DATA-DRIVEN THROUGH-LIFE COSTING TO SUPPORT PRODUCT LIFECYCLE MANAGEMENT SOLUTIONS IN INNOVATIVE PRODUCT DEVELOPMENT

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ABSTRACT

Innovative product usually refers to product that comprises of creativity and new ideas. In the development of such a new product, there is often a lack of historical knowledge and data available to be used to perform cost estimation accurately. This is due to the fact that traditional cost estimation methods are used to predict costs only after a product model has been built, and not at an early design stage when there is little data and information available. In light of this, Original Equipment Manufacturers are also facing critical challenges of becoming globally competitive and increasing demands from customer for continuous innovation. To alleviate these situations this research has identified a new approach of cost modelling with the inclusion of Product Lifecycle Management solutions to address innovative product

development. The aim of this paper therefore is to discuss methods of developing an extended-enterprise data-driven through-life cost estimating method in innovative product development. The paper begins with an introduction of relevant research. This is followed by a section, which highlights problems of performing cost estimates for innovative products, and subsequently the proposed solutions, methods and example applications.

KEYWORDS

Innovative Product Development, Digital Data Library, Product Lifecycle Management, Cost Estimation, Through-Life Costing

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BIOGRAPHICAL NOTES

Wai Ming Cheung is a lecturer at the School of Computing, Engineering and Information Sciences, Northumbria University, UK. He was a Post Doctoral Research Officer at the University of Bath, UK where he conducted research on through-life costing in designing defence electronic systems. He obtained his PhD from the University of Durham in engineering. His current research interests include knowledge management in design and manufacturing, through life costing from design to disposal, Information and Communication Technology in design and manufacturing and sustainability in product development.

Antony R Mileham is Professor of Manufacture and undertakes research in the areas of Manufacturing Processes Modelling, CAPP, Cost Prediction, Flexible Assembly systems, Manufacturing System Simulation and Rapid Changeovers. He has published 1 book, over 137 papers in journals and International Conferences, is editor of the IMechE Journal of Short Communications in Design and Manufacture and book review editor of the IMechE Journal of Engineering Manufacture. He was awarded a Ford Motor Co Ltd fellowship in 1991 and is an Erskine fellow at the University of Canterbury, New Zealand.

Linda B. Newnes received the Ph.D. degree from Loughborough University, Loughborough, U.K. She is currently with the University of Bath, Bath, U.K., where she leads the cost modelling research and manages a team of researchers engaged in numerous projects centred on through-life-cost modelling. Her research interests include cost modelling across all stages of the life cycle of the product, namely, concept–design, development, demonstration, manufacture, in-service, and disposal/recycle. She is also engaged in knowledge management approaches and utilizes the vast array of knowledge and information gathered throughout the life of the product. Dr. Newnes is a member of the Managing Costs Through Life Steering Group, U.K. Ministry of Defence, she has published over 75 refereed papers.

Dr Robert Marsh is a Post Doctoral Research Fellow in the Computational Engineering and Design Research Group in the School of Engineering Sciences at the University of Southampton. He is currently investigating issues in unit cost modelling for engineering design. He has been active in the field of manufacturing cost modelling system research since 1997, and has been mainly concerned with the aerospace sector.

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1. INTRODUCTION

"All innovation begins with creative ideas and is generally understood as the successful introduction of a new thing or method", (Amabile et al, 1996; Luecke and Katz, 2003). The necessity of maintaining innovative and profitability for a company requires tremendous effort and manpower. Therefore new methods of supporting innovative product development are needed. Furthermore, manufacturing industry is undergoing rapid transformation from a traditional local and regional environment to globalisation. Many manufacturers are outsourcing product manufacturing to international suppliers while focusing on high-value activities such as new innovative product development (Baxter et al, 2009). One of the critical challenges of becoming globally competitive is the collaboration and communication with international stakeholders, while also being able to adopt new and innovative product development techniques.

Over the last decade, there were numerous research efforts being conducted on collaborative product development. Noticeably, the advances of these research efforts have improved the product development process significantly in particularly during the new product introduction (NPI) process. One of the common themes of the research projects was that they have adapted Product Lifecycle Management (PLM) solutions as the supporting technology to conduct research in order to enhance the three critical factors in product development, these are: (1) quality of product, (2) reduction of cost and (3) time-to-market.

PLM is a technology mainly focused on utilizing and capturing product data to support collaborative product development (Cheung and Schafer, 2009), it is not developed to be used to analyse the cost of making a product. Therefore, most of the research efforts were primary focused on the integration of PLM and Enterprise Resource Planning (ERP) systems to address the product development process (Gao et al, 2003; Wong, 2006; Cheung et al, 2008; Wei et al, 2009). In terms of product costing, it can be performed using a propriety ERP solution, however, ERP relies on historical data and using a very basic cost accounting method such as the activity-based costing (ABC) technique to perform cost estimation of a product (Cheung et al, 2008). Due to the lack of quality information and data in new and innovative products, cost estimation performed by an ERP system is often inaccurate. To solve this problem arises in innovative product development, a new method of performing cost estimation with the support of PLM solutions is under investigation by the authors of this paper.

In industry, cost estimation is an important procedure to be used to help establish the feasibility of a product. In order to estimate the cost of making a product, there are different costing methods and techniques available. Traditional costing methods and techniques are usually performed using historical data and knowledge (Niazi, et al., 2006) and (Layer, et al., 2002). Whether it is in the design, the manufacturing or other stages of a product's development, cost estimation depends on the availability of data and knowledge. Nowadays, companies are more concerned about preparing lifecycle cost estimates of a product from its conception until the end of its life. In the recent past, there have been a number of research projects undertaken to address various issues in life cycle costing (Cheung, et al., 2007). Typically, methods have been deployed to predict lifecycle costs only after a product model has been built, and not at an early design stage when there is little data and information available. Furthermore, the cost models and systems used require a large amount of detailed data before a cost calculation can be made (Cheung, et al., 2009). As pointed out by Baguley, et al., (2008), one of the main challenges in modelling cost is data identification and collection. Therefore this research proposes a data-driven cost estimation approach with the inclusion of PLM within an extended-enterprise environment. In this research, PLM solution is mainly used to manage product data.

