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▶ **To cite this version:**

Wim Verhagen, Pablo Bermell-Garcia, Pierre Mariot, Jean-Pierre Cotton, Domingo Ruiz, et al.. (Costing) Knowledge-Based Cost Modelling of Composite Wing Structures. International Journal of Computer Integrated Manufacturing, 2010, pp.1. 10.1080/0951192X.2010.531292 . hal-00649053

HAL Id: hal-00649053
https://hal.science/hal-00649053

Submitted on 7 Dec 2011

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Journal:	*International Journal of Computer Integrated Manufacturing*
Manuscript ID:	TCIM-2010-IJCIM-0124
Manuscript Type:	Special Issue Paper
Date Submitted by the Author:	25-Aug-2010
Complete List of Authors:	Verhagen, Wim; Delft University of Technology, Faculty of Aerospace Engineering, Air Transport & Operations Bermell-Garcia, Pablo; EADS Innovation Works, TCC5 Mariot, Pierre; Ardans SAS Cotton, Jean-Pierre; Ardans SAS Ruiz, Domingo; EADS Innovation Works, TCC3 Redon, Romaric; EADS Innovation Works, TCC5 Curran, Ricky
Keywords:	COMPOSITE MATERIALS, COSTING
Keywords (user):	Engineering Knowledge Management

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Knowledge-Based Cost Modelling of Composite Wing Structures

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The progressive industrialization of composite-built aircraft is putting manufacturing engineers on a steep learning curve. An opportunity exists to use knowledge management tools to capture, share and reuse knowledge over multiple aircraft programs and maintain the constant flow of learning gained during aircraft program delivery. This paper reports on research to develop a knowledge-based cost modelling capability for composite part concept evaluation. The approach integrates a knowledge management environment with a process-based cost estimation tool encoded in very large spreadsheets. In order to achieve this, the complexity of the cost model is managed by modularizing it into simple, re-useable components. The knowledge management environment is then used to manage the knowledge lifecycle, knowledge exploitation and knowledge visibility of those components. The result is a flexible cost modeling tool composed of traceable, verifiable and reliable knowledge elements that provides through-life knowledge support for cost engineering. Validation is achieved through functional application of the solution for composite wing top cover cost modelling.

Keywords: engineering knowledge management; knowledge engineering; cost modelling; composites

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1 Introduction

A recent challenge in aerospace engineering is the trend to switch from predominantly aluminium to predominantly composite structures, as evidenced by the development of the Boeing B787 and the Airbus A350 XWB (Extra Wide Body). From the manufacturing perspective, this is a major step change since it imposes the need to create and update existing knowledge bases to adapt industry to this new demand. The UK government has recognized this issue in its national Technology Program. Consequently, a series of research initiatives are being funded to build the necessary industrial foundations and knowledge to face the composite manufacturing challenge (Airbus, 2010, Technology Strategy Board, 2009).

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Competitive pressure is forcing manufacturers to adapt quickly in order to industrialize the use of composites in aircraft design. To successfully face the associated learning curve, manufacturing engineers will need to be supported while encountering composite manufacturing challenges in their daily practice. In this scenario, fast and accurate access to up-to-date knowledge in early-stage design will be crucial to accomplish program objectives while avoiding the undesirable effects of producing composite-made aircraft while having used metal design and analysis principles.

This paper presents an innovative approach to manage manufacturing engineering knowledge through life in the domain of cost modelling for composite components. The underlying research objectives are to illustrate the principles that have guided the development effort and to validate the solution by presenting a functional integration of a knowledge management environment and a real-life, operational cost modelling tool. The developed solution supports cost evaluation of product concepts at early stages of the design process while offering the opportunity for through-life knowledge support. A key aspect of this research is the adoption of the following Knowledge Management (KM) principles in the development of the solution:

- **Exploitation of the knowledge:** The primary aim of the resulting KM capability is to be able to "run" cost models using trustworthy and up-to-date knowledge. The transformation of tacit knowledge into explicit knowledge is secondary but is also supported.
- **Visibility of the knowledge:** The KM capability is designed to improve upon the current black-box implementation of the cost modelling capability. To achieve

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this, the solution does not replace the natural use of spreadsheets to compute the cost of components. However, it manages the knowledge driving the cost model and deploys it to a working spreadsheet from which users can understand the rationale of the computed cost.

- **Lifecycle management of the knowledge:** The KM capability enables taking diverse paths to evolve the cost model. However, it also enables control of the actual standard way of costing parts. Furthermore, it enables storing, justifying and updating cost model knowledge elements and records previous versions of the cost model.

