Employing Product Data Management Systems in Civil Engineering Projects – Functionality analysis and assessment

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Abstract

Product Data Management (PDM) systems are well established in the manufacturing industry. Here, they form the standard solution for the central storage of all data relating to a product and the processes involved in its manufacture. Particularly the consistent management of CAD models, including sophisticated versioning techniques and access rights management as well as the integrated workflow management are attractive features for using PDM systems also for civil engineering projects. This paper investigates the technical concepts behind PDM systems and compares their suitability as a data management solution in civil engineering projects with that of Document Management Systems and Product Model Servers. Alongside a comparative study of the major PDM systems available on the market, we also present a case study involving a PDM system that has been employed for a concrete civil engineering project.

Introduction

Large sections of civil engineering projects are realized today with the help of computers. At the same time, the construction industry is struggling with an enormous data management problem. In the worst, but not uncommon case, the various digital documents produced during the planning and realization of a construction project, including plans, text documents and 3D models, are neither stored centrally nor linked to each other. This results in a great deal of time spent searching when specific data are required, and usually makes the entire construction project more costly, since the risk of delivering incorrect or inconsistent information to the construction site becomes extremely high.

On the other hand, the manufacturing industry, which faced similar data management problems at the beginning of the 1990s, has since introduced powerful IT solutions that are capable of solving much of the data management problem. This is especially true for the automotive industry, where almost all enterprises today make use of a centralized product data management (PDM) system.

The reasons for the technological gap between these two industries are manifold: The most important one is their diverging organizational structure. While the automotive (manufacturing) industry is dominated by so-called original equipment manufacturers (OEMs), who manage large parts of the engineering and production processes and can accordingly determine the IT infrastructure, the construction industry is heavily fragmented into small and medium-sized companies that form ad-hoc teams for the duration of a project. Another important difference is that, in the AEC sector, the planning and construction phases are usually realized by different companies and, in the case of publicly funded projects, are kept strictly separate from one another.

The ForBAU research cluster, sponsored by the Bavarian Research Foundation, was created in response to the construction industry's demands for improved data flow and data management. ForBAU aims to provide the technological foundations for creating a “Virtual Construction Site”, where the planning and realization of construction projects are closely integrated through the extensive use of digital models, computer-based simulation, identification technology (RFID) and modern logistics approaches (Borrmann et al. 2009a). The project focuses on infrastructure projects, i.e. the construction of roads and bridges. One of the main goals of the project is to identify suitable IT solutions for improved data management. This paper presents the results of assessing Product Data Management systems for this purpose.

Related work

According to FIATECH, of all the major problems the construction industry is currently facing, the lack of a suitable data management solution plays a dominant role, resulting in difficulty in accessing accurate data, information and knowledge in time (Shen et al. 2010). The European ROADCON project (Rezgui and Zarli 2006) has also identified the improvement of the data management in construction processes as a major challenge. In a comprehensive survey, Shen et al. (2010) have presented the state-of-the art of systems integration in the AEC/FM sector. According to the authors, systems integration is increasingly becoming an important prerequisite for achieving efficient and effective collaboration.

As early as the late 1980s, the idea of using a shared data model comprising all relevant product and project data emerged in response to the data management challenges. Björk (1989) presented a first proposal for a building product model, other proposals followed (Augenbroe 1994, Katranuschkov 1994, Tolman and Poyet 1995). Today, the Industry Foundation Classes (IFC) provide the most comprehensive data model for storing and exchanging building information (Liebich et al. 2006). However, the IFC do not currently include entities for modeling infrastructure constructions, such as roads and bridges, although corresponding extensions are under development (Yabuki et al. 2006). On the other hand, the neutral data format LandXML provides a means for exchanging roadway design data (Ji et al. 2009).

Standardized product data models, such as the IFC, help to achieve interoperability between different software products. Data conforming to such data models can be exchanged using files or shared using a database solution, called a Product Model Server. Product model servers are especially designed for supporting collaborative work by providing transaction management, concurrency control and access control among other features (Katranuschkov and Hyvärinen 1998, Chen et al. 2005, Bakis et al. 2007, Scherer 2007, Kang and Lee 2009, Beetz et al. 2010). Of particular importance for collaboration in multidisciplinary teams are not only the support for partial model extraction and re-integration (Weise et al. 2003, Nour 2007) but also model versioning (Nour et al. 2006, Nour and Beucke 2008).

Product model servers seem to be the most powerful and sustainable solution to the construction industry's data management problem (Kiviniemi et al. 2005). However, a number of practical issues prevent the widespread employment of product model servers in practice (Plume and Mitchell 2007, Kiviniemi et al. 2007, Howard and Björk 2008, Jørgensen et al. 2008, Gielingh 2008, Rezgui in press), including the loose implementation of the IFC standard by Building Information Modeling (BIM) software, which results in data loss when the neutral file format is used (Pazlar and Turk 2008, Gieling 2008), the missing workflow features as well as the missing support for unstructured documents, such as text or spreadsheet files.

For these reasons, a number of researchers have investigated the use of Electronic Document Management (EDM) systems for construction projects (Turk et al. 1994, Rezgui 1998, Hajjar and AbouRizk 2000, Gabrielaitis and Baušys 2006, Björk 2006). As explained later on in more detail, EDM systems rely on the storage and management of files. They are therefore the technologically simpler but, at the same time, the more flexible solution. Most importantly, it is possible to store files in any format, thus providing a means of handling documents that are not covered by a standardized product data model while simultaneously avoiding the aforementioned data loss. Accordingly, EDM systems are currently used much more frequently in practice than product model servers (Björk 2003, Björk 2006). Within the EU projects ToCEE (Scherer et al. 1997) and Condor (Rezgui and Cooper 1998), approaches enabling a smooth transition from document-centered to model-based data management have been investigated.

For other industries, such as the automotive and manufacturing sector, document management solutions have been significantly expanded to comprehensively support CAD functionalities. The resulting systems have been coined Product Data Management (PDM) systems. Hameri and Nihitilä (1998) present an exploratory study on the use of PDM systems in a one-of-a-kind industry. They used four examples to show how PDM systems are employed to ensure continuous data management throughout the entire product life cycle while supporting distributed design and manufacturing operations. However, all presented examples stem from the manufacturing industry.

Liu and Xu (2001) review PDM technology in general, and discuss how web-based infrastructures enhance traditional PDM systems. A number of PDM systems that implement web technologies are reviewed, and some industrial implementations are presented.

Helms' Ph.D. thesis (Helms 2002) provides some detailed definitions of PDM functionalities. It puts forward the argument that the use of PDM functionality is a prerequisite for concurrent engineering since it makes it possible to handle preliminary information in a controlled release and change process. Helms shows that deploying PDM systems results in more efficient and more effective development processes.

Demands on data management systems in civil engineering projects

A typical civil engineering project, such as the design and construction of a roadway, including its bridges, is a joint effort undertaken collectively by a number of different protagonists. This includes the client and later owner, which is usually a governmental institution, one or more planning offices, diverse information providers (consultants) such as surveyors, subsoil engineers and structural engineers, and the contractors who finally implement the construction of the roadway and the buildings.