The layout of this paper is as follows: Section 2 describes the relevant research related to product development using PLM, ERP and data capture approaches in cost modelling. Section 3 highlights the problems of performing cost estimates for low-volume innovative products. Section 4 discusses the proposed method of using PLM and the data-driven through-life costing approach to address innovative product development. Section 5 discusses the application environment and finally, the conclusion and future work is presented.

2. OVERVIEW OF PREVIOUS RESEARCH

During the mid 1990s to early 2000s, research efforts in product development were focused on business function integration, to integrate business functions into a single system more efficiently by utilizing information technology, and share data with third-party vendors and customers i.e. to reduce the time-to-market of new product introduction (Noori and Mavaddat, 1998; Lee at al, 2003). In recent past, there were several pieces of research focused on the integration of PLM and ERP to support the collaborative product development process. However, advances of collaborative product development cannot be used to improve the problem that arises in innovative product development. One of the main reasons is the lack of information and data available to be used for product cost estimation. This is due to the fact that for innovative product there is often a lack of historical data and knowledge to support the development process, in particular in cost estimation of a new design concept. Since then more research with particular emphases on collaborative product development to address global manufacturing aspects has been carried out. Some of these approaches are summarized as follows:

Gao et al (2003) proposed a model integration that is STEP based (Standard for the Exchange of Product Model Data). STEP is a standard used to exchange product data between different engineering systems. Gao's approach was also focused on heterogeneous systems integration with an ERP and a process planning systems to support collaborative product development at the conceptual design stage. Although cost was one of the aspects that the research outlined, this was not the main objective that the research pursued. Wong (2006) proposed a data model to combine an ERP and a PLM system. The goal was to integrate the shop floor and top level management to achieve easier interoperability between managers and shop floor staffs to monitor the product development process. Cheung at al (2008) addressed collaborative product development and information distribution to support the early design stages with disparate technologies and software tools. The aim of the project was to increase the potential industrial benefits of front-end responsiveness, quality of design and production decisions. The combined disparate technologies include knowledge management using ontological technique supporting by PLM and ERP systems. Wei et al, (2009) developed a methodology of integrating PLM and ERP systems for real time data analysis to rapidly address market and customer requirements. This work was focused and enabled different personnel to work collaboratively and interact in a real time situation.

The research projects reviewed so far have achieved some success in terms of reducing time to market of NPI. Although some of the research has attempted to address costing issues using PLM and ERP solutions. As for the research in linking PLM and cost estimation to address design aspects, Curran, et al., (2007) presented a methodology to facilitate cost modelling with the integration of design and manufacturing at the concept design stage. The methodology was to exploit manufacturing simulation capabilities and PLM solution associated with digital mock-up data to obtain real-time cost estimates for a fuselage of a commercial jet. Scanlan, et al., (2006) launched a project called DATUM with Rolls-Royce PLC to establish a prototype system for the creation of a cost model structure to integrate with a design optimisation system using PLM solutions.

All the research projects reviewed so far have addressed collaborative product development. As mentioned earlier, innovative product development involves new ideas and creativity. In such a scenario, historical data are usually not presented or are unavailable to support accurate cost estimations at the conceptual design stage. As pointed out by Baguley, et al., (2008), one of the main challenges in modelling cost is data identification and collection. A typical example is the research carried out by Emsley, et al., (2002) which introduced a data modelling approach, however, the research relied on previous project data which used neural networks to predict the total cost of construction. This approach does not appear appropriate in terms of innovative low volume products. Another piece of research by El-Haram, et al., (2002) utilized a framework for capturing 'whole life cost' data for a construction project. They proposed that the first step of whole life costing (WLC) was the use of cost breakdown structures that identified the categories relevant to each life cycle phase. The proposed WLC breakdown data structure was divided into five levels: "(1) Project Level, (2) Phase Level, (3) Category Level, (4) Element Level and (5) Task Level". The levels were underpinned by a centralised pool of data and information. Based upon these conditions, they developed a WLC breakdown data structure that was then computed as a system dictionary in which all data was listed and defined. As this framework was developed for the construction sector, it may not be applicable for electronics defence products, the subject of this paper.

Tu et al (2002) presented a cost data index structure with two traditional cost estimation methods namely, generative and variant cost estimation, for the development of a computer-aided cost estimating and control system in mass customization of sheet metal products. For cost optimization, an optimal algorithm for the selection of alternative operation routines and suppliers was developed using the dynamic programming technique. However the methodology relies on past knowledge and experiences.

Shehab and Abdalla developed a prototype object-oriented and rule-based system for product cost modelling and design for automation to support decision making at the early design stage. The prototype system was implemented in a combination of heuristics data, an algorithmic approach and fuzzy logic techniques. The system allowed users to generate accurate cost estimates for new designs by exploring alternative materials and production processes. Deiab and Al-Ansary developed a systematic multi-phase procedure to optimize the design and manufacturing parameters using the genetic algorithm method. The aim was to minimize the total manufacturing cost under dimensional, weight, and machine power constraints. Similar to parametric methods, the approximations were based on past case data where cost was known.

In summary, the research projects reviewed so far are not applicable to defence systems in particular from a point of view of low volume innovative products. The research projects mentioned in this review appear more relevant to high volume products, where typically, past and historical data are available to support their methodologies. It is considered that the association of data-driven through-life cost modelling and PLM solutions could produce accurate cost estimates for low volume innovative product.

