



Citation for published version:

Ding, L, Ball, A, Patel, M, Mullineux, G & Matthews, J 2011, 'Lightweight product lifecycle information management for small enterprises', *International Journal of Product Lifecycle Management (IJPLM)*, vol. 5, no. 1, pp. 21-36. <https://doi.org/10.1504/IJPLM.2011.038100>

DOI:

[10.1504/IJPLM.2011.038100](https://doi.org/10.1504/IJPLM.2011.038100)

Publication date:

2011

[Link to publication](#)

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Lightweight Product Lifecycle Information Management for small enterprises

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Abstract: In an increasingly competitive and global market, small enterprises can benefit just as much from Product Lifecycle Management (PLM) as larger enterprises. However, the software currently available to support PLM is aimed at larger enterprises and does not entirely suit the more flexible business processes and heterogeneous systems environment of smaller enterprises. We argue that some of the most important benefits of PLM may be achieved by small enterprises using the combination of a full-featured CAD system with lightweight visualization formats and a system of overlaid annotations that may be applied to a model regardless of its format. We outline a proof-of-concept implementation of these ideas and indicate where further work is needed.

Keyword: Small enterprises, life cycle management, annotation, CAD models

1 Introduction

Within the current global financial climate, information has become the most prized asset of any enterprise, and information management has been playing an important role in the improvement of innovation, organizational performance and operating efficiency [Chaffey and Wood, 2004]. With the introduction of the concept of Product Lifecycle Management (PLM) in the late 1990's and it's targeting a seamless information management environment, most enterprises became convinced that PLM systems can improve the management of the whole product life and enhance collaboration around the world. Meanwhile, this would also allow enterprises to maintain and add value to a trusted body of digital information for current and future use, a process which the Digital Curation Centre terms 'curation' [Digital Curation Centre, 2007]. Recently, more and more large enterprises have started adopting PLM systems to help with the growth and sustainability of information from the whole product lifecycle across different collaborative partners, although they do not yet provide a full curation solution. This puts small enterprises under pressure as to how to reach their positions of competitive advantage within the global market (we define a small enterprise to be one that employs less than forty staff and has an annual turnover of less than £8 million). Such enterprises perform a vital role in the world's economy by contributing to entrepreneurship, employment and innovation. There are in the region of 23 million small enterprises in the European Union, which provide 65 million jobs and represent 99% of all enterprises. In the US, more than 99% businesses are small. In Australia, these enterprises add to around 96% of non-agricultural industries. In the UK, at the start of 2006 there were an estimated 4.5 million business enterprises, 99.9% of which were smaller enterprises. Such enterprises account for 58.9% of all UK

employment and 51.9% of UK's estimated business turnover of £2,600 billion. Thus these enterprises make up a significant portion of the world's economy [Singh *et al.* 2009]. However, investigations show that the implementation of PLM in smaller enterprises remains a challenge [Kaminski *et al.* 2008, Cheung *et al.* 2009].

Previous research has shown that there are fundamental differences in the way that small enterprises conduct their business in comparison to larger enterprises [Thong *et al.* 1996; Bilis and Raymond, 1993; Longnecker *et al.*, 1994]. Therefore any generalization of user need made for the development of a PLM approach for large enterprises is unlikely to be applicable to smaller ones. One of the major barriers is cost, not only of the software, but also of training staff, changing business processes, and integrating the PLM system with existing software. Furthermore, small enterprises normally have differing business processes in comparison to large enterprises [Longnecker *et al.*, 1994], for example, they prioritize responsiveness and flexibility, and usually have looser collaborative relationships with their partners. Thus, current commercial PLM systems are more appropriate for large organizations, but not entirely suitable for small enterprises. This paper proposes a new solution for the management of product-related lifecycle information which in particular supports small enterprises. The proposed method is built around product models and combines the advantages of lightweight representations and annotation techniques.

2 Background

This section provides an overview of three aspects related to the problem and a solution to the problem. The current state of information management in small engineering companies is summarized; also presented is a literature survey of the two technologies employed to solve the issues raised in the first section – namely, that of product representation and annotation in engineering design.

2.1 Status of information management in small engineering enterprises

To survive the changing global market, small enterprises face the same challenges as large enterprises: consideration of the whole product lifecycle and collaboration between partners across the globe. Prior research has shown that smaller companies do not tend to adopt an information system. In particular, it is not uncommon for smaller enterprises not to operate structured PLM approaches; the variety of information sources that are generated are often lost or kept in a variety of locations. With contemporary information technologies this can seem almost negligent for the future development of the enterprise. Some of the reasons for this are identified in the following paragraphs. The core constraint on small enterprises employing complex PLM systems is their lack of resources, commonly known as *resource poverty* [Thong, 1999]. This is not only financial – costs of implementation, training and the additional cost of attracting and paying trained PLM staff [Thong *et al.*, 1996] – but also in terms of human effort. People need to be diverted from their normal task to enter and maintain information about the product. Such companies have a tendency to employ generalist, rather than specialist staff and this is reflected in their ability to adopt information systems [Bilis and Raymond, 1993]. Small enterprises also operate under different management and innovation structures: they are generally highly centralized, with the managing director making most of the critical decisions [Link and Bozenman, 1991]; the enterprises' information management structuring and practices also reflect this [Harrison *et al.*, 1997].