Throughout all the design and construction phases, a great variety of digital data is generated. Data formats range from ASCII files, representing point clouds captured by terrain surveying, to CAD files, containing digital drawings of the bridges, and scanned versions of material delivery documents. Due to the legal regulations in force in most countries, this data is not normally exchanged electronically but in the form of hard-copy documents. The digital information consequently gets lost, which means that successors in the design workflow have to re-enter data in their software systems which had already been available in digital format. This leads to considerable inefficiency in the overall design process.

However, even if the data is exchanged electronically, two important issues remain: First, the interoperability between the software products involved needs to be assured. This is especially challenging, since each of the different design tasks is usually realized by means of a different program. Secondly, the design and process data must be made available and accessible to the right parties at the right time. Whereas the interoperability problem has been addressed elsewhere (Ji et al. 2009), this paper focuses on the data management aspects.

In a number of interviews and workshops organized within the ForBAU project, the following key requirements for a suitable data management solution for civil engineering projects have been identified:

- Document management: The system should be able to store any type of electronic file. With each file, meta-data should be associated to allow for an easy retrieval. The system should enable the long-term preservation of all data. In addition, the system should be able to associate different documents with one another and arrange them in a hierarchical structure.
- CAD model support. Apart from providing preview functionality for CAD models, the system should also be able to capture aggregation hierarchies

of CAD files. ’Is-part-of‘ associations are especially important to reflect the relationships between CAD files.

- Access control: Read/write access to files should be granted to authorized persons only. Therefore a sophisticated rights management must be available. Every single access to files should be tracked.
- Concurrency control: The system should either prevent concurrent modifications of documents or provide a means of merging different versions. This particularly applies to CAD files which are subject to intensive collaborative work.
- Version control: The system should be able to track the version history of a document and provide a way of identifying who has changed what at which time. It is especially important to associate corresponding versions of different documents that are related to each other. Also a rollback functionality should be provided, both for single documents and for a network of interrelated documents.
- Workflow support: A status should be assignable to each document (such as *in work, approved, released*). For each state, it should be possible to define who is authorized to access, modify or delete the document. Status changes initiated by a user should optionally invoke one or more actions to be performed by the system, such as notifying the succeeding person in charge per email.
- User interface: The user interface should provide easy access to the system, comprehensive search features and preview functionality for the most typical file formats. A web interface should allow access to the system from any computer or mobile device.
- Federated system: According to (Bakis et al. 2007) ’in the construction industry, the use of a single central repository to store the design information is not usually a viable option due to the fragmented nature and adversarial behavior that characterizes the industry‘. Therefore, each of the organizations or companies involved should have an individual data management system forming part of a decentralized architecture. When a document is released and handed over from one party to another, it has to be duplicated and transmitted to the target system. This ensures that the hand-over is clearly documented.

These demands extend those presented in (Amor and Clift 1997) and form the basis for assessing and evaluating PDM systems as a data management solution for civil engineering projects.

Comparison of data management solutions for civil engineering projects

There are solutions potentially suitable for managing data arising in construction projects. The following sections discuss the most feasible ones.

Electronic Document Management Systems

Electronic Document Management (EDM) Systems help to organize electronic documents (files) for distributed work teams by providing a central data platform. EDM systems specializing in the construction sector are also called *project extranet* or *construction collaboration technology* (Wilkinson 2005). Examples of commercial products available include *4Projects, Autodesk Buzzsaw, Aconex, Asite, BIW Technologies* and *Sword CTspace*. These systems, which are usually based on web-server technology, are already in extensive use in the construction industry (Björk 2006).

Files managed by EDM systems are associated with so-called meta-data. This includes the author or originator, date created and a document description. Accordingly EDM systems are realized as hybrid systems (Figure 1) consisting of a central file repository, also called an electronic vault, and a database that stores the meta-data and links to the actual files (Crnkovic, Asklund and Dahlqvist 2003; Björk 2002). Direct access to the central file storage is prevented, since this would result in inconsistencies with the stored meta-data.

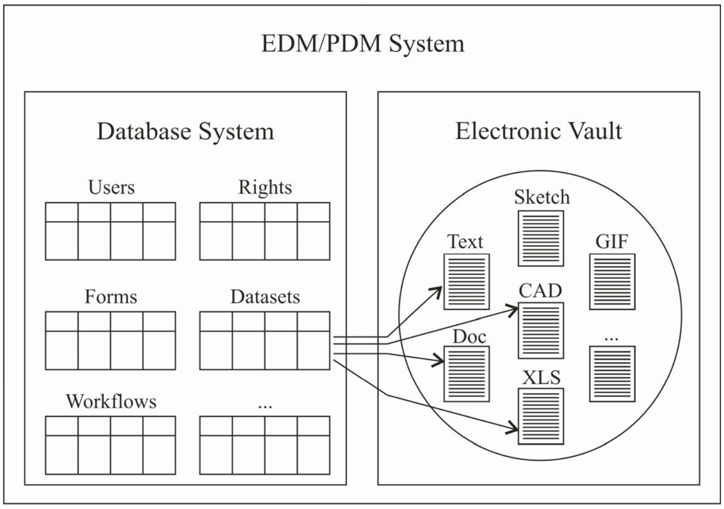

Figure 1: EDM as well as PDM systems consist of two basic components, a database managing the meta-data and a “vault” containing the actual files.

One very vital aspect of meta-data is the *status*, which represents a data set’s maturity. For example, it might state 'at the planning stage' or ‘construction approval granted’. This, combined with the ability to link connected data sets, subsequently helps to organize and retrieve the required information.

Another important part of the meta-data is the document description, such as ‘receipt’ or ‘construction schedule’. It is usually captured when the user checks-in a file for the first time using customized templates. As all the captured meta-data can be used for locating documents, a structured document description forms the basis for powerful search functionalities allowing the user to specify not only the desired document type, but also its content, owner, status and modification time, among others.

As all modifications to checked-in files and meta-data are tracked, a transparent documentation of the content’s development is guaranteed. In this respect, data are typically not updated by modifying files, but by creating new versions of these files. A sophisticated rights management tool makes it possible to attach groups and roles to individual users and accordingly to manage the user’s rights to read, modify or store either files or meta-data. Users accessing construction data in EDM systems typically make use of a so-called ‘rich client’. It provides direct access to all documents managed by the EDM system including the associated meta-data, sophisticated preview and search functionalities as well as the possibility to check-out (download) and check-in (upload) particular documents (Figure 2). So-called integrations are frequently provided, i.e. data can be imported directly to the EDM system from the design system using special gateways. Some vendors also provide a limited ‘web client’ function to aid access to required data directly via the internet browser. Consequently, subcontractors or project members using mobile devices are also able to access the central information platform.