This short introduction of the research problem, objectives and solution elements is substantiated in the remainder of the paper. First, the research background is evaluated. This includes a brief assessment of relevant theoretical aspects, which is followed by a more involved description of the research problem in terms of managing engineering knowledge and associated elements. Subsequently, an explorative case study is performed which analyses cost modelling of aerospace composite components through life. The research problem and the case study elements are combined to lead to a knowledge-based framework for managing cost models through life, which is discussed in Section 4. First, semantic unification of the cost model elements and knowledge base structure is achieved. Next, the framework principles and architecture are proposed. Finally, a proof of concept application is described which illustrates the functional implementation of the framework principles and architecture. This proof of concept serves as an initial validation of the knowledge-based cost modelling approach. A final discussion with conclusions and limitations wraps up the paper.

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2 Research background

In this Section, literature is reviewed to establish the context of the research. First, current approaches to cost estimation are categorized, which allows the cost modelling approach used in this paper to be placed into context. Subsequently, the concept of knowledge is briefly explored, followed by its application in engineering knowledge management. Next, three major KM principles are explored. This serves to show which elements in KM are currently insufficiently addressed in theory and practice, and thereby guides the approach for the case study and the solution framework.

2.1 Categorization of current approaches to cost estimation

A number of authors discuss and categorize current approaches to cost estimation. The most universally adopted perspective on cost modelling (Feldman & Shtub, 2006, Newnes *et al.*, 2008, Curran *et al.*, 2004, Price *et al.*, 2006) refers to three approaches, namely analogous, parametric and bottom-up cost modelling. Curran *et al.* (2004) present a matrix of comparative assessment for these methods, which is given here in Table 1. It is important to note here that one of the subsets of bottom-up modelling is physical process modelling, which focuses on the time required to carry out work (Curran *et al.*, 2004) as this principle is used in the cost modelling approach outlined in this paper (see Sections 3.1 and 4.1.1).

Table 1: Assessment matrix for traditional cost estimation methods (Curran *et al.*, 2004)

Curran *et al.* (2004) also distinguish between 'traditional' and 'advanced' estimating approaches. The three approaches mentioned in Table 1 are deemed to be traditional, whereas advanced estimating approaches include the use of feature-based

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modelling, fuzzy logic, neural networks, uncertainty modelling, and data mining. Curran *et al.* (2004) also introduce the genetic causal cost model to address the need for a more scientifically based methodology for cost estimation.

Newnes *et al.* (2008) add a more upper-level categorization perspective by considering cost estimation approaches as being 'generative' or 'parametric'. In the generative process, the cost estimation builds upon the data that is gathered during the design process. Consequently, the costing estimate accuracy depends on the level of data detail. In parametric approaches, estimates are 'achieved based on past experience, using findings from past products and estimating the expected cost' (Newnes *et al.*, 2008). Parametric approaches distinguish themselves by the use of cost-estimating relationships (CER).

Newnes *et al.*'s (2008) categorization relates closely to the level of fidelity of the cost estimation approaches; as Price *et al.* (2006) indicate, 'analysis fidelity relates to the degree of detail and accuracy contained in a given analysis model'. Price *et al.* (2006) distinguish three levels of fidelity. Low fidelity models use simple equations and look-up tables, and frequently do not have associations with geometric models. Medium fidelity models use some form of linear analysis in combination with geometric model information and high fidelity models contain a lot of detail while modelling non-linear behaviour. When looking at the issue of fidelity from a more multidisciplinary perspective, a number of research gaps can be identified (adapted from Price *et al.*, 2006) – see Table 2.

Table 2: Disciplines versus fidelity (modified from Price *et al.*, 2006)

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It is interesting to note that significant gaps exist for the cost discipline (at the medium to high fidelity levels) and manufacturing (at the low to medium fidelity levels). This conclusion will be revisited when inspecting the cost modelling approach outlined in this paper (see Section 3.1).

2.2 Engineering knowledge management

Nonaka (1994) defines knowledge as 'a justified belief that increases an entity's capacity for effective action'. Alavi and Leidner (2001) offer a deep and involved literature review on the concept of knowledge; in particular, their main conclusions are that 1) literature focuses heavily on distinguishing between data, information and knowledge, 2) knowledge is personalized and should therefore be expressed in such a manner that it is interpretable to receivers, and 3) only information that is actively processed in the mind of an individual or individual(s) is useful. These realisations are carried through in this paper; in its applied form (see Sections 3 and 4) 'knowledge' covers the engineering domain and encompasses parameters and their values as well as formulas (together constituting data and information), as well as the justification for these parameters and formulas (constituting the conventional 'knowledge' as used in literature). Furthermore, the realisations that knowledge must be interpretable to receivers and must be processed by users to have an impact are guiding the solution development effort (Section 4).