3. INDUSTRIAL PROBLEMS AND THE PROPOSED SOLUTION

According to Wujec and Muscat (2002), time is one of the driving factors in new innovative product development, however, increasing demands from customers for continuous innovation have signalled a massive switch from anticipatory to adaptive styles of development of new innovative products (Highsmith, 2009). The traditional ways of focusing just on reducing lead time and improving quality of new innovative products remain the focus of much industrial and research activity. But since there are three factors in product development (quality, cost and time) a new and effective way of performing cost estimation during the new innovative product development process is needed. However, there are several problems when estimating new and innovative products, including: (1) lack of historical data and knowledge, and (2) insufficient statistically significant data, during the early stages of product design (Newnes and Mileham, 2006). For the design and development of such products, cost estimation is a critical task, in particular the requirement to predict the cost committed for a product’s lifetime. A typical example is naval platform defence systems which usually consist of a number of sub-systems and components and in which further problems can be added due to the nature of this type of products (Hedvall, 2004). For instance, the interdependences between various sub-systems might create additional costs and differences in life span and upgrade characteristics are usually difficult to predict and manage. Therefore, a new methodology to support cost estimation of this kind of product is needed.

The proposed solution of this research is shown diagrammatically in Figure. 1. It is considered that the application of PLM coupled with an extended-enterprise digital data library could enhance the product innovation development process. PLM software helps companies to better manage their products throughout their lifecycle. In addition, PLM systems are designed to manage the entire product's information from initial concept to end of life (Cheung and Schaefer, 2009). PLM software also provides benefits during the product's design and development phases when engineers make the critical design decisions that determine the quality and cost of the product over its lifetime.

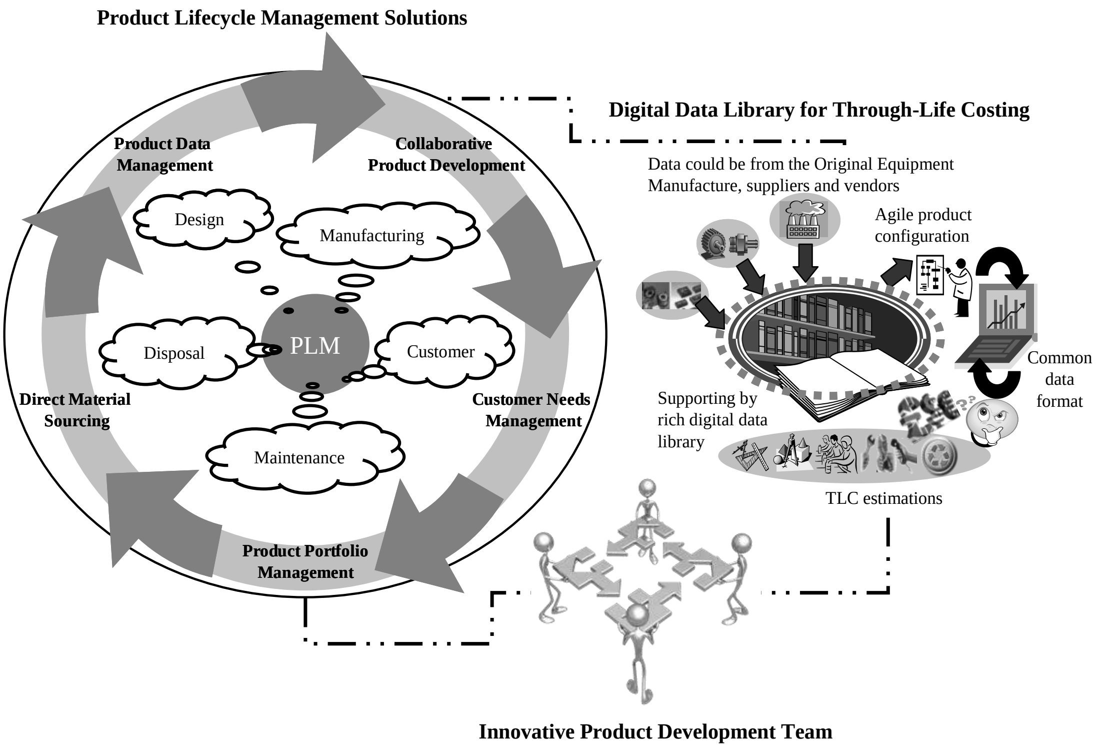

Figure 1 The Proposed Solution in Through-Life Costing of Innovative Products

As discussed in the introduction, ERP is not considered to be an appropriate solution for the cost estimation of innovative products. The new methodology withthe proposed data-driven through-life costing approach has been designed to achieve this requirement by the integration of the following: (1) an extended-enterprise digital data library to allow agile product configuration, (2) a common data format to represent data and information of costing analysis; and (3) facilities to support and predict the

TLC from the initial concept stage of a design until the end-of-life of a product using a PLM's PDM portal. Tools such as PLM also enable collaboration within and between enterprises. The term extended-enterprise means that data can be collected from beyond the original equipment manufacturers, for example, the suppliers and vendors. Potential industrial benefits should include the demonstration of increased front-end responsiveness and improved decision making in innovative product development, thus enhancing the opportunity of winning business contracts by tendering the appropriate bids.

4. THE EXTENDED-ENTERPRISE DATA-DRIVEN THROUGH-LIFE COSTING APPROACH

This section introduces the methods of developing a generic digital data library to support a PLM system in innovative product development. The digital data library is referred to as the 'Electronics and Mechanical Modular-based Library (EMMbL). The notion of the EMMbL is used to support an extended-enterprise data-driven cost modelling approach as illustrated in Figure 2. The overall integration environment is categorised into three levels.