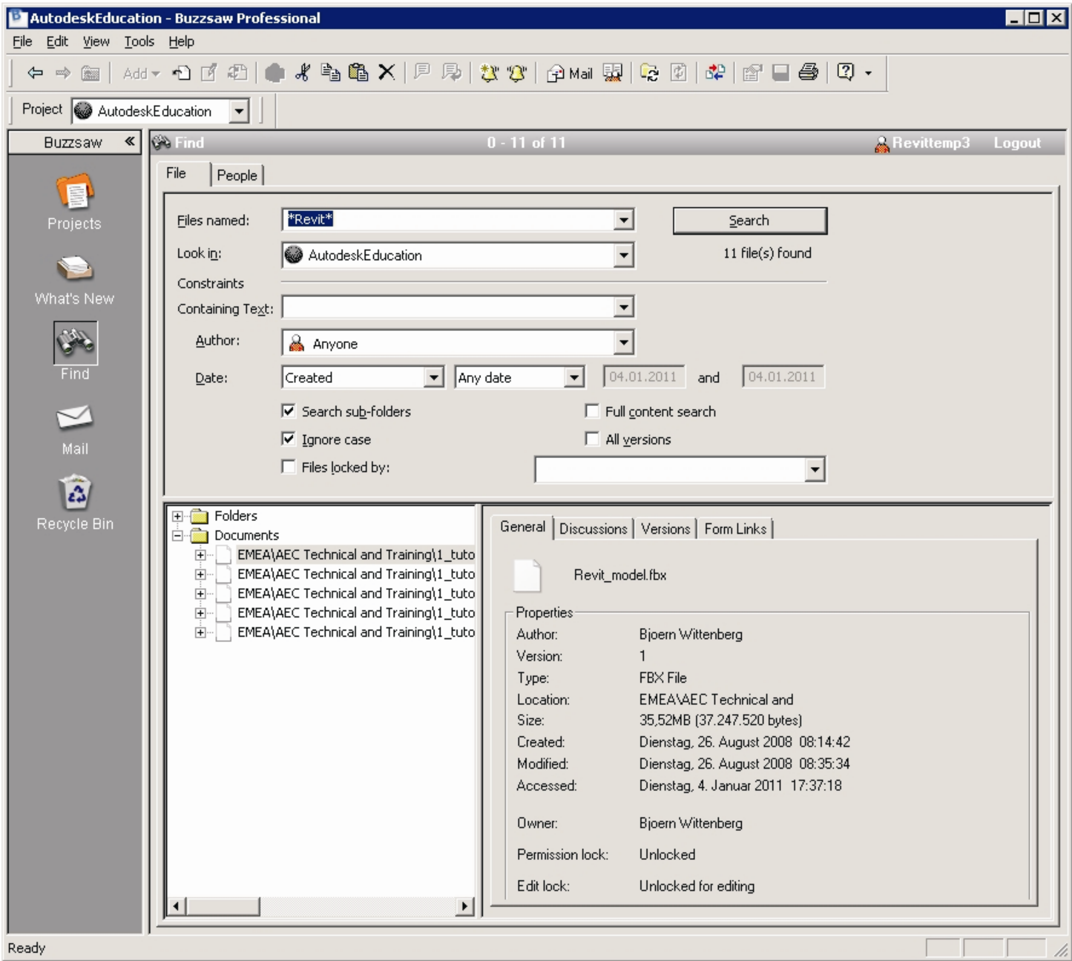

Figure 2: Rich client application of Autodesk Buzzsaw. It provides direct access to all documents managed by the EDM including the associated meta-data, sophisticated preview and search functionalities as well as the possibility to check-out (download) and check-in (upload) particular documents.

Another important feature of EDM systems is the provision of so-called workflow management modules, which allow users to speed up operational procedures, such as the circulation of plans. Assuming that a construction planner is entitled to change the status of a planning document from 'at the planning stage’ to 'under review', two reviewers can automatically be instructed to survey the plan. These reviewers can now either reject or approve the work of the planner. If the planner's document is rejected, the reviewer can add explanatory notes (red-lining) and send the plan back for revision. The status of the document consequently changes either to ‘construction approval granted’ or ‘under revision’, as the case may be, and the EDM system records every process as it occurs. Additionally, most systems provide notification mechanisms that inform the respective users about status changes or assigned tasks.

Examples like this demonstrate how a sophisticated workflow management system can accelerate and accurately document recurring processes in construction projects. Apart from workflow management, some EDM systems also support a shared calendar, virtual discussion forums or an integrated task management.

EDM systems can be used either for communication within a company or between different companies (intra-corporate). So-called Enterprise Content Management (ECM) systems usually manage all the documents generated by a company. A project extranet, on the other hand, provides an easy-to-use intra-corporate document management functionality. Thus, contractors, planners or construction companies can always access the latest, valid files.

However, despite the huge range of functions provided by EDM systems, there are serious limitations in handling CAD model data. Since EDM systems are document-oriented rather than component-oriented, they are not able to manage the hierarchical structure of CAD models. Moreover, an information granularity problem arises: EDM systems can only keep track of the modification of files as a whole, but do not have any information about which modification has been performed within the file. If a file contains large parts of a CAD model, the users are unable to track any modifications. A similar problem occurs with respect to the locking mechanism: Only an entire file can be locked – the locking of parts is not possible.

Product Data Management Systems

Product Data Management (PDM) systems enhance EDM systems by smoothly integrating CAD data (Helms 2002, Saaksvuori and Immonen 2004). They originate from two different roots. As designing products in mechanical engineering became increasingly computerized, CAD data and corresponding product structures had to be managed with the help of a computer, as well. The first PDM systems to be developed featured this functionality only (Crnkovic, Asklund and Dahlqvist 2003).

Over the years, companies became aware of demand for managing unstructured documents, such as requirements or data specifications within the PDM environment, too. Accordingly, manufacturers added EDM functionalities to their PDM systems. However, producers of EDM systems also kept their eyes on the needs of the market and likewise generated auxiliary modules for handling product structures and engineering data. This demonstrates the second branch of the development of PDM systems.

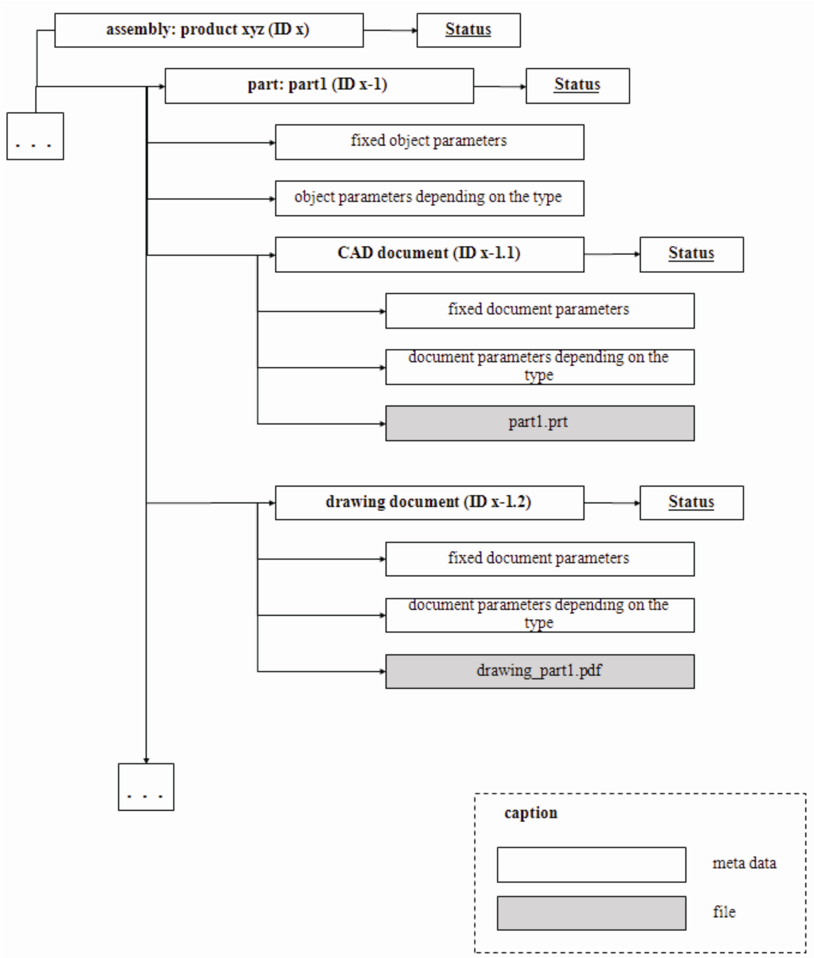

Figure 3: Structuring of projects, parts/containers and documents within PDM systems