Currently, as with larger enterprises, the information collected by the partners at later stages of a product is becoming more and more important for re-use in developing upgrades and customizations. It is no less true for the small enterprises that design processing and packaging equipment, whose products are used by their customers as resources (e.g. manufacturing equipment) in the production processes. The representatives from technical and service teams/partners frequently visit customers; they generate large amounts of information relating to a product's performance [Sanders and Bromacher, 2000]. Such

information can improve the enterprises' competitiveness by not only strengthening product development (both product upgrades and new product development), but also increasing their customers' productivity by means of higher equipment up-time and reduced investment costs through life. However, the technical or service teams are usually located in different places, and worse, they normally have a very loose or contract-based collaboration with small enterprises. Thus, it is nearly impossible to require that all partners install a single PLM system to share information as in a large enterprise.

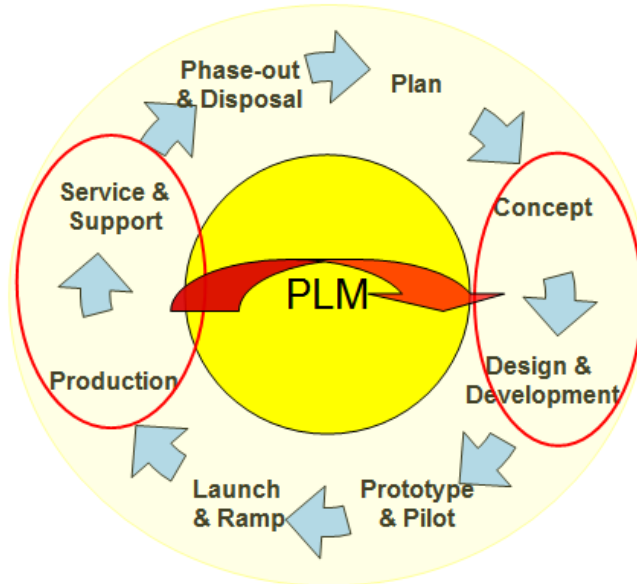


Figure 1 The relationship between the proposed solution and PLM

An investigation has reported into the current state of information collection from manufacturing and service stages, and its influence on small business [Ding *et al.*, 2008]. The results show that the way in which technicians and service engineer's record information is still very informal and includes: notes in personal logbooks, marking up of hard copy drawings, emails and even memories. This leads to three major problems: unknown modifications, incorrect rationale for modifications and inaccurate mark-up of modifications. The investigation highlighted that companies need strong and stable support tools to capture, organize and retrieve product information through life. In response to the above issues, this paper aims to present a solution in a simplified fashion, but achieve some of the most important benefit of a PLM system –information fed back through the whole product lifecycle for re-use in upgrades, maintenance and new product development (as shown in Figure 1).

2.2 Product representation

Conventional Computer Aided Design (CAD) models focus on geometric and topological depictions of the product (McMahon and Browne, 1999). Generally, they are built on one of two basic types of representation: Boundary Representations (B-Rep) or Constructive Solid Geometry (CSG). In addition, most CAD systems integrate further modeling techniques such as freeform surface modeling and feature-based models or parametric-based models. CAD models have been popularly used for product design by both large enterprises and small businesses. During design activities the CAD model is generally produced at the late conceptual and early embodiment stages. The adoption of CAD modeling technologies has provided enterprises large and small with proven advances in product development, and

cost saving throughout the design activity [Astebo, 2002; Hicks *et al.*, 2007, Yan and Firoto, 2002]. With intensive and geographically distributed collaboration, some technical problems and limitations of CAD models have been highlighted, many of which are particularly pertinent to small enterprises. For example, most of their collaborations are based on contracts external to the organization. Thus, they are often unwilling to share all the details of their product models directly to avoid exposing commercially sensitive information to their competitors. Meanwhile, each CAD system has its own proprietary format. It is not a feasible or economically viable solution for every partner to install a copy of each CAD system to view or manipulate product models in their native representations. In addition, the large file sizes of CAD models hamper information transmission between geographically distributed applications and users.

In recent years, a number of lightweight representations have been devised to improve the capability of product representation in collaborative product development. The major formats include: U3D, which aims to develop a universal standard for various 3D data for inter-exchange [Ecma International 2007]; X3D, an ISO standard and successor to VRML, tailored for use by Web applications [Brutzman *et al* 2005]; 3D XML, a lightweight and standard XML-based format that enables users to access and share accurate 3D data quickly and easily [Versprille, 2005]; JT format, which combines facets and B-Rep (Boundary Representation) geometry along with Product and Manufacturing Information (PMI) and textual attributes [JT Files]; PLM XML [PLM Component - UGS, 2005], which integrates collaborative product lifecycle processes by offering a standardized protocol for data interoperability, etc. A comprehensive review has been undertaken by Ball, *et al* [Ball *et al* 2008]. Compared to full CAD model formats, lightweight representations have some advantages, for example, they are typically generated with approximate geometry using various compression methods, so as to protect sensitive information. The small file sizes speed the communication of the models. Furthermore, lightweight representations can be viewed without the aid of expensive CAD packages. For example, U3D is supported from Version 7 of Adobe Acrobat (PDF Version 1.6); X3D tools and applications are freely available (<http://www.web3d.org>) and there are several popular X3D plug-ins for Web browsers, e.g. Xj3D (www.xj3d.org), Flux™ (www.mediamachines.com) and BS Contact™ (www.bitmanagement.de); JT Open Toolkit has been developed to create, read and access JT formatted data on various hardware and operating systems.