- The first level is a top-down approach, which consists of using the EMMbL to support designers and cost estimators particularly during the early stage of design concept configuration.
- The second level is the data mechanism level, which consists of its 'data searching' and 'data exchange' abilities.
- The third level is used to support a bottom-up approach of development, demonstration, manufacture, in-service and disposal stages of a product's lifecycle. It is at this level that the PLM solutions will be used to support an

extended-enterprise approach, thus PLM is an enterprise system and typically used to support a collaborative environment.

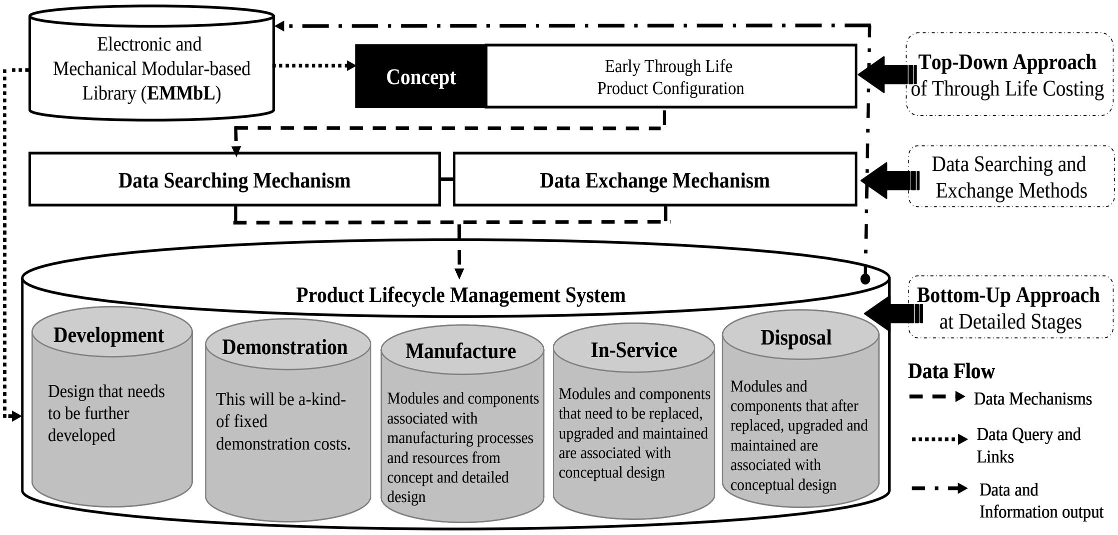

Figure 2 Integrated Data-Driven Multi-level Through-life costing

4.1. METHOD OF DEVELOPING THE DIGITAL LIBRARY

Figure 3 illustrates the steps of developing the EMMbL. The initial process was to use the Unified Modelling Language (UML) (Blaha, et al., 2004) to define an abstract representation of the EMMbL. The second step was to create a main directory for the EMMbL and was followed by defining the subdirectories as shown in Step 3. The resulting cost elements were established in Step 4 which is explained in the following paragraph.

The EMMbL is a data structure to be used to capture cost data and information of a group of specific domains as illustrated in Figure 4. Each of the domains is categorized into electronic, mechanical modules/components, process capabilities and resource requirement. The final step is to populate cost data within a subdirectory.

The EMMbL also has included in it, two further modules, namely process and resource. The process module consists of a set of pre-stored cost datasets on assembly, machining and surface mount technology processes. The resource module contains the cost information of factories, machines and tooling data, which is directly linked to the capability of the processes.

Overall, the EMMbL enables designers to configure a product from existing modules. These modules will allow users to define the relationships with the components from the EMMbL. The library should allow designers and cost estimators to perform rapid configurations of a product once the requirements have been received from a customer.

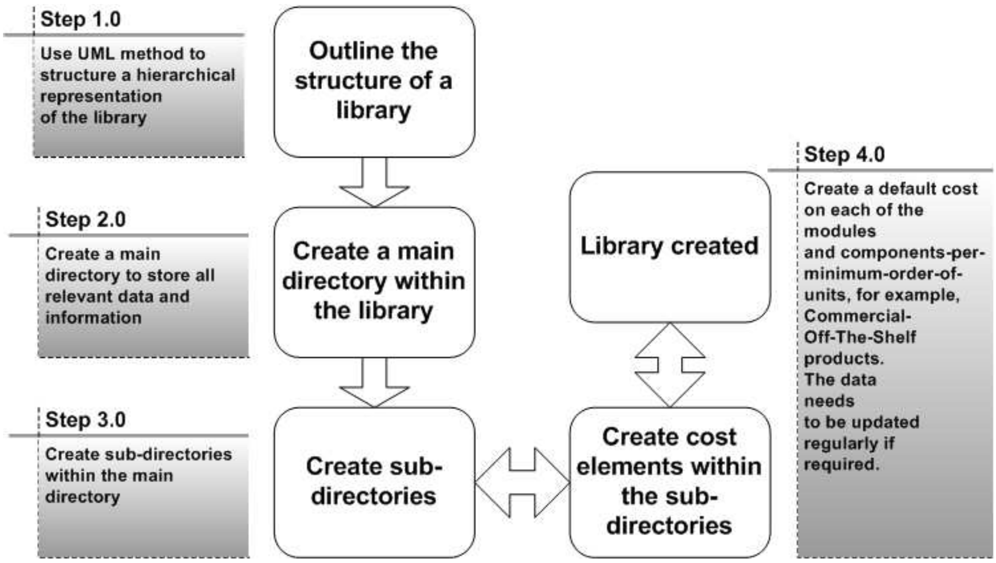

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Figure 3 Steps of Developing the EMMbL