EDM and PDM systems differ in the structuring of the data. Whereas EDM only handle projects and documents, PDM systems are additionally able to manage product components. These abstract items can be regarded as containers, where all the data relating to a particular component is included, such as CAD files or drawings. The CAD files contained therein which only represent one single component are geometrically linked to other components in an assembly file. Projects, parts and documents are tagged with meta-data. Figure 3 shows a typical data structure of a PDM environment.

The procedure of decomposing the entire CAD model (CAD assembly document) into several small files (CAD documents) representing individual components is typical for the functioning of Mechanical CAD (MCAD) systems. However, this technique is also supported by Architecture, Engineering and Construction (AEC) CAD systems by using external references (XRefs), as in Autodesk AutoCAD or Autodesk Revit. For each MCAD file or single component, one part is created within the PDM system. Other related documents, such as drawings derived from the 3D model are then imported into this container. Unfortunately, this function makes the smallest unit of information concerning CAD model data depend on the granularity of files imported. Consequently, the constructing engineer is responsible for manually dividing the CAD data into reasonable portions of data sets in order to achieve component-oriented results. Assuming the basic operating principles are accurate, however, PDM systems pave the way for part-oriented work and clearly arranged product structures (Eigner and Stelzer 2001).

Cross-references make it possible to locate components and the quantities involved and access the documents pertaining to this particular part. Bills of material (BOM) are generated automatically on the basis of the product structure. Creating product structures and geometrically linking the parts to one another within the PDM environment is convenient, as there are so-called in-depth integrations available for many CAD systems. In that case, the corresponding CAD program provides direct access to the CAD data stored in the PDM system, automatically synchronizes the product structure, and releases all locks as soon as the CAD document is closed.

Linking parts and creating the product structure are automated background processes. Gateways to Enterprise Resource Planning (ERP) systems ensure the data is embedded properly into the companies' IT infrastructure. Like most EDM, PDM systems offer a preview of content stored in the database within the user interface. Another important feature that PDM systems inherit from EDM systems includes the possibility to define and execute workflows (Figure 4).

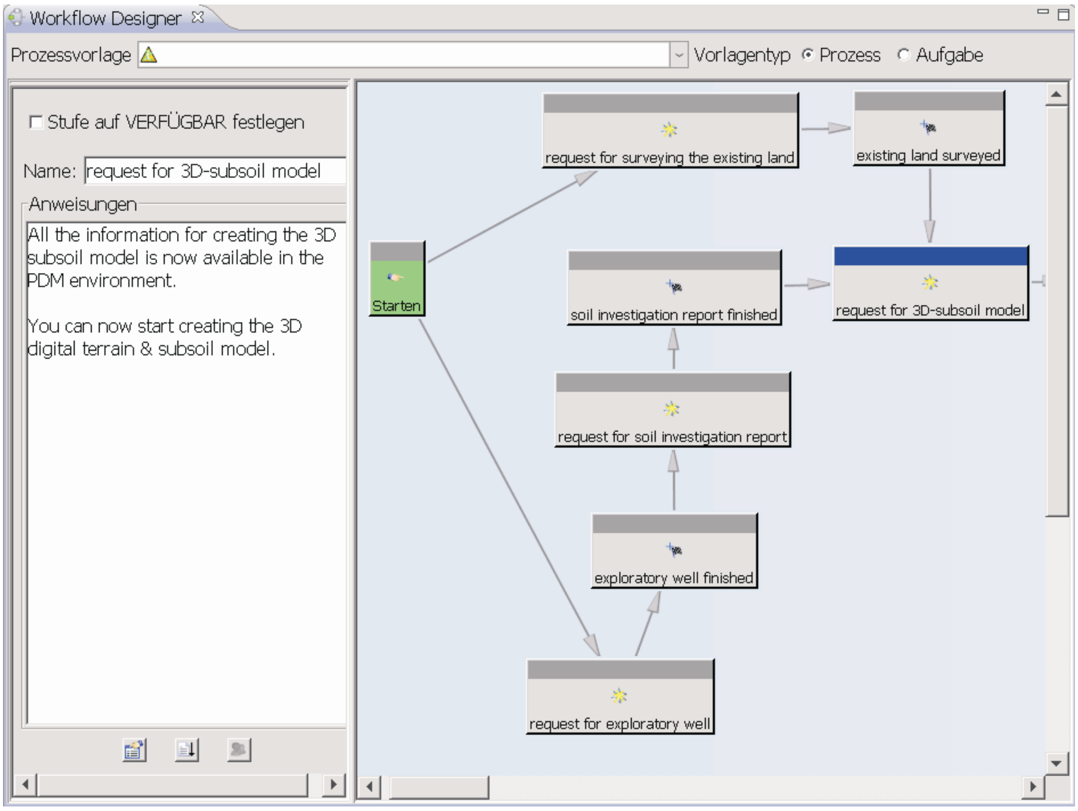

Figure 4: Screenshot of a simple workflow template. Each box corresponds to a certain state of a document, part or data container. Arrows indicate status changes initiated by the user. Each status change can be associated with one or more actions to be performed by the system, such as user notification via email, for example. (Product: Siemens Teamcenter 2007)

Beyond the scope of services, there are several good reasons why today's PDM systems have failed to penetrate the construction industry market. Apart from general purpose CAD systems, such as AutoCAD and Microstation, the aforementioned deep CAD integrations are only available for MCAD systems. Moreover, as PDM systems are used at intra-company level over a long period of time, the producers of PDM systems have not put much effort in making their systems easy to customize. Hence, the costs and labor hours required for adjusting them are immense. In addition, there are neither templates nor add-ons for construction projects but only for mechanical engineering matters.

Product Model Servers

Product Model Servers offer an object-oriented management of product models defined using the Standard for the Exchange of Product model data (STEP). For exchanging digital building models, there is a specific STEP-based data model called Industry Foundation Classes (IFC) (Liebich et al. 2006). Once CAD models have been converted into the neutral IFC format, they can be uploaded to the central product model server, where everyone involved in the project is able to access the data. The key aspects of product model servers are (Jørgensen et al. 2008):

- the sharing of product models via data net;
- a rights management with regard to data access;
- concurrent engineering on the basis of one central product model;
- version control and model update history;

However, the mode of functioning differs considerably between EDM and PDM systems. In both EDM and PDM systems, the lowest information unit for CAD model data depends on the granularity i.e. level of detail of the imported files. It is only by dividing up the entire CAD model that multiple users can access those sections of the model for which they are responsible, or rather lock them and make modifications. By contrast, product model servers store the whole CAD model in a database, thus making it possible to access data in a high resolution irrespective of the granularity of the original file. Hence, users will only check out single elements of the model and rework them, leaving all the other remaining parts on the server unrevised.