2.3 Annotation techniques

Annotation can be simply defined as adding any extra information for various purposes, such as further explanations, viewpoint interpretation, extra descriptions of or comments on the existing entity. Annotation has been used to augment engineering depictions of products with information that is difficult to represent unambiguously pictorially such as information required for manufacturing a product – tolerances, machining processes, surface finishes etc. – using formally specified systems of symbols normally recorded in some level of standard, such as the American Society of Mechanical Engineers (ASME) Y14.41 [ASME Y14.41 2003] issued in 2003. Researchers have identified the use of annotation as a means to reflect an individual's cognitive efforts (e.g. learning, correcting) while interacting with text documents [Cabanac *et al.*, 2008]. Hisarciklilar and Boujut have proposed an approach based on the concept of annotation for supporting design communication, their approach was aimed as a support for collaborative design [Hisarciklilar and Boujut, 2007]. Bottoni *et al.*, produced "MADCOW" a system that offers the possibility to annotate many objects simultaneously and to use multimedia documents as annotations (audio registrations, figures...). Kitamura *et al.* 2006 produced a schema "FUNNOTATION" that enables the user to annotate web-documents with Metadata, which represents the functionality of engineering devices.

2.4 CAD models, annotation and PLM

In more recent times large enterprises such as General Motors (GM), General Dynamic, Boeing and Alliant-Thiokol have expressed the need for a standard to define a unique *Digital Master* (CAD model) as a PLM data repository [Fiorentino et al., 2009]. This idea has not been missed by academia. Work on annotation of product models has been carried out by several researchers. For example, Elinson and Nau [Elinson et al 1997] use a graph to represent machining features, whose nodes and edges correspond to features and its relationships of features. The nodes and edges are annotated with labels by various parameters that may be useful for classification purposes; Hoffman and Joan-Arinyo [Hoffmann and Joan-Arinyo 1998] proposed an architecture for a product master model federating CAD systems with downstream application processes for different feature views, and especially addressed the need to make persistent associations of design information with net shape elements. Ding et al [Ding et al 2007] have shown the knowledge retention capabilities of extending ‘annotation’ in CAD systems to aid constraint-based redesign activities; Davies and McMahon [Davies and McMahon 2006] explored the application of a markup approach to the attachment of information to CAD models. Jung et al (2002) produced a web-based system “Spacepen” using standoff annotation, to draw in and on the virtual environment. It was based on their previous system “Redliner” [Hanson and Wernert, 1997] where users leave text annotations on surfaces in three-dimensional models. Ding et al [Ding et al, 2009b] proposed an annotation approach to allow the association of product data from throughout the whole development process with the geometric form of the product, this was further expanded in Ding et al [Ding et al, 2009c] where an Extended Product Model (EPM) was exploited to revisit and retrieve the information throughout the product development process. Fiorentino et al. developed a graphical user interface “TaDiMa” to address the low usability of Digital master based systems for non CAD experts [Fiorentino et al., 2009].

3 Methodology

The proposed approach considers the aspects noted in section 2.1, i.e. lost cost in production and operation; the need to be controlled by non-specialist staff, simple to operate (not consuming too much staff time) and fit into the centralized operating characteristics of small enterprises. As shown in Figure 2, the framework of the proposed solution includes four aspects: CAD as the central carrier of information, lightweight formats supporting users, lifecycle product information and geometric matching of CAD models with its light weight derivation.