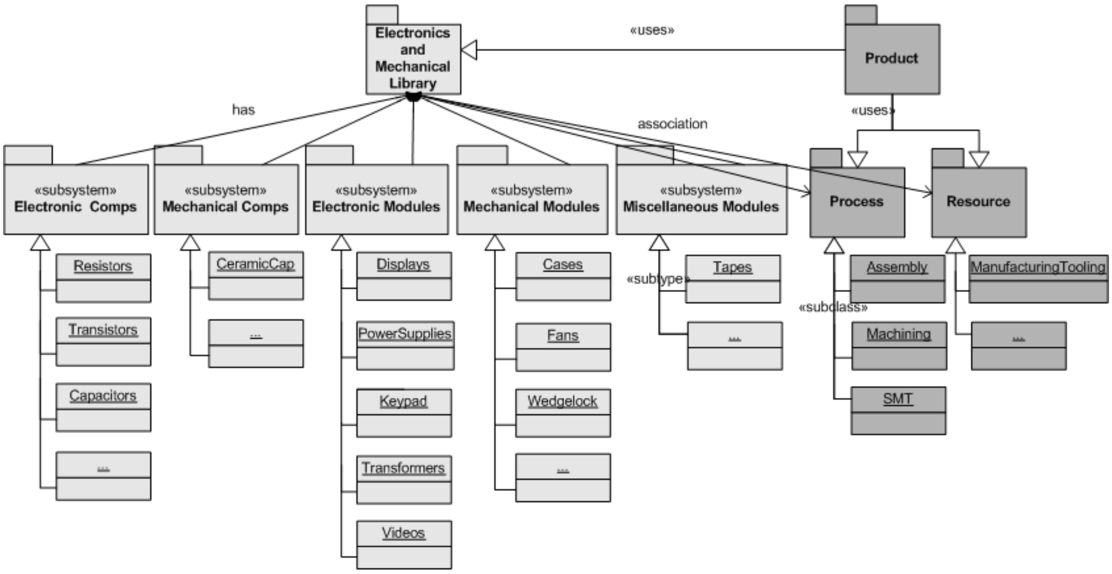

Figure 4 – UML representation of the EMMbL

4.2 EXAMPLE DATA

The developed EMMbL is shown in Figure 5. For example, Figure 5(a) represents the values of a group of capacitors and its associated cost data within an 'Electronics Comps' subdirectory. Relevant data of other electronic components such as connectors, resistors and transistors have also been stored in the same format. Figure 5 (b) represents the tooling costs of printed circuit board (PCB) processes. As discussed in Section 4.1, the resource module contains the cost information of factories, machines and tooling data, which is directly linked to the capability of the processes in the process module.

Figure 6 illustrates an example of how a designer can select the subsystems and components to configure an early design idea. For example, in the first step, a designer can select a group of relevant subsystems to configure an abstract representation of an initial design concept (as shown in step 2). An initial cost of this design can be estimated along with its associated manufacturing cost.

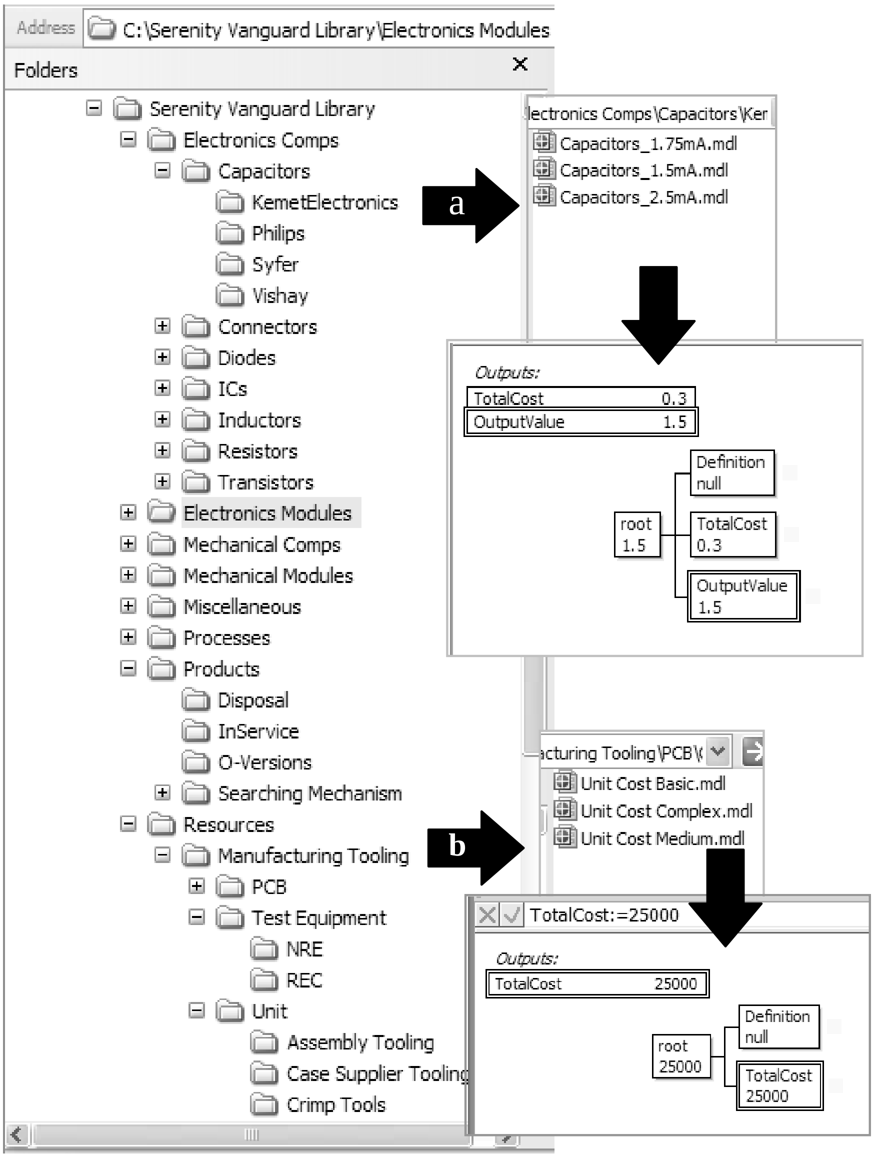

Figure 5 - Electronics and Mechanical Modular-based Library (EMMbL).