Another significant difference lies in the management of changes. As mentioned above, EDM and PDM systems lock files when they are modified. This approach is called *pessimistic concurrency control* (Menasce and Nakanishi 1982), basically preventing the concurrent modification of individual files and thus preventing the occurrence of inconsistencies regarding its content. If a file corresponds to a CAD model part, this part is accordingly also locked. To allow for suitable degree of concurrency, the file granularity of a CAD model has to be carefully chosen. If the granularity is too coarse this can result in a lot of time wasted while waiting for the locks to be released. This is especially critical when employing conventional AEC-CAD systems and storing the model in a single, monolithic file.

Product Model Servers, on the other hand, allow different participants to modify the same items concurrently (*optimistic concurrency control*). Conflicts or inconsistencies that may occur during the simultaneous modifications have to be resolved manually before the extracted sub-models are re-stored in the central server (Borrmann et al. 2009b). Design and engineering in the AEC industry is typically realized within *long transactions* taking up to several weeks (Weise et al., 2004). Since in the case of pessimistic concurrency control, the files under modification are locked during the entire modification phase, all other participants are forced to wait for an inadequately long time span before being able to continue their work. This becomes even more obstructive if large monolithic files are used for storing the entire building model, as common today in the AEC domain. Optimistic concurrency control on the other hand, allows all participants to work in parallel, thus providing more flexibility and achieving a better overall performance. Accordingly, most researchers deem optimistic concurrency control to be more adequate for the workflows common in the AEC industry (Amor and Faraj, 2001, Weise et al. 2004, Nour 2007, Koch and Firmenich 2011).

Although product model servers seem to be a feasible solution for a part-oriented management of data arising in construction projects, they have not succeeded in widely penetrating the market so far. One reason is that neither proprietary CAD files nor unstructured documents characterizing building components such as special requirements or quality related reports can be attached (Froese 2003). In addition, practical work with IFC files, which Product Model Servers require, often fails due to conversion errors (Jørgensen et al. 2008, Björk 2003). Finally, today's Product Model Servers hardly support workflow management features and get into difficulties with large amounts of data.

Comparison with requirements

The features provided by the different data management technologies have been compared against the requirements identified above. The results shown in Table 1 indicate that today product data management systems have to be seen as the most suitable data management solution for civil engineering projects.

	Document Management System	Product Data Management Systems	Product Model Servers
Document Management	✓	✓	✗
CAD Model Support	✗	✓	✗
Access Control	✓	✓	✓
Concurrency Control	✓	✓	✓
Version Control	✓	✓	✓
Workflow Support	✓	✓	✗
Customizable User Interface	✓	✓	✓
Federated System	✓	✓	✗

Table 1: Comparison of provided features of different data management solutions with the requirements identified.

Comparative study

To identify the most suitable PDM solution, a study was performed comparing major Product Data Management systems available on the market. These included Aras, Autodesk Vault Manufacturing, Bentley Projectwise, CIM Database, Dassault SmartTeam, keytech PLM, Procad PRO.FILE, Siemens Teamcenter and Solid Works PDM Enterprise.

The evaluation was based on a requirements list. An extensive literature research (Amor and Clift 1997, Björk 2003, Chan and Leung 2004, Rezgui and Cooper 1998, Turk et al. 1994) as well as interviews and workshops with German building authorities, construction planners, building firms and software manufacturers such as *SSF Ingenieure GmbH - Consulting Engineers, Obermeyer Planen + Beraten GmbH, Max Bögl Bauservice GmbH & Co. KG, Bauer AG, RIB Software AG* or *Siemens Industry Software GmbH & Co. KG* helped gathering and structuring as many requirements as possible.

Definition of benchmarking criteria

The following benchmarking criteria have been derived from these requirements:

1. Data management
   - consistent management of hierarchic CAD models
   - management of derived drawings
   - concurrent engineering: multiple participants working with the CAD model
   - vault with check-in / check-out: locking of items under modification
   - versioning of data sets, modification tracking
   - management of data containers: option of pooling multiple documents
   - independence of CAD system: deep integration for numerous CAD systems
   - document management: management of documents other than CAD files and drawings
   - automatic generation of files in neutral formats
   - notification system
   - association of attributes for classifying items
   - integration of external tools and databases
   - referencing of datasets
   - unique identification numbers on dataset level
2. Visualization
   - file viewer: should support many CAD formats, Office files as well as PDF
   - visualization of 3D models
   - model interaction (generation of cross-sections etc.)
3. Requirements management
   - integration of contract documents / tender documents
4. Project management
   - integration of construction time schedule
   - 4D visualization
   - task management
   - unique identification numbers on project level
5. Process management
   - free modeling of workflows
   - redlining / mark-up for documenting changes and change requests
6. Rights, roles and persons
   - rights management

- roles management
- group management

7. Interfaces
   - easy integration of legacy software
   - programming interface available
   - documentation
8. Communication
   - web client
   - multi-language support
9. Ergonomics
   - intuitive design of GUI
   - personalized GUI
10. Administration and customizing
    - creation and adaptation of workflows
    - creation and adaptation of meta-data attributes
    - involvement of team members
    - project-based customizing
11. Costs
    - licensing costs
    - customizing and consultation costs
    - training costs

At an interdisciplinary workshop with the consortium of construction planners, building firms and software manufacturers cited earlier, these benchmarking criteria were weighted according to their importance (Figure 5). Besides proper Data and Rights Management functionalites, particularly ergonomic aspects and the possibility to easily adjust the system to the building project's special requirements are important.