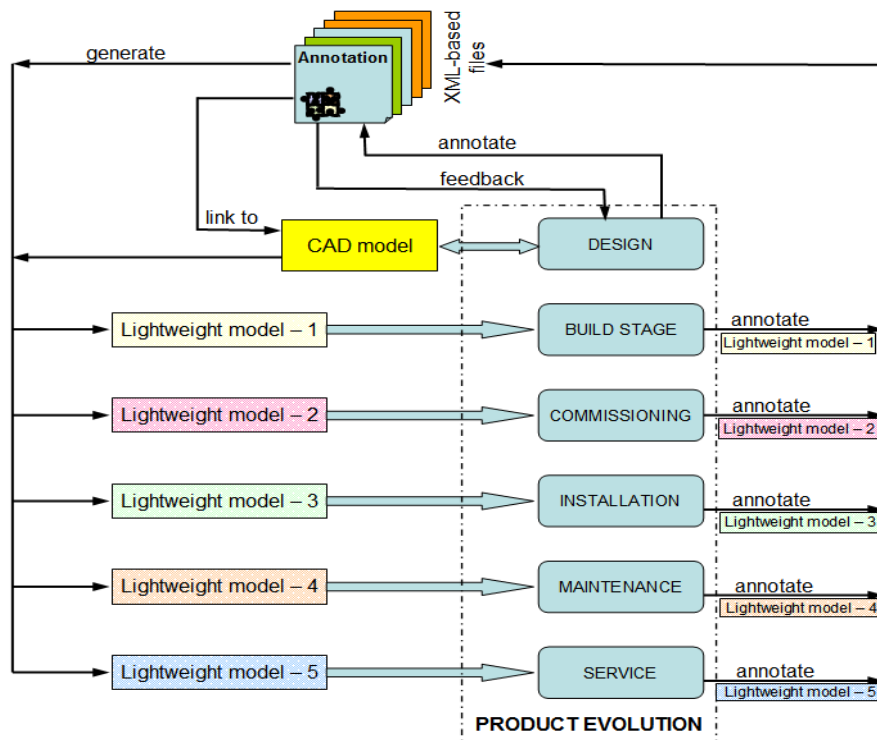


Figure 2 Framework of the annotation of digital models

3.1 The CAD model as a central carrier of product information

A CAD model is defined as a central carrier to link the information generated from the build stage to the in-service phase of a product. The implementation of a PLM system requires companies to adapt their business processes, which involves all staff and their working practices. The ways in which small enterprises do business, though, can be quite different from the business processes of large enterprises. Small enterprises tend to exhibit greater flexibility, for they are able to mobilize themselves to meet market demands in a shorter time than large companies [Baldwin, 2000]. Their collaborative relationships are usually looser and there is a lack of PLM knowledge among staff. Thus, current commercial PLM systems, available for large enterprises, may not always be appropriate for small enterprises [Aitchison and Shaw, 2006]. In contrast CAD systems have been widely accepted and applied in small enterprises. With properties like the clear representation and visualization of geometry and topology, CAD models have the advantage of recording information related to different entities of the product concisely.

3.2 Lightweight formats supporting users at later stages of a product

The industrial workflow is becoming digital all the way from design through production to service. An investigation shows that a common factor across all service and support engineers visiting sites where machinery has been supplied is that the engineers take a laptop, on which they carry a variety of service-based information about the equipment [Ding *et al* 2008]. However, this is generally not used for any kind of design update or capture, except for emails. One of the main reasons is that CAD models are one of the most important pieces of product information; they are rarely shared or used by service or support engineers due to security concerns. With ever widening support for lightweight formats – the 3D capabilities introduced in Portable Document Format (PDF) version 1.6 are a case in point – the barrier hindering technicians and engineers accessing/editing digital models of products is being removed. Thus,

lightweight versions of CAD models are well placed to become the primary vehicle for sharing product representations between technicians, supporting engineers and partners. Being simpler and in general much better documented, with wider and less expensive software support, lightweight formats also show promise as remaining readable for far longer than full CAD formats, which are typically proprietary and only reliably readable by a single version of software.

3.3 *Lifecycle product information being updated through annotation*

Annotation support has already been introduced by many CAD and Computer Aided Manufacturing (CAM) packages and lightweight representation systems. However, as the ‘annotation’ functions provided are normally limited to a single type (e.g. free-text, URI or hyperlink), they cannot satisfy the requirements of annotation schemes supporting context-specific information and multiple viewpoints. Furthermore, the annotation information is actually associated with CAD models, and therefore it is only reusable for invariant topologies. Thus, an extension to existing ‘annotation’ functions is required. Prior research [Ding *et al* 2007] has shown the knowledge retention capabilities of extending ‘annotation’ in CAD systems to aid constraint-based redesign activities. The current research expands on this using a ‘stand off’ annotation method, in which the annotation is stored in a separate file and linked to an element of the model (such as a face or feature) using a system of references or pointers. The ‘stand-off’ annotation method offers many advantages:

- The same annotation file can be applied to any copy of the model in any format; this allows the annotation information to be shared by a wide variety of users.
- Multiple independent annotation files can be safely applied to the same CAD model. Thus, it allows context-specific information to be stored in a number of separate files and passed around only as needed.
- Annotations can be edited, circulated, and processed independently of the model, whilst the CAD model remains unchanged. This is significant as it allows downstream processes to be independent of the CAD model by only re-using annotations.

3.4 *Geometrical matching of a CAD model with its lightweight derivations*

In order to use lightweight representations to capture and update product information, it must be possible to match up the geometry of the lightweight representations with that of the original CAD model. Most lightweight formats currently use facet representations to reduce the file size, but do so at the cost of losing the geometry identifiers within the CAD models. The lack of bi-directional linkages between the entities in the original CAD models and those in their lightweight derivations has become a major barrier for applications. To explore a solution, an experiment using UGS NX6 and Adobe Acrobat 3D 8.1 has been carried out [Ding *et al.*, 2009a]. The results show that the face labels in the original CAD model did survive during its translation to PRC format in PDF, meaning that all the faces of the product model could be persistently identified; it is therefore possible, at least in principle, that features based on a specific viewpoint could be constructed as combinations of the faces of the model. Correspondingly, if the original CAD model remains constant, the annotations could also survive within both the CAD model and the lightweight formats. There is a risk that the linkage between the CAD model and the annotation may be lost when the entity referred to is deleted in the CAD model. However, CAD models are relatively stable at the later stages of a product’s lifecycle, and the annotation within the old version of the CAD model could still be retraced using a version control system.

