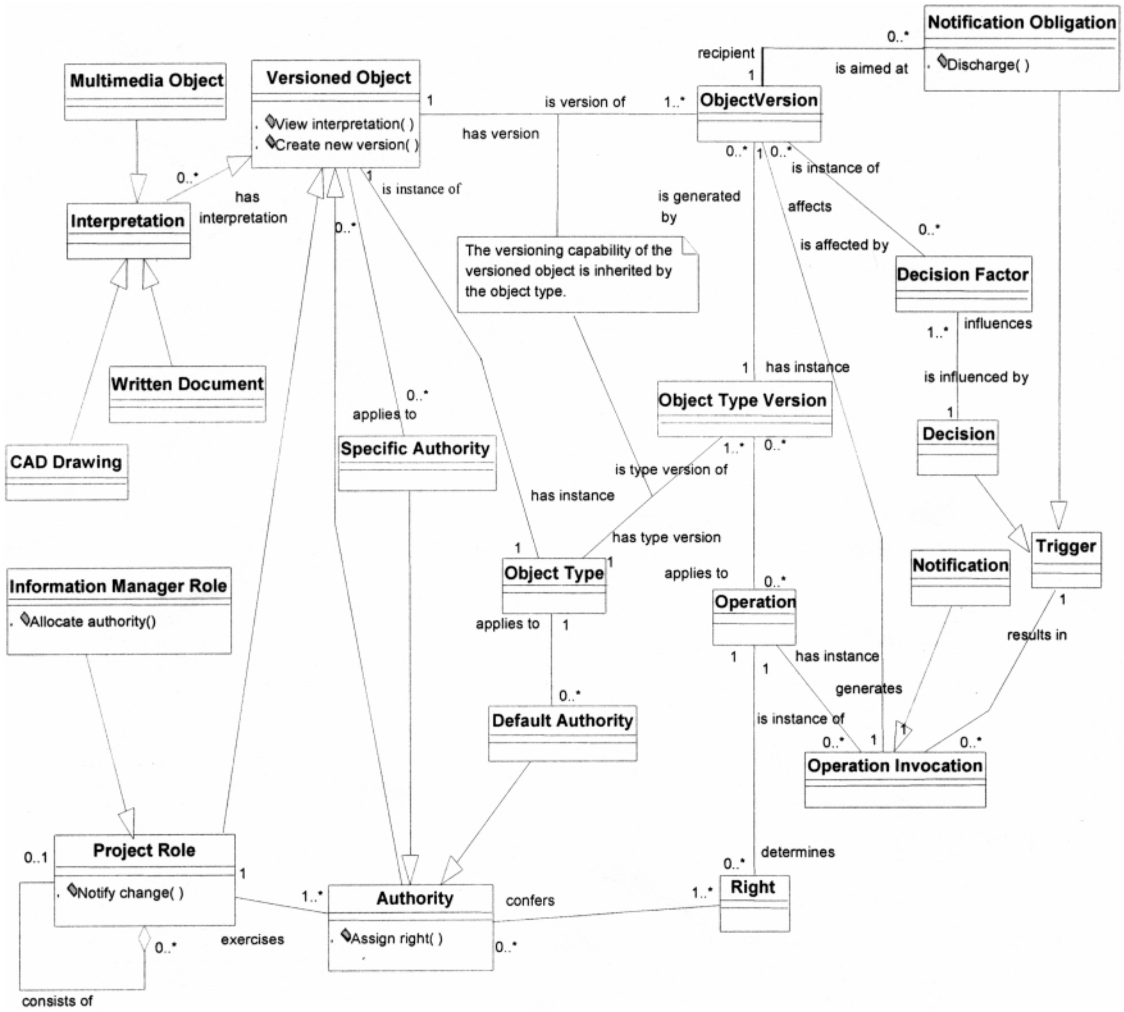

Figure 3 Simplified view of the CIMM classes using UML

of this approach is that it allows the COMMIT functionality to be demonstrated in the context of industry standard tools such as AutoCAD, improving the ability of the project to communicate with practitioners and to gain valuable feedback, helping the research team to refine and extend the COMMIT information management model. A comprehensive description of the COMMIT prototype V1 can be found in Rezgui *et al.* (1998).

Because of technical restrictions in the tools available, it was not possible in the first prototype to demonstrate some of the more advanced aspects of the CIMM, such as schema evolution, nor to achieve the proposed level of proactive information management. In the later part of the project, therefore, a new implementation of the prototype was created using the Java language in order to demonstrate some of these more advanced aspects. Java provides much greater flexibility in relation to schema evolution, the ability to analyse classes at run-time, and the ability to add and instantiate new object classes dynamically in the system at run-time. In Java, classes are represented as objects in their own right, allowing the versioning of classes and the full implementation of schema evolution to be achieved as defined in the CIMM. This also provides the possibility for new classes to be downloaded into systems from libraries and brought into applications under the control of the COMMIT system at run-time. The object/class browser in the Java prototype provides the ability to load and instantiate classes, manipulate objects and manage the rights and notification obligations of classes and instances.