This solution effort focuses on the application of knowledge management to support an engineering task. Knowledge management can be defined as 'a systemic, organized, explicit and deliberate ongoing process of creating, disseminating, applying, renewing and updating the knowledge for achieving organizational objectives' (Ammar-Khodja and Bernard, 2008). Knowledge management helps organizations in various

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ways, such as retaining knowledge after loss of key staff and ensuring effective use of structured knowledge, which enables quicker identification, retrieval and leverage of existing company knowledge (Alavi and Leidner, 2001).

For the engineering domain, the need to effectively use structured knowledge to improve engineering work has attracted considerable research effort in the last decades (Oldham *et al.*, 1999, Stokes, 2001, Curran *et al.*, 2010). For instance, the MOKA project (Methodology and tools Oriented to Knowledge-Based engineering Applications) (Oldham *et al.*, 1999, Stokes, 2001) has been a key research effort focused in applying Knowledge Engineering principles in the engineering design domain. It focused on the conversion of tacit knowledge to explicit knowledge through the application of informal and formal models. However, it has become apparent that having an approach to make knowledge explicit is a necessary but insufficient condition to support knowledge intensive work. Siemieniuch and Sinclair (1999) asserted that knowledge – in a manufacturing context – has a lifecycle that needs to be managed. More recently, this issue has been recognised and addressed by the engineering design research community with the aim of capitalising engineering knowledge and information in the long term. Examples of research initiatives in this field are the UK-based project "Knowledge and Information Management Through Life", (McMahon *et al.*, 2005) and the Manufacturing Interoperability programme from the US National Institute for Standards and Technology (NIST, 2007). From a research perspective, the challenge is not anymore on producing working knowledge management capabilities but primarily on making them resilient to changing knowledge and capable to support the multidisciplinary learning process through-life.

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2.3 Managing engineering knowledge: exploitation, visibility and lifecycle

The previous discussion indicated a number of aspects that together constitute the fundamental elements of the research problem from a theoretical perspective. First of all, the research challenge is on producing knowledge management capabilities that support the use of dynamic, evolving knowledge through-life. Furthermore, the knowledge contained in such capabilities must be interpretable to receivers and must be processed by users to have an impact. These elements are further addressed in this subsection under the notional headings of the operational **exploitation of knowledge**, the **visibility of knowledge**, and the **knowledge life-cycle**.

Historically, the exploitation of knowledge was at the forefront in the development of knowledge-based systems. Exploitation of knowledge often simply meant that organizational knowledge was incorporated into a KM application; more recently, there is an increasing recognition of the fact that KM applications should put any required knowledge as close as possible to the operational needs of the user (Mariot *et al.*, 2007b). The operational **exploitation of knowledge** must be sufficiently addressed in knowledge management capabilities. As Redon *et al.* (2007) note, 'the exploitation of Knowledge Management within an engineering context … is about providing the right information [*sic*] to the engineer, at the right time, in the right format, in a collaborative environment that promotes learning within the organization'. When a user is in a given context the business tool must include the relevant knowledge in this context. Moreover, this knowledge must support decision making and can sometimes even partially automate decision making. If implemented otherwise, knowledge remains in a separate application which can be subsequently be typified as black-box (Kulon *et al.*, 2006, Choi *et al.*,

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2007). Users will not optimally (if at all) acquire and use this knowledge in their daily practice; the visibility of knowledge will be too low.

The required **visibility of knowledge** enabled through KM is only achieved if users accept the knowledge management solution. As mentioned before, this is complicated in practice as many knowledge-based applications are perceived as 'black-box' applications: in short, the user does not know what is going on inside the application and has to rely on the results. A survey by Bermell Garcia & Fan (2008) indicated that one of the most important business functions to be supported by knowledge-based engineering systems is to 'increase the transparency of KBE application functionalities and data processing'. Another critical aspect in achieving visibility is that users have to be involved in knowledge updating. Again, this observation is supported by Bermell Garcia & Fan, as 'the increase of efficiency in maintaining and updating KBE applications' is ranked second on importance for support. Knowledge updating and maintenance is obtained only if knowledge management provides a real added value to users. This is relatively easy to achieve for newcomers but more difficult for already experienced engineers, which is frequently the case at established industrial consortia. For experienced engineers, only knowledge integrated with business applications can bring the required added value. This issue has been recognized for many years, but has not yet been adequately addressed. The aforementioned MOKA project (Stokes, 2001) also tried to solve this issue. MOKA exploited previous research efforts on Knowledge Engineering by the adoption of the CommonKADS methodology and its principles (Schreiber *et al.*, 1999) into the development of engineering knowledge systems. The key point of MOKA with respect to knowledge visibility was to avoid going straight to

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application coding without providing for representation of knowledge in a human-readable format, which is vital for user support. In particular, MOKA's informal model is an attempt to provide this representation. However, it has been argued that MOKA provided limited (technological) support to manage the transitions between the informal and formal knowledge views (Preston *et al.*, 2005).