3.5 Management and preservation of annotation evolution

The design process [Pahl and Bietz, 1996] involves complicated interactions among tasks and people. Thus, it is presenting unavoidable inclusion of iterations and rework, which results in the constant insertion, elimination and modification of annotations (e.g. constraints) through the whole process. Such evolutions not only reflect the design process, but also highly possible embed the rationale behind the decisions-made. Meanwhile, the design process is also accompanied by the evolution of the product model, and therefore there is a high risk of loss of annotations, if the corresponding entity associated with the annotations disappears. To address these issues, a strategy of management and preservation of annotation evolution is proposed, including:

- Evolution metadata: The evolution of annotations can be retraced if and only if evolving histories are clearly recorded in an organized way. Normally, the modifications of the associated annotations can happen at two levels: document-level or element-level. Correspondingly, two types of metadata are introduced: *<pre_versions>* and *<evolve_att>*. The *<pre_versions>* at document level records all previous versions of the annotation document and their corresponding documents' points/references. The *<evolve_att>* identifies whether the annotation inside the document is newly added or removed compared to previous version.
- Reference point: A core limitation of previous research [Ding *et al.*, 2007; Davies and McMahon 2006] is that the annotation may not be retraced when the CAD model changes, e.g. if the entity to which it is anchored [Wang, 2005] is deleted. To solve this problem, each entity (e.g. a face, a feature) is assigned to a point near the entity in the model, which is called as reference point (cf. Figure 3). The annotations associated with this entity are anchored to the corresponding reference point. The reference point remains even if the entity is removed from the model. Thus, the annotations can always be traced from the reference point no matter whether the entity is removed.

Figure 3a shows the end of a motor driven shaft of a transmission system. The undercut is firstly designed according to manufacturing requirement. Due to failure on stress analysis, the undercut was removed and replaced with a radiused feature (Figure 3b). The point in the space where the undercut was can still be seen, and the user can investigate its purpose by placing the cursor over it. The dashed lines have been manually added to the figure just to show where the previous feature was.

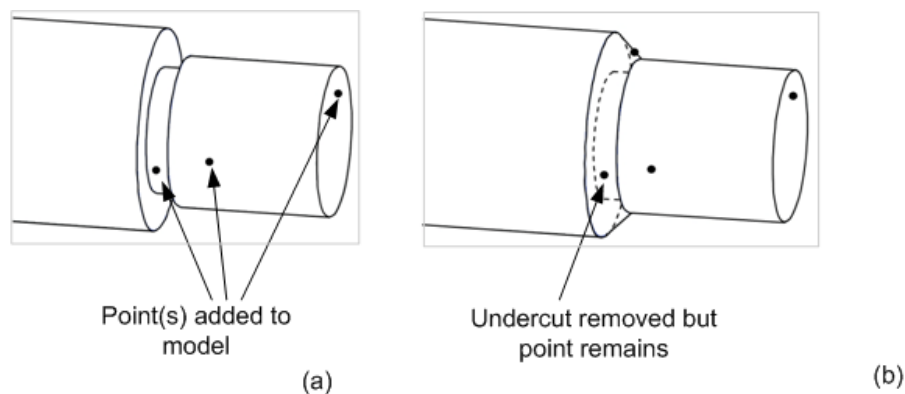


Figure 3 Reference points.

4 Implementation

An implementation (shown in Figure 4) has been developed based on two commercial software packages that have been widely adopted in both academia and industry – Unigraphics NX6 and PDF version 8.1.