The decision to base the second COMMIT prototype on the Java language has been validated by the imminent release of the Java-based Microstation/J by Bentley Systems, and the whole approach adopted by COMMIT is endorsed by Bentley Systems' very strong commitment to being involved in a follow-up project based on the application of the COMMIT Java-based technology in conjunction with Microstation/J (IMI project: "Advanced Decision Support for the construction Design Process", started 1 January 1999).

The COMMIT project uses the latest information technology techniques to provide an information management system which addresses the problems of information versioning, change notification and recording of intent behind decision. It provides a model-based environment that can be used to track dependencies between information in order infer the rationale behind modifications introduced throughout the project life cycle. It provides an ideal environment for knowledge reuse based on construction and project information. It also defines mechanisms for handling the proactive management of information to support decision-making in collaborative projects.

7 Decision-support systems

Since the introduction of knowledge-based systems, numerous implementations have been undertaken and deployed in various industries, including construction, with varying levels of success (Levitt & Kartam, 1990). The UK department of Trade and Industry reported in one of its surveys (DTI, 1992) over 2000 knowledge-based systems deployed in business operations in industry, including manufacturing. These systems worked fairly well on problem domains that had an explicit model-based representation implemented through rules or objects.

However, as reported in Watson and Marir (1995), developing KBS without an explicit problem-domain model remains problematic. That is where other forms of reasoning, including case-based reasoning, have been explored. Case-based reasoning organises the structured archival of past experiences for future potential reuse. These experiences, commonly referred to as cases, are archived along with their unique domain characteristics expressed through well-defined indexes that describe the essence of the case (Watson & Marir, 1994). The success of this type of reasoning is largely explained by its simplicity, along with its similarity with human problem-solving mechanisms. Case-based reasoning, compared to knowledge-based systems, provide many advantages (Watson & Marir, 1994), including the following:

- it does not require an explicit domain model and so elicitation becomes a task of gathering case histories;
- implementation is reduced to identifying significant features that describe a case;
- CBR systems can learn by acquiring new knowledge as the number of cases increases.

CBR is still in its infancy in the construction domain. Several studies and prototype implementations have been proposed which highlight the benefits of decision-support systems using CBR techniques (Rezgui & Farhi, 1997; Farhi & Watson, 1995).

Most available knowledge-management systems (including KBS and CBR) rely on users' input to orchestrate the information and knowledge discovery and elicitation. This is, however, becoming increasingly complex as the electronic sources of knowledge are vast and rapidly growing with the successful deployment of IT systems within organisations. In addition, these systems have limited collaborative functionality and do not encourage information and knowledge discovery (Berney & Fernley, 1999) – they require the user to have a clear idea of the appropriate search terms. Such systems also require the tacit knowledge giver to be able to clearly articulate their knowledge and experiences. Prior to the introduction of technology to facilitate collaboration, an appropriate organisational culture must be in place to make use of the technology effective (Skyrme, 1999). This an area where the agent technology can provide potential solutions. The usefulness of the application of the agent technology has been highlighted in Bradshaw *et al.* (1997).

However, most agent-based systems available today operate on proprietary frameworks. They make use of proprietary underlying models and legacy script languages, and target corporate proprietary and legacy databases. This results in limited application interoperability, poor integration in large-enterprise information systems and limited ability to extend (e.g. by direct integration of other pre-built components not based on the same agent network) and to follow the market evolution (Zarli *et al.*, 1998).

8 Data warehousing solutions to knowledge management

Data warehousing emerged as a result of two major developments in information and communication technologies: improvement in relational database management systems, and advances in middleware products that enable database connectivity across heterogeneous platforms (Hackathorn, 1993). On the other hand, there was increasing demand to separate informational processing (designed to support decision-making based on stable historical data) from operational processing (designed to run businesses in real time based on current data) (McFadden *et al.*, 1999). Moreover, a data-warehousing solution proceeds by first extracting data and information from a variety of distributed operational systems and organising it in a centralised repository, then adding value to the extracted data through cleansing and transformation that improve its quality and consistency for exploitation by decision-support applications. As a result, a data warehouse has the potential to reduce drastically the need for important resources in order to filter useful data from confounded informational and operational information. This process is illustrated in Figure 4.