This ties in with the increasing realization in the knowledge research community that knowledge management applications should govern the whole knowledge life-cycle (Bernard and Ammar-Khodja, 2008, Mariot *et al.*, 2007a). The **knowledge life-cycle** is conventionally interpreted as the continuous, iterative transfer of tacit to explicit knowledge (Nonaka, 1994) and vice versa. The previously mentioned MOKA project (Stokes, 2001) provides well-established methodological support for engineering knowledge acquisition. Although MOKA was not intended to provide a solution for management of the knowledge life-cycle, its methodological approach provides a proper starting point to address the knowledge life-cycle challenge. MOKA aims to support the seamless transition from informal knowledge to formal knowledge through its use of interrelated informal and formal knowledge models. MOKA's informal model consists of ICARE forms: these knowledge forms aim to capture knowledge related to Illustrations, Constraints, Activities, Relationships and Entities. MOKA's formal model consists of an abstract model to represent engineering design information. The roots of this meta-model can be traced down to Function-Behaviour-Structure formalisms developed in the context of Artificial Intelligence in design research (Umeda *et al.*, 1996). There is relatively little research published on the actual use of the MOKA informal model, though some examples are available (e.g. Skarka, 2007). Also, a similar approach has been used to

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represent engineering knowledge in other research initiatives such as the 'Core Product Model' research (Sudarsan *et al.*, 2005). MOKA's methodological approach in its guise of interrelated informal and formal models addresses a key part of the knowledge life-cycle, namely the iterative conversion from tacit to explicit knowledge and vice versa. However, MOKA does not fully address the many nuances of the knowledge life-cycle. For example, an important part in managing the knowledge life-cycle is to ensure full traceability of knowledge and its source(s), as well as the accompanying enrichment process. Also, the traceability argument extends over the design process: throughout this process, concepts are created, trade-offs are performed, and decisions are taken. If the supporting knowledge for this process changes, the impact this has on the design process must be evaluated. Management of the knowledge life-cycle can valuably assist in such an evaluation. Unfortunately, theoretical support for these specific issues in the knowledge life-cycle and practical examples for the implementation of the knowledge life-cycle are limited. In this paper, this research gap will be addressed by covering the life-cycle from an applied perspective.

3 Costing aerospace composite components through life: a case study

In this section, a current business approach towards cost modelling of aerospace composite components through life will be studied. It will be shown that the evolution of the cost model and its use in the business process interrelate highly with the fundamental theoretical elements that need to be addressed for knowledge-based applications.

3.1 Cost model evolution

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Three fundamental elements of the research problem (knowledge exploitation, visibility and life-cycle) have been identified and put into a theoretical context. In this subsection, a specific business case will be evaluated that shows how these elements also form a challenge from a business perspective.

The business case concerns a bottom-up cost model that has been developed to address current issues on costing concept designs of composite parts and assemblies. In literature, research on cost modelling is rich and varied, both from a general perspective (as discussed in Section 2.1) and from more applied perspectives, for instance through-life costing (Curran *et al.*, 2003, Curran *et al.*, 2007b, Curran *et al.*, 2008a), manufacturing cost estimation (Curran *et al.*, 2006a, Curran *et al.*, 2008c) and composite material costing (Curran *et al.*, 2008b). Likewise, a number of cost estimation methods and tools using principles established in literature have been developed for business use in aerospace Original Equipment Manufacturers, or OEMs. However, the aforementioned bottom-up cost model is filling a business gap that is not covered by other approaches within the aerospace OEM that cooperated in this research. In fact, the cost model addresses the medium level of fidelity gap that has been identified in section 2.1. Furthermore, its results enable the parameterisation of the costs and times associated with the discrete manufacturing processes for composite parts. Going down to this level of detail in the model enables the generation of discrete event simulations in order to evaluate the initial proposed manufacturing system for meeting a required production rate. In other words, the cost model functionality also acts as an enabler towards low-fidelity estimation for the manufacturing discipline. The cost model evaluation enables the generation of improved manufacturing systems that respond better to the required rate

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under some specific criteria (cost, time, etc.). This results in a revised manufacturing system that meets production requirements against improved performance.

The research problem addressed in this paper emerged from the difficulties of coping with the complexity added to the cost model during its evolution. A snapshot of this process is illustrated in Figure 1.