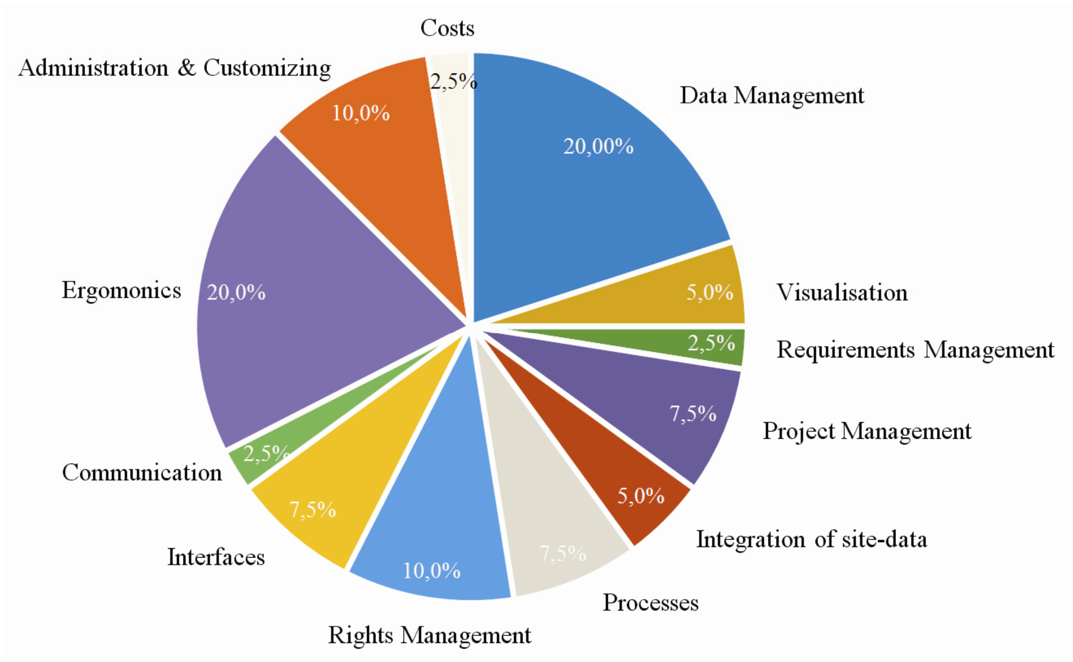

Figure 5: Weighting system for benchmark criteria

Assessment

In order to benchmark PDM systems based on the weighted catalog of criteria, it was first necessary to develop an evaluation system. The degree of performance of each requirement was quantified by a utility value analysis (Lindemann 2009). Qualitative information was converted into quantitative data by means of value functions. The requirement's degree of performance score was calculated by multiplying its degree of performance by the weighting factors set in advance. Figure 6 illustrates the evaluation system.

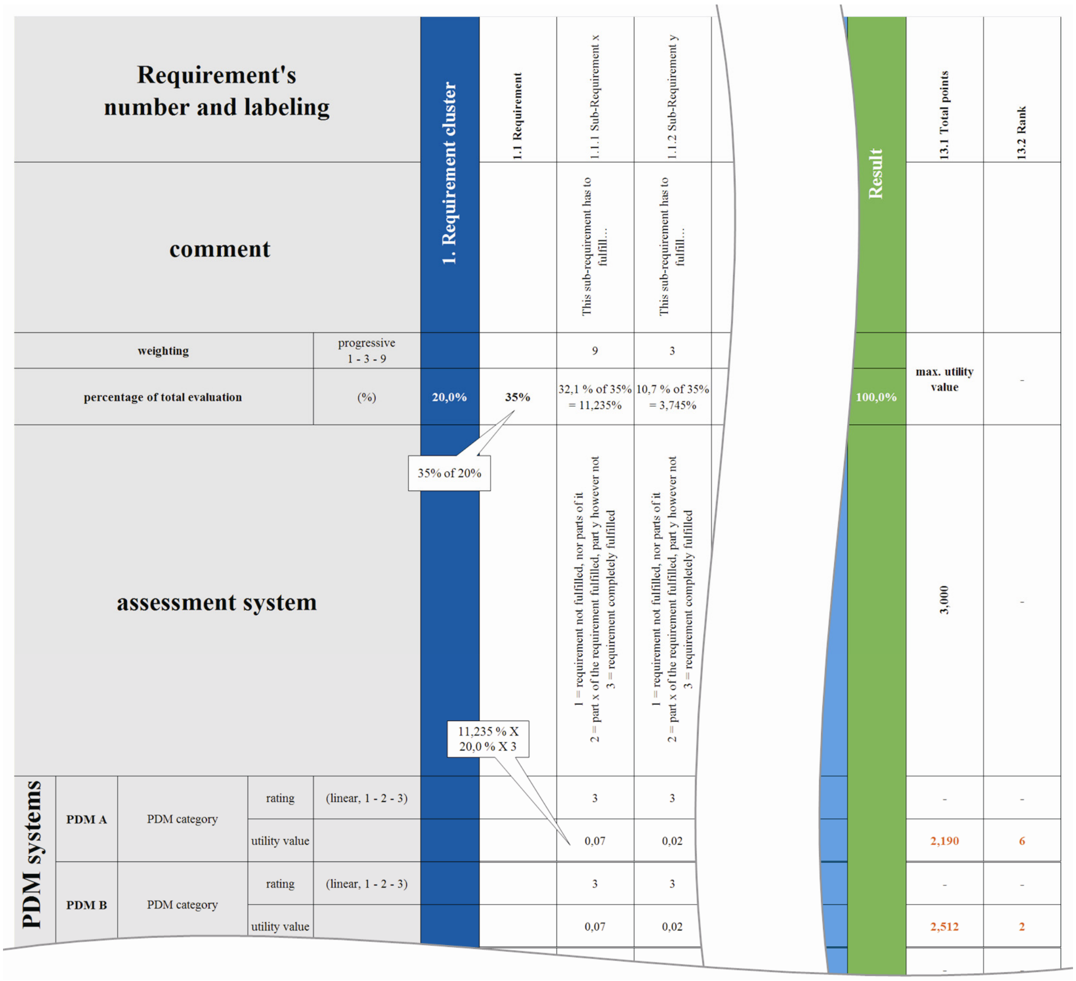

Figure 6: Rating scheme for assessing PDM systems as a basis for managing data in construction projects

By summing up the degree of performance scores of each requirement, it is possible to assess the degree of suitability of each PDM system. Before analyzing the market in order to identify an adequate PDM system as a basis, conclusive criteria such as “workflow management module enabling the release of groups of components” and “multiple statuses which can be defined freely” were defined to set limits. This helped to reduce the number of key feasible systems from 43 to 9 in the analysis. The remaining products were classified and assessed systematically according to the rating system presented. Amongst other factors, the assessment is based on live demonstrations, interviews, statements from reference customers, course of instructions and experience with test installations. Figure 7 shows the result of the PDM benchmark for construction lifecycle management.

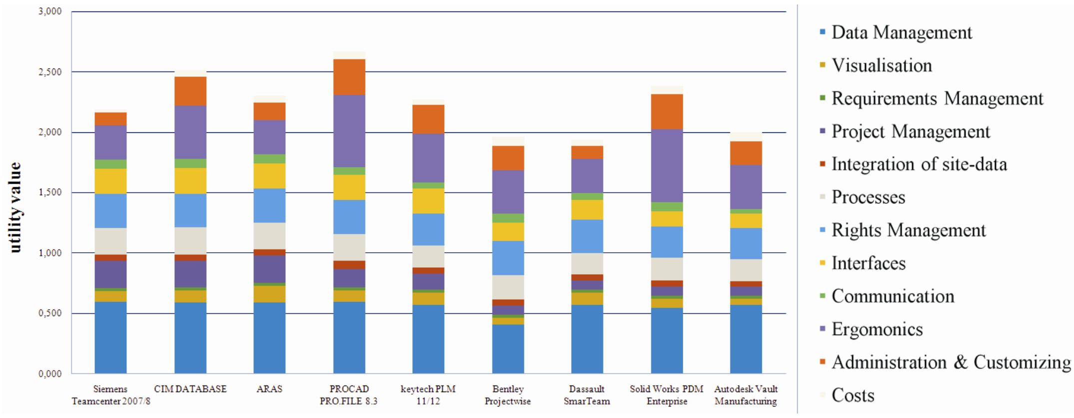

Figure 7: PDM system benchmark for managing data in construction projects – results

The result shows that there are few differences in terms of the total score, especially with the most feasible systems. As Procad PRO.FILE fulfills most of the requirements apart from a sophisticated project management functionality, CIM Database is very good at managing and monitoring tasks and schedules within the PDM environment. Regrettably, the user-friendliness is inferior to PRO.FILE. Aras is an open source PDM tool providing a wide functional range including document and product data management, workflow management and project management. Again the user-friendliness lags behind that of keytech PLM, Procad PRO.FILE and Solid Works PDM Enterprise. The latter, in turn, has a suboptimal rights management and can only deal with a few CAD systems. keytech PLM 12 appears to be a suitable PDM basis, but unfortunately version 12 was not completely finished at the time the PDM benchmark was executed. Siemens Teamcenter indeed fulfills various requirements but is lacking in terms of customization and maintenance effort as well as user-friendliness.