The author, at the time of writing this paper, did not come across any reported effective deployment of data-warehousing solutions in the construction sector. This is still in a stage of implementation and experimentation. It is worth mentioning the KMCOP experience, where several leading European construction companies have investigated the use of a large-scale data-warehousing architecture to manage corporate construction knowledge (KMCOP, 1999). The major components of the KMCOP architecture include the KMCOP knowledge-management services, the KMCOP API (which defines an interface to the KMCOP services), and the extensions on top of a set of chosen legacy and commercial applications (Figure 5). The KMCOP services are intended to provide a means of

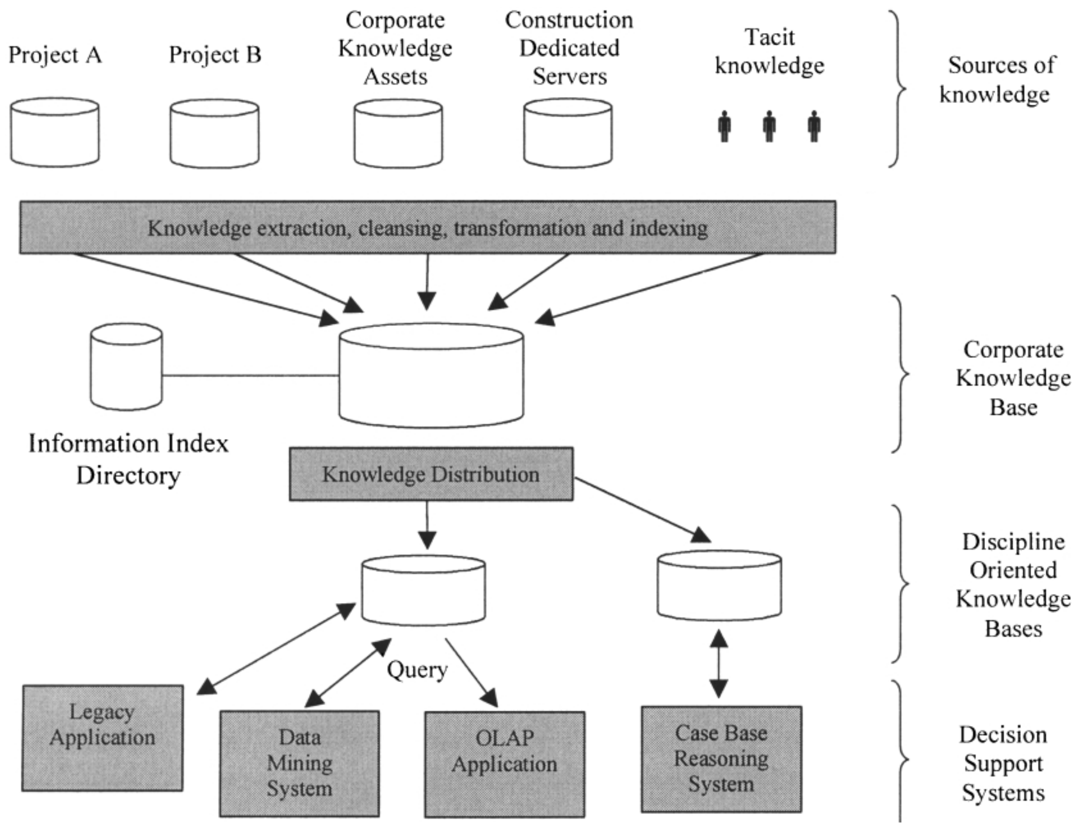

Figure 4 Overview of the knowledge-management process using a data-warehousing solution