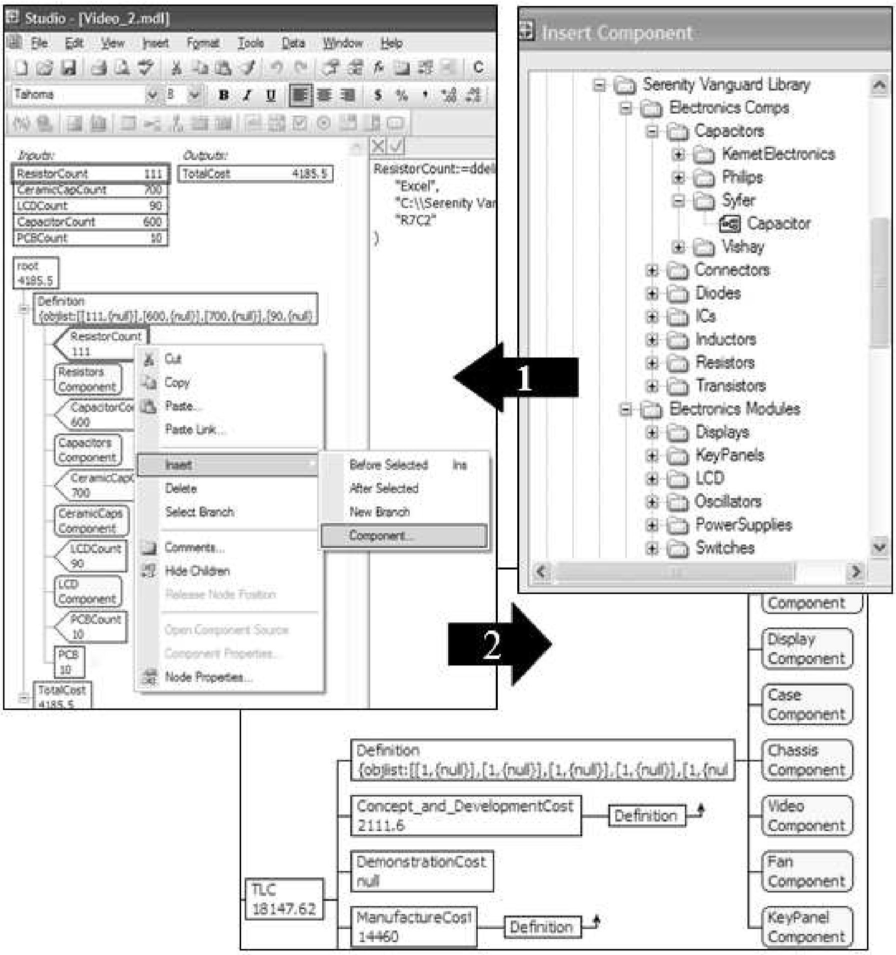

Figure 6 – Select Subsystems / Components / Processes and Resources

4.3. DATA SEARCHING AND TRANSFER MECHANISMS

4.3.1 DATA SEARCHING

In the EMMbL, there are five types of data set that have been identified which could influence the impact of the accuracy and confidence levels of the cost estimated. They are, ‘variant’, ‘Commercial-Off-The-Shelf’ (COTS), ‘Parametric’, ‘Detailed / Bill-of-Materials’ and ‘Uncertain Technology’. The data set is referred to as the Data Searching Mechanism (DSM). The definition of the ‘data searching algorithm’ is shown in Figure 7 which is represented as ‘if/then’ statements. The algorithm represents the procedural steps of performing data searching, and these procedural steps are based on the set of rules in the DSM. For example, in order to search what kind of data is used, a search will begin to check the existing data type as follows:

1. If it is 'variant' then return a new value based on 'existing product data', this could help the designer to adapt or modify the nearest existing product to perform cost estimation.
2. If it is commercial-off-the-shelf 'COTS' then return a new value based on a 'fixed price'.
3. If it is 'Parametric', derive the cost from a Cost Estimation Relationship (CER).
4. If it is a 'detailed/BoM' then the search will iterate again or perform a detailed design to accurately predict the cost in the early stages.
5. If it is an 'uncertain technology' then 'run a Monte Carlo simulation' or run the 'technology forecasting technique'.