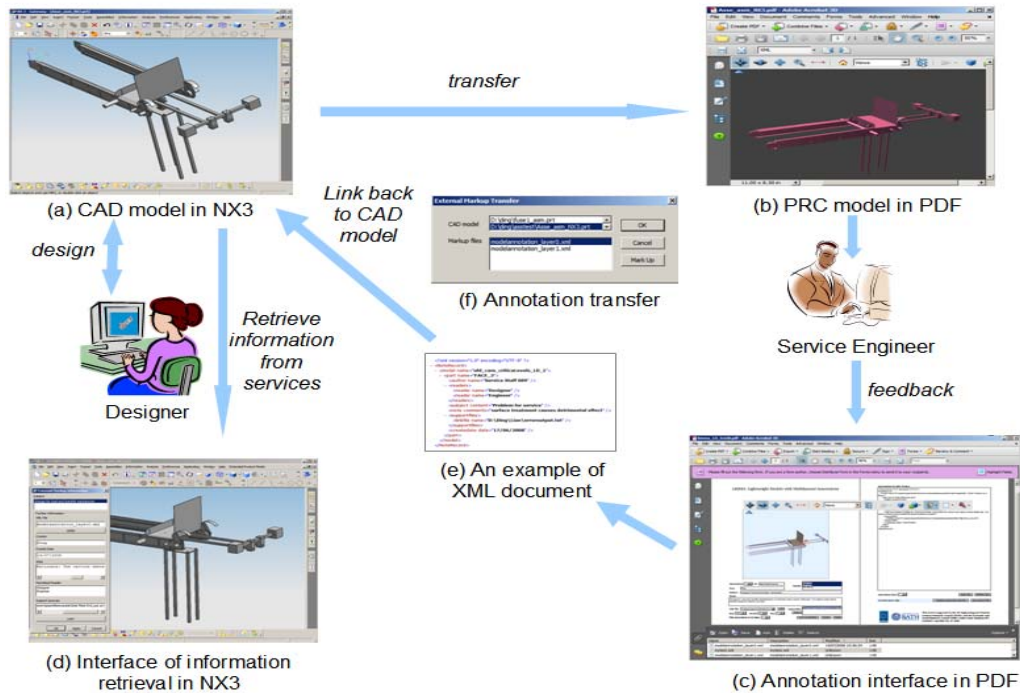


Figure 4 Implementation of the annotation of digital models

4.1 Annotation of CAD models

To demonstrate the annotation of a full CAD model, an NX6 model is used. The contents of the annotations are recorded into separate XML (Extensible Markup Language)-based documents [Bray et al., 2006]. Due to the characteristics of XML, such as platform/application independence, structure extensibility and information adaptability [Ball et al 2008]; it is possible to define different schemas and freely manipulate the associated annotations according to different requirements and security/IP profiles. A program to write/read the XML documents has been developed using Visual C++ and Microsoft XML Core Services (MSXML). The NX6 Open C API is employed to build a reference system between the XML documents and the CAD model. Figure 4 (d) gives an example of how a designer retrieves the information coming from technicians: the load and transfer mechanism for the front load carton erector has been changed because the cartons were being marked during the erection process.

4.2 Annotation of PDF

Since version 1.7 (corresponding to Acrobat version 8.1), PDF [Adobe Systems, 2007] has supported two formats of 3D model: U3D (editions 1 and 3) and PRC. In terms of 3D annotation, Acrobat 8.1 only has support for measurement annotations, which cannot be saved or exported; indeed, the only way these may be preserved is through screen shots. Therefore standard PDF annotations cannot be associated with

the 3D model in a robust computer-interpretable way. However, Acrobat does have a JavaScript API which allows one to extend the functionality of the 3D interface. In the API a node – an object with a 3D representation within a scene hierarchy – has the properties ‘info’ (Acrobat 7.07+) and ‘metadataString’ (Acrobat 8.1+), which give access to information associated with the node, presented as strings [Adobe Systems, 2007]. In addition, Acrobat 8.1 introduced a new property of the scene object, selectedNode, which enables one to query which node in the tree currently has focus. This is used to provide alternative annotation tools. As shown in Figure 4 (c), the annotation interface in PDF allows engineers to select a specific node (e.g. a face and a part) in the model that they want the annotation to link to, insert comments, attach supporting files, and finally export an external XML document.

4.3 *Linkages between CAD models and PDF*

Each surface in a facet-based representation is drawn as a series of planar regions, usually triangles. It is possible to identify a surface in an exact geometric model, with a tessellation in an approximate model, if all the facet points from the tessellation are contained in the exact surface. This matching method will sometimes fail for curved faces and edges as points in the approximate geometry may not match up with faces/edges in the exact geometric model. Therefore, an approximate matching method must be used with a tolerance appropriate to the algorithms by which the exact geometry is approximated. In the test implementation presented here, the conversion procedure permitted deviations no greater than 0.1mm between the approximate and exact geometry; thus a persistent geometry identifier was developed to match faces if the points of the tessellation all lay within 0.1mm of the exact surface. The identifier is written using Visual C++ and the NX6 Open C API. As the entities in both the CAD model and PRC format are identified consistently, the annotation XML documents generated in PDF environment are able to be read and linked back to specific entities of the original CAD model through a transfer interface shown in Figure 4 (f).

5 **Conclusions**

With more and more companies considering through-life support, the information coming from technicians and service engineers, is becoming more and more important for re-use in upgrades, maintenance and new product development. While large enterprises employ a PLM system to strengthen their competitiveness, small enterprises are still struggling with the capture and retrieval of such high-value information due to the lack of effective support tools. To address these problems, we have presented a new solution to enable small enterprises to capture product lifecycle-related information (e.g. the information fed back from technicians and service engineers) so as to re-use such information in upgrades, maintenance and new product development. The proposed solution enables one to:

- Rapidly update a product's design as issues are discovered, as well as changes made to it during later stages (e.g. build stage, commissioning, installation, maintenance or service);
- Associate problems or errors with the correct entity in the design, whether that is an entire assembly or an individual face;
- Minimize the loss of high-value information, especially that generated from technical departments and service engineers; and
- Capture the process of decision-making and the rationale behind it, to strengthen a company's long-term sustained competitiveness.

There are two notable barriers to the successful widespread adoption of the proposed method. The first is that, in order to integrate the annotations into existing workflows, either patches/plugin must be applied to each of the existing tools in use, or else custom annotation tools must be developed. The second is that it relies on user intervention. Just as with paper workflows, there is a danger that if the engineers forget to

update their design changes, or the design office neglects to retrieve the information, the underlying issues will still exist. The success of the method thus depends on good company 'house keeping': making sure the engineers see this as a vital part of their work. However, the advantages of adopting this method are significant in enabling the collaborative use and reuse of engineering product information over considerable periods of time.