Figure 1: Cost model evolution

In studying the evolution of the cost model, the following stages from Figure 1 and associated observations are discerned:

- **Cost model creation:** An initial cost model using manufacturing process aspects that influence the cost of composite wing stringers and panels has been captured within a spreadsheet. The information used is not completely new since some of the parameters and their values come from existing cost estimation data and tools. The resulting spreadsheets not only unveil tacit knowledge but can also be used as a working tool to produce cost and time estimates.
- **Cost model growth:** The cost model has gained enough relevance and trust among cost engineers, resulting in an expansion of scope. Further developments on the cost model have allowed users to consider costs for various product-process combinations using up to 5 different composite materials / material types. The necessary knowledge has been distributed across spreadsheet tabs. In this growing process, new knowledge has been added to the model. However, existing pieces of knowledge are reused

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across the material tabs. At this stage, over 400 assumed parameters lie at the basis of the model, augmented with some 30 parameters for which the values are chosen by the user. These parameters drive hundreds if not thousands intermediate calculations, frequently with unique formulas to take into account user configurations, to arrive at process time and cost estimates. The model has become a very complex web of knowledge interactions, in which most knowledge elements have again become tacit in nature as these elements require the explanation of an expert to make sense to outsiders.

- **Cost model decomposition:** Further enrichment of the cost model (addition of materials, products and processes) has forced its developers to split it down into pieces. At this point, the complexity of the spreadsheet makes it difficult for management and involved use by anyone other than the creators. Other reasons to decompose the model can be found in the need to distribute it to different users responsible for the cost estimation for different composite materials and material types. In this process, some of the knowledge gets classified and distributed to its consumers. However, a significant risk of inconsistency and duplication of the information emerges.

3.2 Cost model research elements: knowledge exploitation, visibility, and life-cycle.

Following the analysis of the cost model, it is apparent that the evolution of this cost model has made it very difficult to manage its complexity, as the evolved model consists of many interrelated formulas and inputs that are insufficiently classified. An associated

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drawback is that the inputs used for the model are not maintained on a shared base, but are instantiated for each version of the model: each user has a 'unique' spreadsheet model. If a user makes changes to parameter values to adjust for new knowledge, these changes are not shared with other cost model instances in the business. Knowledge exploitation is a significant problem.

Besides these elements of the industrial problem, the existing cost model has a further number of drawbacks. A significant drawback is the rather inflexible, monolithic nature of the model: the current spreadsheet implementation is focused on certain process-product combinations and does not allow for easy mixing of different materials or sub-processes. A possible route to address this would be to enable the assembly of cost model elements that are stored in a managed environment. Also, the cost model is maintained principally by only two persons, as the complexity of the model precludes more direct governability by the end users (even though the latter can still configure user-defined parameters, variation in the pre-defined parameters and formulas is discouraged). This is of course a business risk, as the full set of required modelling knowledge resides with only two persons in the organization. Both the inflexible nature of the cost model and the lack of more direct governability by the end user provide significant challenges for the exploitation and visibility of knowledge. Also, in its evolved form the cost model can be typified as a 'black-box' application. Because of its complexity and its distribution over multiple spreadsheets and spreadsheet tabs, a user effectively has no other option than to trust the model output. The user must go to considerable lengths to retrieve the original knowledge sources behind the implemented formulas and parameters; the

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supporting informal knowledge is also very hard to find. Consequently, knowledge visibility is hardly achieved.

Finally, the assumptions, inputs, operations and outputs of the cost model are not managed from a life-cycle perspective. As mentioned, there are currently little to no provisions for explanation of the rationale behind assumptions. Furthermore, the model inputs, operations and outputs change during the lifetime of the cost model, but these changes are not stored, let alone tracked. The enrichment of these knowledge elements during the model life-cycle is not taken into account. This lack of knowledge life-cycle management is a significant stumble block in the learning process towards composite component production and associated cost estimation.

To summarize, three fundamental knowledge management research elements must be addressed from both a theoretical and a business perspective: the knowledge life-cycle, knowledge exploitation and knowledge visibility. The aim of this paper is to present a functional integration of a knowledge management environment and a real-life, operational cost modelling tool. The resulting knowledge-based cost modelling solution will provide both theoretical and practical relevance by addressing the aforementioned fundamental research elements.

4 A knowledge-based framework to manage cost models through life

In this Section, a knowledge-based framework to manage cost models through life is posited. The primary aspect of this framework is to tie in the cost model with an underlying knowledge base, which offers the opportunity to manage the model's complexity. Furthermore, it increases operational usability and attractiveness by

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addressing the elements of knowledge life-cycle, exploitation and visibility. The central idea for the framework is to store the cost model knowledge in a managed environment and integrate this managed environment with the spreadsheet application in which the current model is embedded. This allows for assembly of a cost model and its managed evolution (see Figure 2), as opposed to the existing cost model evolution (Figure 1). Figure 2 expresses that the user can access the managed environment and retrieve modularized cost model building blocks to assemble a cost model. If the user changes parameters or functions in the cost model, the resulting changes are highlighted and the costing knowledge base can be manually updated after subjecting the proposed change(s) to configuration management provisions (e.g. user group acceptance of a proposed change).