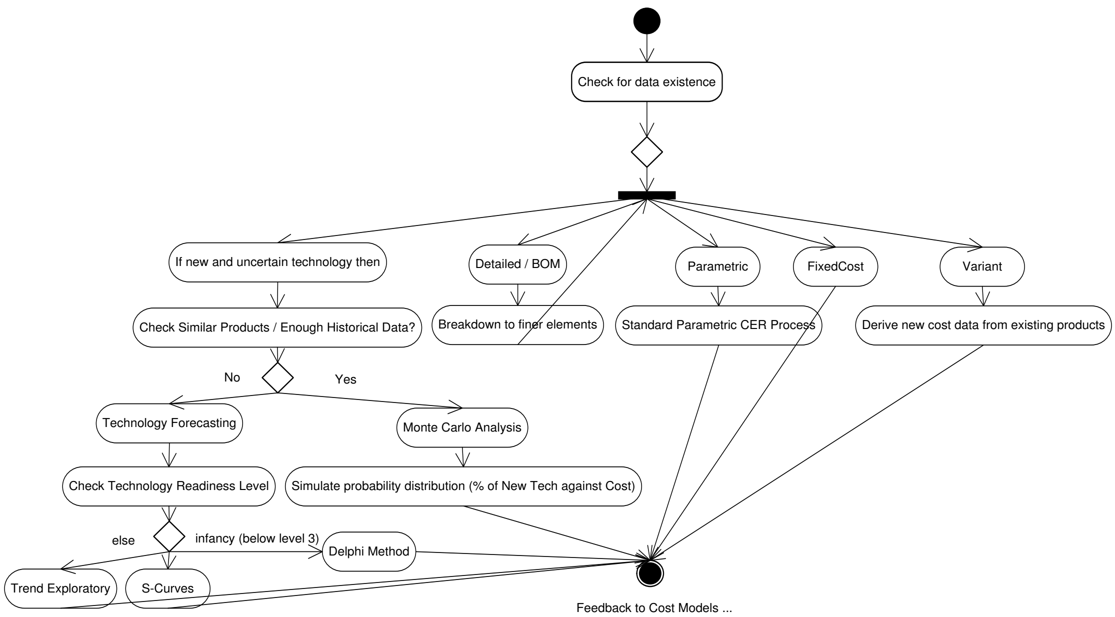

Figure 7 Rules for Data Searching Mechanism

Currently, the DSM has been implemented using a forward chaining method (also known as data-driven reasoning) using a First In, First Out queue processing technique (Finlay, 1996). As illustrated in Figure 8, the purpose of the DSM is to search for relevant cost information during the early design configuration process. It is at this stage that the cost of alternative design concepts need to be determined and as precisely as possible to support a designer's decision making in the product development process.

A pilot demonstrator has been implemented as shown in Figure 8, where rule evaluation is fired from the button on the Graphical User Interface. This utilizes a standard inference engine with if/then statements. The inference engine then matches the agenda contents to the rules in the rule-base(s). If they match, the appropriate rules are fired which produce new facts on the agenda. This mechanism repeats until the agenda is blank or the goal is satisfied. A goal is used in the case of a known model being selected. The percentage (%) new product is used to select the best kind of model. If a reasonable proportion of the product is new then a variant approach is favoured. The novelty of the approach is a combination of (1) a data driven, (2) multi-model selection process, and (3) an evaluation of the models in parallel with a measure of relevance to the available data attached.

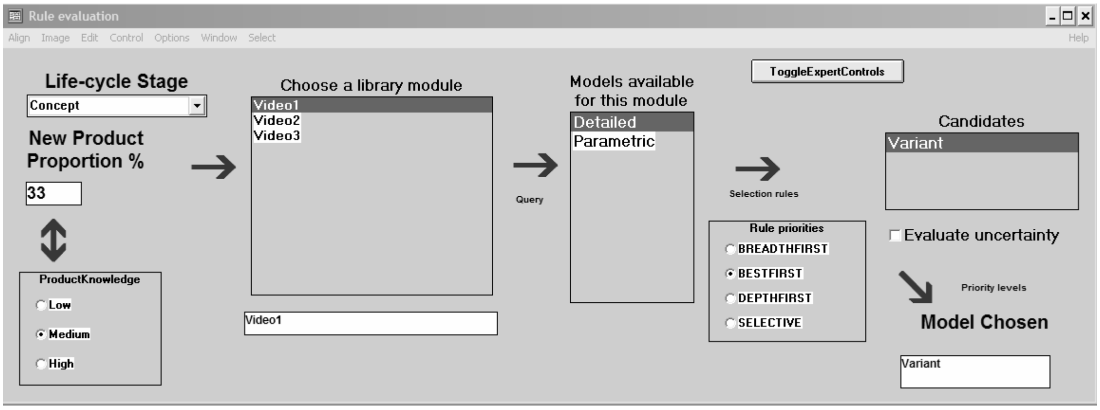

Figure 8 The DSM user-interfaces

4.3.2 DATA TRANSFER

Once the initial product configuration has been accepted, the designer can then transfer the design and manufacturing parameters into a commercial cost estimation software for further analysis. Figure 9 illustrates the user interfaces for activating the SEER-DFM system (SEER, 2009). The data in the spreadsheet will then be transferred into SEER-DFM to create the Engineering and Manufacturing Bill-of-Materials.

- From the SEER-DFM template, the user can change the design and manufacturing parameters.
- At this stage knowledge which relates to the selected modules can be added which would not be possible to do at the top-down stage. The detailed design stage can be used to input additional data such as ‘knowledge’, ‘weight’ and ‘dimensions’, or the ‘detail process and resource’ parameters which are currently not considered at the concept stage

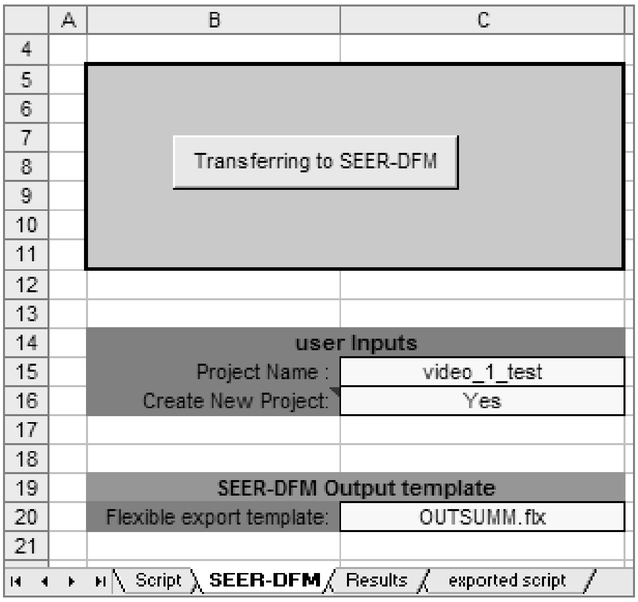

Figure 9 - User Interfaces for Detailed Design

4.4 THE PRODUCT LIFECYCLE MANAGEMENT SOLUTIONS

One of the main functions of a PLM system is the ‘Product Data Management (PDM)’ portal. PDM manages design data in such a way that it offers versioning control for a design and the ability to see the history or evolution of a design through all its iterations. PLM also provides benefits of a ‘Lifecycle’ function that defines the timing of the development stages, in particular during the product's design and development phase when engineers make critical design decisions that determine the quality and cost of a product over it's lifetime. With this capability, clearly, it is one of the obvious solutions to be used as the foundation for innovative product development, in particularly from an extended-enterprise point of view.