6. Future work

While conducting this research and through interactions with collaborating companies, the following areas of future research have been identified:

- Further investigation is needed to understand what the users of the CAD models actually want to annotate and why they need the annotation; much richer understanding would be gained if this investigation was cross domain.
- As many companies employ a variety of different versions and formats of Computer Aided Engineering (CAE) tools to support both design and manufacturing activities. Investigation into how annotations should and could be integrated within these various tools is required.
- Explorations into how annotations should be reorganized for knowledge management using techniques like data mining and the Web Ontology Language (OWL) also merit investigation.

Acknowledgment

The work reported in this paper has been supported by the UK Engineering and Physical Sciences Research Council (Grant ref GR/R67507/01). The research has involved a number of industrial collaborators, to whom the authors gratefully express their thanks for the advice and support of all concerned. The Digital Curation Centre is funded by the UK's Joint Information Systems Committee (JISC).

References

- 1 Adobe Systems (2007) JavaScript for Acrobat 3D Annotations API Reference. Adobe Acrobat SDK version 8.1. http://www.adobe.com/cfusion/entitlement/index.cfm?e=acrobat_sdk
- 2 ASME Y14.41 (2003), http://en.wikipedia.org/wiki/ASME_Y14.41-2003
- 3 Aitchison, D. and Shaw, A. (2006) 'Data Management in Small and Medium-Sized Enterprises using Metadata Acquired by 'Spyware'', *Proceedings of the I MECH E Part B Journal of Engineering Manufacture*, 220, 797-800
- 4 Alpar, P and Reeves, S (1990) Prediction of MS/OR application in small businesses. *Interfaces*, 20(1), 2-11.
- 5 Astebro, T (2002) Non capital investment cost and the adoption of CAD and CNC in US metal working industries. *The RAND journal of economics*. 33(4), 672-688.
- 6 Ball, A., Ding, L. and Patel, M. (2008) 'An approach to accessing product data across system and software revisions', *Advanced Engineering Informatics*, 22(2), 222-235
- 7 Baldwin, J.R. (2000) 'Innovation and Training in New Firms', *Statistics Canada*, Ottawa,

<http://www.statcan.ca/bsolc/english/bsolc?catno=11F0019MIE2000123>

- 8 Bilis, S and Raymond, L (1993) Information technology: threats and weakness for small and medium sized enterprises. *International of Information Management*, 13(6),439-448.
- 9 Bray, T., Paoli, J., Sperberg-McQueen, C., Maler, E., Yergeau, F., & Cowan, J. (2006). Extensible Markup Language (XML) 1.1 (2nd ed.). W3C Recommendation. Available at <http://www.w3.org/TR/2006/REC-xml11-20060816/> (accessed 13/10/2009).
- 10 Brutzman D., Blais C., and Harney J. (2005), *Visualising Information Using SVG and X3D – Chapter 3: X3D fundamentals*, ISBN 1-85233-790-7, Springer – Verlag
- 11 Cabanac, G., Chevalier, M., Chrisment, C., Julien, C., « Exploiting the Annotation Practice for Personal and Collective Information Management ». *Proceedings of the International Workshop on Model Driven Information Systems Engineering MoDISE-EUS*, 2008, France, p. 67-78
- 12 Chaffey, D. and Wood, S (2004) *Business Information Management, Improving Performance using Information Systems*, Addison-Wesley.
- 13 Cheung, W.M., Yarrow, G.F.Y. and Schaefer, D. (2009): ‘Product Lifecycle Management: State-of-the-art and Future Perspectives’, *Enterprise Information Systems for Business Integration in SMEs: Technological, Organizational and Social Dimensions*, (*Advances in Information Management book series*), IGI Publishing.
- 14 Davies D., and McMahon C.A. (2006) ‘Multiple Viewpoint Design Modelling through Semantic Markup’, *Proceedings of IDETC/CIE 2006*, ASME 2006 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Philadelphia, Pennsylvania, USA.
- 15 Danesi, F., Gardan, N., Gardan, Y and Reimeringer, M (2008) P4LM: A methodology for product lifecycle management. *Computers in Industry*. 59, 304-317.
- 16 Digital Curation Centre. (2007). About the DCC: What is digital curation? <http://www.dcc.ac.uk/about/what/>.
- 17 Ding, L., Matthews, J., McMahon, C. and Mullineux, G. (2007) ‘An Extended Product Model for Constraint-based Redesign Applications’, *International Conference on Engineering Design, ICED’07*, 28–31 August 2007, PARIS, FRANCE.
- 18 Ding, L., Matthews, J., McMahon, C. and Mullineux, G. (2008) ‘ExProMod, a product development support tool’, *Advanced Materials Research*, 44-46, 345-353.
- 19 Ding, L., Ball, A., Patel, M., Matthews, J., and Mullineux, G. (2009a) ‘Strategies for the Collaborative Use of CAD Product Models’, *International Conference on Engineering Design, ICED’09*, 24–27 August 2009, University of Stanford, California, USA.
- 20 Ding, L., Davies, D. and McMahon, C.A. (2009b) The integration of Lightweight Representation and Annotation for Collaborative Design Representation, *Research in Engineering Design*, 19(4), 223-238.
- 21 Ding, L., Matthews, J., McMahon, C.A. and Mullineux, G. (2009c) An information support approach for machine design & build companies, *Concurrent Engineering: Research and Applications*, 17(2), 103-109, DOI: 10.1177/1063293X09105325.
- 22 Elinson, A., Nau, D. S. and Regli, W. C. (1997) ‘Feature-based similarity assessment of solid models’. *Fourth Symposium on Solid Modeling and Applications*. New York, NY. Ed. By C. Hoffman & W. Bronsvort. ACM Press: Atlanta, GA. 297–310.
- 23 Fiorentino, M., Monno, G and Uva, A .E (2009) Tangible digital master for product lifecycle management in augmented reality. *International Journal Interactive design and Manufacture*. 3, 121-129.
- 24 Harrison, D.A., Myktyyn, PP, jr and Riemrnschnider, C.K (1997). Executive decisions about adoption