In conclusion, the impartial benchmark test resulted in Procad PRO.FILE currently being the most appropriate PDM basis. Although there are some weak spots concerning the project management functionality, it illustrates a proper solution for part-oriented model and document management. Furthermore, it is easy to use and customize, which was one of the key requirements.

Case study: Customization and employment of a PDM system

PDM systems only come with basic functions and cannot be used out of the box. An implementation concept has to be developed for each case of application. The following section describes both the conceptual design and the implementation of a PDM system originally developed for the manufacturing industry for the needs of civil engineering projects (bridges and roadways). The system has been successfully employed in the design and construction of a highway project in Bavaria, Germany. However, due to the high financial risk, it was not used by the parties directly involved in the project but was employed in parallel operations conducted by the researchers.

Within the project, the conventional roadway planning program Autodesk Civil 3D has been employed for designing the roadway and combined with the mechanical engineering CAD system Siemens NX for fully parametric 3D design of bridges (Borrmann et al. 2009a). In consequence, the generated bridge models could be managed by the PDM system in a part-oriented manner.

Figure 8 presents an overview of basic PDM functions and the work carried out within the ForBAU project. As many building related templates can be created by configuration (adjustment), special add-ons had to be developed by programming (customization).

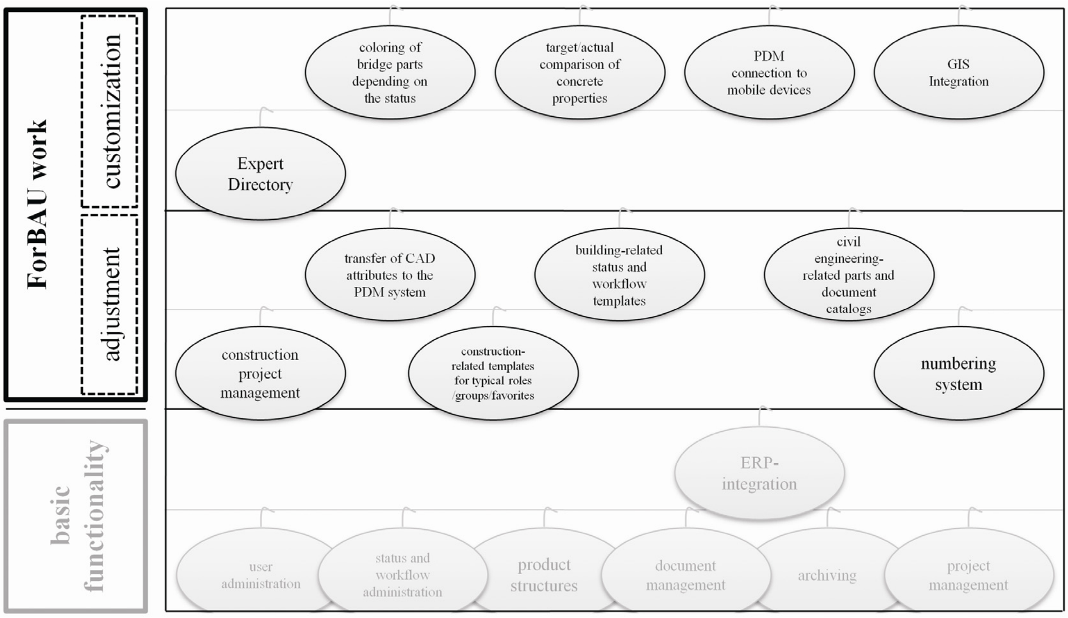

Figure 8: Basic functionality of PDM systems vs. work carried out within the ForBAU project

Civil engineering-related parts and document catalogs

Since there are neither parts catalogs nor templates for typical parts required for bridge and roadway construction projects, they had to be developed. With regard to bridge components, the ongoing work on the IFC bridge standardization contained valuable information which proved to be a useful basis (Yabuki et al. 2006). The requirements were documented during concept workshops with renowned construction planners, building firms and software manufacturers and the PDM database was subsequently upgraded using the relevant data. The screenshot in Figure 9 shows the wizard popping up when creating a new part of a bridge in the ForBAU PDM system.

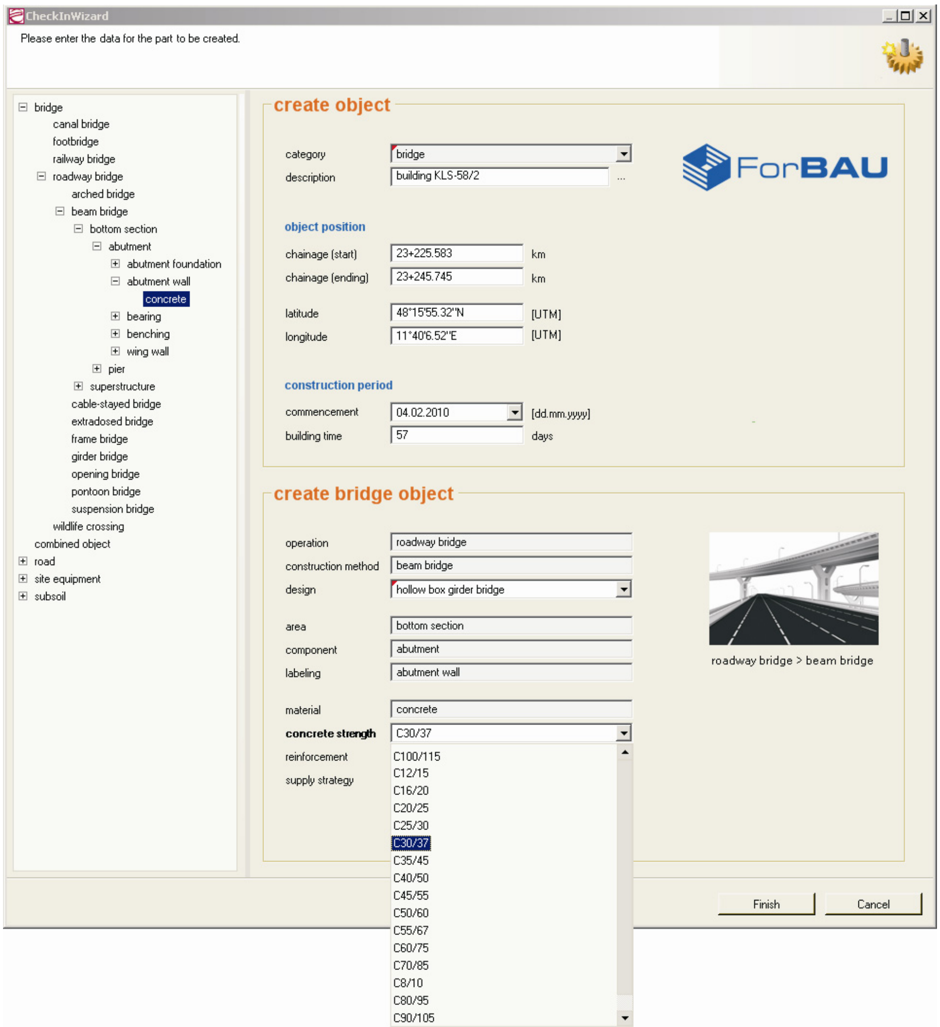

Figure 9: Wizard popping up when creating a new part of a bridge in the ForBAU PDM system