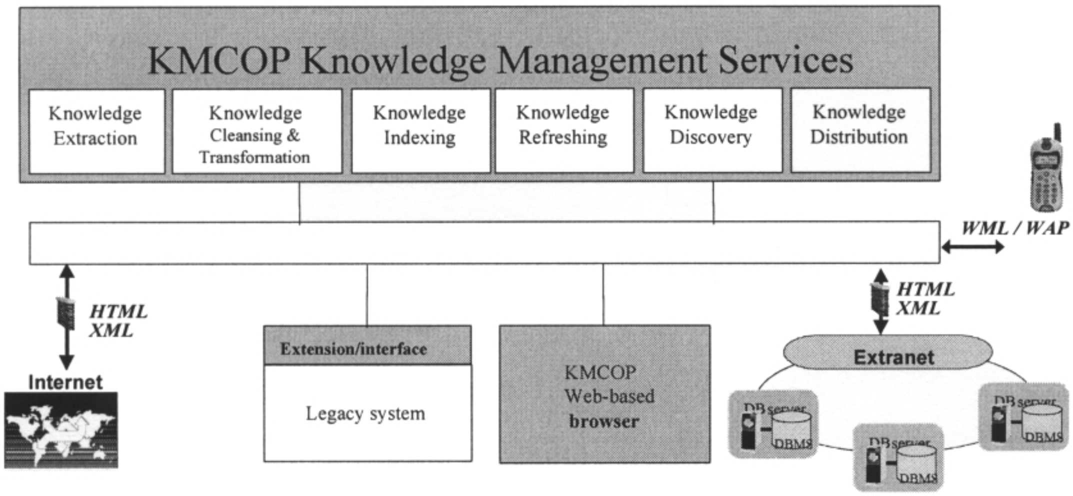

Figure 5 KMCOP system architecture

extending existing legacy, proprietary and commercial systems with knowledge-management capabilities.

It was proposed that the services will be supported by the concept of three-tier architecture, which is well adapted to intranets and virtual enterprises (security, reliability, performance and maintainability) and can also be based on existing standards, including CORBA services, web-compliant formats such as XML and associated document object modelling interfaces (for document-handling) and industry foundation classes (for engineering data).

Data-warehousing is a promising technology that lends itself to the latest developments in relational database-management systems. A variety of end-user interfaces are today available from the leading database vendors to access and analyse decision-support information stored in the data warehouse. These tools are commonly known as OLAP (On-Line Analytical Processing) applications. They provide users, including decision-makers, with a set of graphical tools that give a multidimensional view of their information base.

9 Conclusion

This paper has described a wide range of technologies and approaches relevant to the construction industry in the area of information and knowledge management. First, the paper presented the current problems and limitations faced by practitioners in the construction domain. The different categories of knowledge in the industry were described. Emphasis was put on the potential benefits of knowledge-management approaches in terms of improving working conditions, health and safety, as well as improving the overall quality of buildings. The paper also introduced the characteristics of current technology solutions used in industry. The remainder of the paper was then dedicated to the description of current as well as emerging technologies that can provide potential solutions to managing information and knowledge in the industry. Techniques identified include electronic document management, product data technology, groupware systems, advanced information-management systems, decision-support systems and data-warehousing solutions.

Document management systems are gaining wide acceptance in the construction industry. While a plethora of commercial implementations are today available, there seems to be a lack of integration and inter-working between these systems. The paper introduced the Condor experiment. This provides a framework for integrating heterogeneous EDM systems as well as managing the internal semantics of documents in a way that promotes knowledge reuse. The author believes that document management systems constitute a fairly basic but promising approach to managing knowledge in the construction industry.

In terms of product data technology, available standards (e.g. STEP and the IAI/IFCs) normalise product information for the purpose of data exchange and sharing. This constitutes a valuable basis for product information and knowledge reuse. However, these standards do not address interoperability issues between product components. Some leading CAD vendors, including Bentley Systems, are undertaking promising developments in the area of engineering components. The author believes that these will constitute, in the near future, a major improvement in the way knowledge is captured, structured, shared and reused.

In terms of groupware technologies, despite the availability of several commercial offers, construction project actors do not seem to be yet ready to embrace workflow-based processes. The paper introduced the OSMOS project, which aims at developing Internet-based services that support teamwork in the construction domain. OSMOS is expected to make advances in the area of knowledge management by proposing tools and also investigating the human, social, organisational, and process issues impacting on knowledge management in the context of construction virtual organisations.

The paper then presented the COMMIT project, aimed at providing advanced information management solutions to the problems of information-versioning, change-notification and recording of intent behind decision. COMMIT provides an ideal environment for knowledge elicitation and reuse as its proposed model-based environment can be used to track dependencies between information in order to infer rationale behind modifications introduced throughout the project life cycle.

In terms of advanced decision-support systems, a plethora of KBS and CBR prototypes or systems have been developed. While these systems provide satisfactory solutions for specialised domain problems, they remain seldom when facing the increasingly complex variety of sources of knowledge and the formats and media in which they are stored. This is an area where agent technology promises to deliver adequate solutions.

Finally, data-warehousing techniques have been described and presented as a potential solution for knowledge management in the construction industry. The author gave a brief presentation of a project that brings together several leading European construction companies in order to explore the applicability of data-warehousing to construction.

However, the organisation and processes of construction projects must change in order to adopt effectively the technology-based solutions to knowledge management in the industry. In this context business process re-engineering is an important ingredient for the deployment of the techniques and approaches mentioned above. This is a very complex area of research as related in Vakola (1999).

It is hoped that the present paper, through its information and knowledge management review, will stimulate researchers and practitioners around this very important topic, and will help to remove some cultural barriers that still exist within construction organisations as regards the use and deployment of process and technology-based solutions to knowledge management.

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