- of information technology in small businesses: theory and empirical tests. *Information system research*. 8,2, 171-195.
- 25 Hanson ,A. J and Wernert, E. A (1997) Constrained 3D navigation with 2D controllers, Proceedings of the 8th conference on Visualization '97, p.175-ff., Phoenix, Arizona, United States
 - 26 Hicks, B. J., Mullineux, G., Matthews, J and Medland, A. J (2007) Towards an integrated CAD/CAM process for the production of forming shoulders. Proceeding of the Institute of Mechanical Engineers Part B. 221, 1521-1531.
 - 27 Hisarciklilar, O. and Boujut, J. (2007) An annotation-based approach to support design communication, *International Conference on Engineering Design, ICED'07*, 28-31 August 2007, PARIS, FRANCE.
 - 28 Jung, T., Gross, M.D. and Do, E.Y.-L. Sketching Annotations in a 3D Web Environment. in *CHI 2002, Conference on Human Factors in Computing Systems*, ACM Press, Minneapolis, 2002, 618-619.
 - 29 JT Files – File Structure, http://www.jtopen.com/technology/jt_files_overview.htm
 - 30 Hoffmann, C. M. and Joan-Arinyo, R. (1998) 'CAD and the product master model'. *Computer-Aided Design* 30(11). 905–918. doi: 10.1016/S0010-4485(98)00047-5.
 - 31 Kaminski, P.C., De Oliveira, A.C and Lopes, T.M. (2008) 'Knowledge transfer in product development processes: A case study in small and medium enterprises (SMEs) of the metal-mechanic sector form São Paulo, Brazil', *Technovation*, 28, 29-36.
 - 32 Kitamura, Y., Washio, N., Koji, Y., Sasajima, M., Takafuji, S and Mizogouchi, R (2006) An ontology-based annotation framework for representing the functionality of engineering devices, Proceeding of ASME Design and Engineering Technical, and Computers and Information in Engineering conferences Philadelphia USA. 10 pages on CD.
 - 33 Link, A, N and Bozenman (1991) Innovation behaviour in small businesses. *Small business economics*. 179-184.
 - 34 Longnecker, J. G., Moore, C. W and Petty, J. W (1994) Small business management: an entrepreneurship emphasis. Cincinnati: Southwestern publishing.
 - 35 McMahan, C. A and Browne, J (1999) CAD/CAM: Principles, Practice, and Manufacturing Management. Prentice Hall, NY. ISBN: 0201178192
 - 36 Pahl, G. and Beitz, W(1996) Engineering Design A Systematic Approach, Second edition, Ken Wallace (Ed.), Springer-Verlag (London), ISBN 3540199179.
 - 37 PLM Components, UGS, (2005) *Open product lifecycle data sharing using XML*, Write paper: PLM XML, www.ugs.com, October, 2005.
 - 38 Sanders, P. C and Bromacher, A. C (2000) 'Analysis of quality information flows in the product creation process of high volume consumer products.' *International journal of production economics*, 67(1), 37-52.
 - 39 Singh, B., Matthews, J., Mullineux, G., Medland, A. J (2009). Product development in manufacturing SMES: Current state, challenges and relevant supportive techniques. In *Eds Norell Begergendahl et al (2009) Design Methods and Tools, Part 2*. 157-167. Design Society, Milton Keynes UK, ISBN 9 781904 670100
 - 40 Thong, J. Y. W., Yap, C.S and Raman, K. S (1996) Top management support, external support and information system implementation in small businesses. *Information system research.*, 7(2), 248-267.
-
- |

- 41 Thong, J. Y. W (1999) An integrated model of information system adoption in small businesses. *Journal of Management Information Systems*, 15(4), 187-214.
- 42 Versprille, K. (2005) *Dassault Systèmes' Strategic Initiative: 3D XML for Sharing Product Information*, July, 2005, Technology Trends in PLM.
- 43 Wang, S (2005) Annotation persistence over dynamic documents. Thesis (Ph. D.)--Massachusetts Institute of Technology, Dept. of Civil and Environmental Engineering.
- 44 Yan, H and Firoto, S. S (2002) Communication CAD/CAM adoption in US textile and apparel industries. *International Journal of Clothing Science and Technology*. 14(2), 132-140.