The user can choose what kind of part should be imported into the PDM environment. As shown in Figure 9 above left, he can pick either

- bridge
- road
- site equipment
- subsoil

The top right section of Figure 9 illustrates how the user enters fixed object parameters such as geo-coordinates, chainage or commencement, whereas the bottom right section indicates the labeling of the part, the material or the delivery concept that can be chosen from the drop-down boxes. In the current example the user creates an abutment wall. The information is saved in the database by clicking ‘Finish’. Hence, all parts or components of bridges and roadways can be created within the PDM environment and associated with descriptive attributes.

Similarly, more than 20 typical document types occurring in construction projects can be categorized, such as

- quality reports
- receipts
- minutes of meetings
- CAD documents
- notifications of claim
- pictures
- webcams
- surveying results.

All those document types in turn comprise different attributes, which can either be filled out manually, with the help of predetermined lists, or – for known meta-data such as the creator or the file extension – automatically. For CAD documents, an add-on developed within the scope of ForBAU calculates the volume, mass and bounding box of 3D models within the CAD system Siemens NX and passes the data automatically to the PDM system when importing the model. Accordingly, it is possible to query the PDM database for parts that are heavier than 300kg but do not exceed 1 x 1.5 x 2 meters, for example.

As all construction projects are unique, the templates developed in the ForBAU project are very easy to adapt. Predetermined lists, such as the labeling of the part, can be exported to Microsoft Excel, revised and re-imported to the PDM platform. To structure the data, parts and documents can be linked to each other during the importation process or after the data has been indexed and imported.

Building-related status and workflow templates

The last few sections have focused mainly on introducing solutions for managing construction data, but not the construction processes. In the ForBAU concept, several statuses representing the maturity of parts and documents were developed and implemented. These include:

- planning completed
- construction approval granted
- parts/material delivered
- under construction
- construction completed
- maintained

Thus, all the parts and documents contain information concerning the construction progress. Subsequently, workflow templates were created for recurring processes such as

- integrated planning of roadways and bridges
- construction change management
- request for construction simulations
- request for target/actual analysis.

The workflow template 'integrated planning of roadways and bridges', for example, makes surveying data for the road construction engineer accessible, as the status of the surveying data changes to 'surveying completed'. Afterwards, the road construction engineer draws up the alignment. When he is finished, he changes the status of the data concerned to 'road planning completed'. The bridge construction engineer is immediately informed that he can start modeling the bridge, as the layout of the line is now fixed. This example of one of the workflow processes developed in this context serves to accelerate the planning process, helps to keep everyone involved informed and controls access to the imported data over the building's lifecycle. The rights management can be adjusted for each status and construction section.

In order to keep records of the construction work, building progress information such as 'component delivered' or pictures of damaged parts can be entered and directly transferred into the PDM environment by means of a mobile handheld device (Klaubert et al. 2010). Vital components, such as concrete precast elements, are fitted with a Radio Frequency Identification (RFID) tag during the manufacturing process. By using the same ID on both the real part's RFID tag and the digital part in the PDM system, the information is automatically attached to the corresponding part in the PDM environment. In addition, the parts are colored in a different shade depending on their status. This special building add-on was programmed with the help of the NXopen interface and facilitates the depiction of the building progress.

Geographical Information Systems (GIS) interface

Beyond that a bi-directional interface between the PDM system and Google Earth was created. Consequently the location of construction elements can be visualized by pressing a button implemented in the PDM system. Immediately Google Earth is started and location and corresponding coordinates are displayed. All relevant data corresponding to a construction element can in turn be accessed by following a link attached to the element in Google Earth.

Benefits and shortcomings

The use of PDM systems for infrastructure projects involve (1) costs for licensing, implementing and customizing the system as well as (2) additional, individual efforts for the project members. This additional, individual effort is caused by adjusting to the new way of working and keywording every single object and document. It should be noted that the question of who owns and pays for the system is a problem which has to be solved. However, the overall benefit for the project participants and the success of building operations is immane when employing a PDM system; major advantages include:

- all members stay comparably informed, which results in earlier correction of defects, as there is a binding project platform for all the partners over the entire building lifecycle
- up-to-date models / plans at the construction site due the availability of consistent data and hardly any duplicates
- templates for documents and objects induce standardized technical documentations throughout the construction lifecycle and ease analysis for future projects
- explicitly available document status, history and hardly any conflicts regarding parallel processing due to versioning of content data and change management

- insider trading decreases, as copying or forwarding of data is documented
- search times decrease as a result of multilingual keywording, full-text search and links between objects and documents
- processes such as plan inspections or construction approvals accelerate due to electronic workflows
- object oriented status management permits faster overview of the building progress
- automatic conversion to neutral formats such as TIFF or PDF eases long-term archiving

The aforementioned benefits base on expert assessments of the ForBAU project practice partners.

Conclusion

Product data management systems are basically a suitable option for the data management in civil engineering projects. They provide powerful features including revision and preview functionalities for CAD models, highly customizable workflows and a tight integration with process management solutions and enterprise resource management tools.

Product data management systems can be seen as an ideal interim technology for managing data and documents, en route towards completely model-based planning processes in construction projects. Nowadays, the greatest part of the data generated in construction projects is stored in (native) files and not as part of a building product model. In fact, only a small minority of planning offices apply product modeling (BIM) technology (Kiviniemi et al. 2007). Accordingly PDM systems are currently a more suitable data management solution than product model servers, since they provide a more flexible method for handling any digital document. This applies in particular to civil engineering projects, because no standardized product model is available to date for bridges and roadways.

However, the underlying file-based approach behind PDM technology imposes some serious limitations on the use of PDM systems for civil engineering projects. Most CAD systems employed in a civil engineering context today store their data in large, monolithic files, which results in a granularity that is too coarse with respect to modification tracking, versioning and locking. Mechanical engineering CAD systems that store such parts of a CAD model as individual files and thus provide the required granularity can be used as an alternative, but they lack important features for an efficient application in civil engineering projects.

In contrast to the manufacturing industry where the development of a product is usually carried out under the lead of an original equipment manufacturer, the construction industry is characterized by projects which are realized by a number of stakeholders. Their demand for non-disclosure of critical company data results in the need for establishing a distributed structure of federated product data management systems which exchange documents in a well-defined and controlled manner.

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