Figure 2: Managed cost model evolution

To achieve a knowledge-based cost modelling solution, a supporting framework must be developed. This framework uses a number of principles and incorporates a architectural solution proposal. To establish these principles and the architecture, it is necessary to determine the relevant cost model elements. Therefore, a representative part of the cost model will be evaluated. After this, the cost model will be subjected to semantic analysis to constitute a contextual model. This contextual model unifies the semantics necessary for governing the alignment between the cost model and the knowledge management application (see Section 4.3). This unified semantic approach (Section 4.1) is combined with a number of principles leading to the development of a framework architecture (Section 4.2). The framework supports the development of a

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knowledge-based cost modelling solution, which is tentatively validated in a proof-of-concept study in Section 4.3.

4.1 Semantic unification to enable knowledge-based cost modelling

In this Section, an analysis will be performed on one part of the full cost model focusing on carbon fibre-reinforced plastic (CFRP) wing top cover manufacturing.

4.1.1 Cost model entities

The cost model is spreadsheet-based and primarily process-oriented. For a given product with adjustable characteristics, it allows for the flexible estimation of time and cost associated with manufacturing options. The model can be classified as bottom-up, as it uses a physical process modelling approach to estimate costs. The model uses manufacturing processes and underlying sub-processes in combination with relevant manufacturing parameters to arrive at estimates for process times and costs, which are subsequently added to arrive at totals for cost and time. A simple example is shown in Table 3 for some steps in the cost modelling of T-stringer (a stiffening structural member) production, which is part of CFRP wing top cover manufacturing. This example shows the first steps in arriving at process time estimates for the individual sub-processes. First, a set of parameters are derived from geometric models that are coupled with the cost model spreadsheets. These parameters are allocated per detailed process (as given in the left-most column under the 'Calculation' heading). The geometric parameters are then multiplied with or divided by applicable constants or rates, both in baseline (current performance) and target (required performance) forms. This results in time estimates for the individual detailed processes. This is followed by a considerable number of

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calculations to arrive at cost estimates (e.g. through the simple step of multiplication of process times with labour rates) and logistical implementation (e.g. capital outlay). The actual values for the calculation parameters in Table 3 have been excluded for confidentiality reasons. A further important element to note is that the aforementioned detailed process parameters (e.g. 'set time', 'weight', 'slab perimeter') are themselves dependent on a string of calculations that are driven by pre-defined and user-defined parameters, as well as the aforementioned geometric information. By and large, the rates and constants in the right-most 'Calculation' column are based on 'assumed parameters' that almost invariably lack justification of the supporting knowledge.

Table 3: Predefined Manufacturing Process: T-stringer Production – Initial Parameters

The previous analysis of the partial cost model can be schematically summarized into a use process with a number of generic elements, as illustrated in Figure 3.

Figure 3: Cost model – Generic Process

When analysing the full cost model, the previously mentioned generic model elements can be generalised and more properly classified. The following basic cost model elements are identified:

- **Assumed definitions:** These are single values associated to parameters such as machine costs per hour or autoclave times. In some cases, they come from existing cost estimation data and tools. For the rest of the definitions, cost estimators have investigated across experts to identify the best possible assumptions since they are not available in existing models.

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- **User definitions:** These are the values that the user of the cost model can modify to drive the cost model. They are usually choices that modify the behaviour of the cost model formulas through the use of "IF-THEN" rules.
- **Predefined formulas:** These are formulas that use either assumed or user definitions to compute relevant values for each predefined manufacturing process defined in the spreadsheet.
- **Predefined manufacturing processes:** The manufacturing processes are compositions of formulas and references to assumed and user definitions. Their end results are process time and cost estimates. Their explicit representation on the spreadsheet enables users to easily visualize the range of available processes and their influence on the final cost of the parts.

4.1.2 Cost model context

The previously identified basic cost model elements are difficult to introduce into a contextual model as individual parameters and formulas are used multiple times in the cost model. Thus, identification of a context by way of these basic elements may lead towards multiple, disparately used, knowledge elements. This would cause difficulties in the necessary modularization of the cost model (see Section 4.2). For example, using the contextual descriptor 'Number of stringers (N Stringers)' would already lead to five disparate detailed processes in the small example given in Table 3. Therefore, other more suitable semantic cost model concepts are necessary to constitute a contextual model.