The next section illustrates how these would be used for an innovative product development process.

5. THE APPLICATION ENVIRONMENT

Figure 10 depicts an example of the extended-enterprise data-driven through life cost estimating for innovative product development. The first step is to perform a product configuration (1) by selecting the most appropriate modules to meet the conceptual requirements. The selection of the appropriate modules is based on the input and output of each module selected from the EMMbL. For example, if a display unit requires a maximum power of 50 Watts, then a power supply of that power rating must be used. Once the right modules have been put in-place and stored within a PLM system's PDM portal, the next stage is (2) to use the 'data searching mechanism' to search the relevant cost information and data to enable a suitable cost estimation to be performed. If a detailed design or modification is required for a specific module, this will then be transferred to the development stage (3). The EMMbL has been developed with the most up-to-date cost information, and thus total design costs at the concept and development stages can be determined. After a design has been specified and a series of processes and resources in relation to the design have been defined, the associated manufacturing cost can also be determined. As for cost estimation of the 'in-service and disposal' stages, they will be supported by estimated reliability and upgrade data. Thus, once the design of a product and manufacturing design have been finalised, the 'in-service and disposal' stages (4) can be carried out. The 'in-service' evaluation process is based on the selected modules and components. In the process, 'when' and 'which' specific module and component needs to be replaced, upgraded and maintained can be identified from the timelines and failure estimated rates. The subsequent 'disposal' costs can also be calculated based on the weight of material to be recovered, transportation and landfill requirements for example.

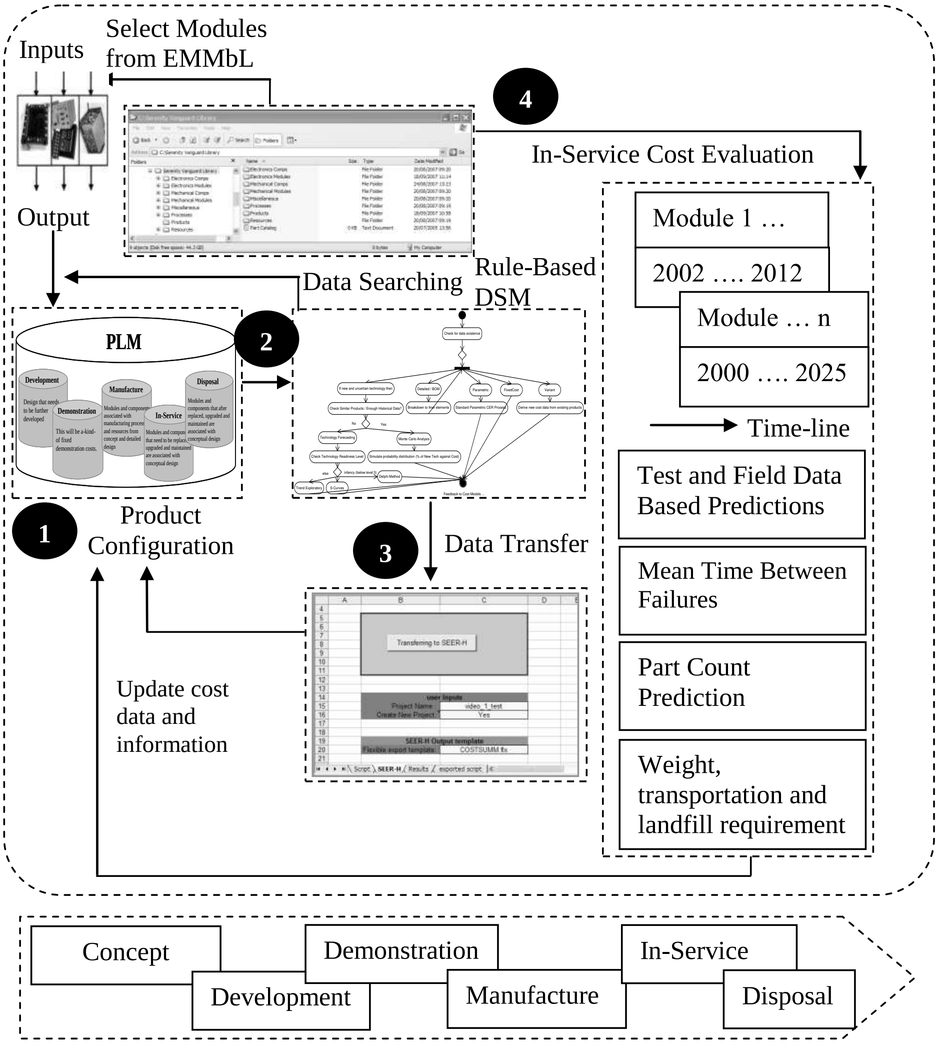

Figure 10 The Application Environment

6. CONCLUSIONS

This paper has presented and discussed the development of an extended-enterprise digital data library coupled to the integration of PLM solutions. An extended-enterprise digital data library has been used to support the cost estimation process of new innovative products, although the method can be applied to a variety of other products. The data library is the core of the integrated cost modelling approach in order to support through-life costing of innovative product development. The overall contributions of this work are the methods of a data-driven through-life cost estimation method coupled with PLM solutions that allow agile product configurations and rapid decision making to accelerate responsiveness in the business bidding process of low volume long life defence system products.

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