Fortunately, the cost model itself has been organised to conform to a very basic classification after its evolution into several decomposed spreadsheets. This

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decomposition was made on the basis of the composite manufacturing technology, which incorporates material type and material processing form: similar models exist for different materials and forms, e.g. CFRP prepreg, CFRP dry fibre or CFRP sandwich. Besides this elementary subdivision, the cost models themselves are organised according to manufacturing breakdown structure and manufacturing processes. The breakdown structure is a hierarchical breakdown of assemblies and products. In the cost model, on a product level similar calculations are performed for different products, for instance the bottom and top covers of the wing box. Furthermore, similar manufacturing processes are employed for parts of these products. For instance, the T-stringer production from Table 3 is used in both bottom and top cover production. An inspection of the full cost model has shown that the basic semantic elements of composite manufacturing technology (a combination of material and form), manufacturing breakdown structure and manufacturing process are sufficient to describe the context of a knowledge element, under the assumption that these contextual elements are developed into more detailed hierarchies for actual use (see Section 4.3). Reassuringly, this categorization conforms to the basic elements utilized for the Genetic Causal costing methodology advanced by Curran *et al.* (2006b).

These semantic cost model elements form the context dimensions for a top-level contextual description model that can be used to structure knowledge in the knowledge management application (see Section 4). A contextual description model contains the semantics that can be used to specify the context in which the user, application or model operates (Redon *et al.*, 2007). The context dimensions are ‘classes or attributes that describe the context’ (Redon *et al.*, 2007). As mentioned, the cost model semantic

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elements are summarized into the contextual model under the top-level headings of composite manufacturing technology, manufacturing breakdown structure and manufacturing process. The overall top-level contextual description model for the cost model, consisting of three primary context dimensions, is given in Figure 4. This contextual model serves as the basis for the hierarchy adopted in the KM application; the three contextual dimensions are the major classes in this hierarchy (see Section 4).

Figure 4: Contextual description model for cost modelling of composite structures

In Section 4.3, the above contextual model will be instantiated for CFRP wing top cover T-stringer production to show how it is used in practice.

4.2 Framework principles and architecture

To move towards a successful knowledge-based framework for composite cost modelling that improves upon the current cost modelling approach and answers to the aspects of knowledge exploitation, visibility and life-cycle management, a number of principles have to be obeyed. These principles are briefly illustrated below. Three distinct steps are identified:

- **Modularization & Classification:** the cost model has been modularized to allow for flexible assembly of unique cost models. To achieve this, the existing cost model has been reverse-engineered to define 'building blocks' that describe all the pre-defined inputs, user inputs and model formulas that belong to a sub-process (see also Figures 5 and 6). The use of building blocks in this manner has the desired effect of achieving central management of the inputs and formulas, instead of having multiple

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spreadsheet instances of the cost model. The building blocks are categorized according the previously introduced contextual model. To support this, the context dimensions of composite manufacturing technology, manufacturing breakdown structure and manufacturing process have been developed into hierarchies that offer the necessary classification richness (see Figure 10 in Section 4.3 for an example of this). Using these classification hierarchies allows for unique combinations of knowledge elements in order to find a specific building block.

- **Search & Retrieval:** the classifications established in the previous step are used to search for building blocks in the managed knowledge environment. Various search techniques (standard text search, context-sensitive search, etc.) can be used. In the case of context-sensitive searches, multiple consecutive search choices can be made along hierarchical trees to filter down towards the desired end result. The found building blocks can be selected and consequently exported towards the spreadsheet application.
- **Cost Model Composition:** the building blocks are used to construct an integrated cost model. The proposed solution must be able to manage duplicated knowledge elements when multiple building blocks with similar knowledge inputs are selected and exported. Also, the solution must have the capability of coping with changes in the spreadsheet environment and feeding back these changes into the knowledge base. Of course, this process must be subjected to a validation process: updates in

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the knowledge base must be shared and agreed upon before acceptance of knowledge base changes.

The solution principles have been used to devise an implementation architecture that is shown in Figure 5.

Figure 5: Implementation architecture

The architecture consists of the following main elements:

- **Structured Knowledge Repository:** the repository holds a classification of the knowledge elements that are used to compose the cost model building blocks. Each element is represented by a knowledge base instantiation, e.g. into a knowledge article.
- **Knowledge Reuse Engine:** this architectural element drives the queries that are used to retrieve building blocks from the knowledge base solution. After selection, the building blocks are automatically exported to the spreadsheet environment.
- **Knowledge Reuse Spreadsheet:** the spreadsheet application retrieves the building blocks and automatically builds the resultant cost model, with all inputs, formulas and outputs in place. The cost model inherits default values from the knowledge base for the user definitions, but these and the other parameters can be changed to suit the user needs. A function is included to compare the cost model elements with the knowledge contained in the knowledge base; if the user makes changes in the open spreadsheet, they can then compare the resulting changes with the original

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values and subsequently choose to update the knowledge base based on the outcome.

An overview of the solution principles and its translation into a functional architecture is shown in Figure 6.

Figure 6: Overview of solution principles (left) and integrated solution (right)

Minor and major evolutions of the cost model (e.g. changes in formulas or changes in building blocks) can be performed by updating the relevant knowledge articles. Through the modularised approach, the changes are automatically incorporated into the building blocks and subsequently into any generated spreadsheet-based cost model.

4.3 Proof of concept

To establish the feasibility and validity of the framework, a proof-of-concept solution for knowledge-based composite cost modelling has been developed. This proof-of-concept is illustrated here by introducing the KM application and its use to implement the framework architecture, and by giving an instantiated solution example and the attendant user process.

The KM application of choice for managing the cost knowledge base and its elements is Ardans Knowledge Maker (Mariot *et al.*, 2007a). This application offers a range of options designed to enable user-friendly management of knowledge, for instance through easy categorization and creation of knowledge articles. The application also complies with vital knowledge requirements by focusing on traceability, security and knowledge life-cycle management provision. Traceability and knowledge life-cycle management are achieved through various knowledge article features, including author

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tracking, tracking of version history, status accounting through user group authorization and article status management. Security provisions include amongst others: password authorization, user rights administration, and knowledge base rights administration. Each knowledge element (e.g. parameter or formula) has been stored into its own AKM knowledge article, which retains the traceability, security and life-cycle management provisions described above. Each knowledge article has the facilities to represent not only the formal knowledge (parameters, formulas), but also the informal and/or tacit knowledge behind the formal knowledge (e.g. rationale for formulas – see Figure 7 for an example knowledge article[2]). The knowledge articles are subsequently grouped into specific building blocks. Therefore, one knowledge article can be used in multiple building blocks.

Figure 7: AKM knowledge article example

To illustrate how the knowledge-based cost modelling solution works in practice, an example is presented here that was used as part of a validation exercise at a major aerospace OEM. As presented in Section 4.1.1 previously, the example concerns the production of CFRP T-stringers for a wing top cover, for which the process representation was presented in Table 3. The contextual model described in Section 4.1.2 has been instantiated for this example; the result is shown in Figure 8.

Figure 8: Contextual model – CFRP Wing Top Cover: T-stringer production

[2] The knowledge justification has been omitted from this figure for reasons of confidentiality. However, the knowledge article contains the structural elements necessary for explicit knowledge representation.

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The contextual dimensions and their associated hierarchies – evidenced in Figure 8 for the product and process dimensions – have been implemented in AKM. These hierarchies can be partially seen in Figure 9.

Figure 9: AKM search environment – hierarchical knowledge representations

The user now follows the following process, which is also illustrated in Figure 10. The Figure shows that after opening a spreadsheet-integrated Visual Basic macro (step 1) and calling the AKM environment, the user employs the contextual information displayed in Figure 8 to select the relevant entries in the hierarchical trees (also shown in Figure 9). The corresponding search result displays the suitable building block(s) (step 2). This building block is subsequently selected (step 3) and exported to the spreadsheet application. The supporting Visual Basic macro automatically generates the cost model (step 4) that belongs to the building block(s). After this, the user is free to make choices and changes in the spreadsheet environment to arrive at customised process time and cost estimates (step 5). The changes can be checked against the existing knowledge base as a 'live link' is maintained between the two applications. If necessary, the knowledge base can be manually updated to support knowledge evolution (step 6).

Figure 10: Knowledge-based cost modelling solution – user process

The user process (Figure 10) has been validated at the OEM company through the above exemplar and through expert opinion and user feedback. The functional solution itself is validated through its successful application in practice, for which a representative proof-of-concept example has been presented herein. The validation exercise was specifically

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designed so that the knowledge-based cost modelling solution addressed the three key identified fundamental knowledge management research elements.

Firstly, the solution to the case study provided knowledge life-cycle management through the inherit capabilities of the AKM tool and through the chosen solution methodology. In particular, the provisions for explicating the justification behind knowledge elements, the 'live link' between the knowledge base and the spreadsheet application, and the possibility to track the evolution of knowledge through the retention of historical knowledge articles contribute to a significant improvement on the life-cycle aspect.

Secondly, the solution also facilitated knowledge exploitation through the retention and exploitation of existing and legacy models, e.g. spreadsheet use, which ensured that users keep using familiar tools and processes. Furthermore, the use of a dedicated knowledge base, with the associated provisions to ensure the availability of trustworthy knowledge, assures users that the right knowledge is available at the right time.

Thirdly, the solution addressed knowledge visibility by including provision for knowledge explication. The difficulty with actually understanding complicated or dense legacy tools has been highlighted so that visibility is interpreted primarily in terms of the user being able to understand the rationale embedded into the tool. Users can adjust their confidence levels relative to the output results. Other features found to be of significance through the validation exercise included the traceability and retrievability of knowledge, potentially at the click of a mouse button.

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5 Concluding remarks

A framework and solution for knowledge-based cost modelling has been described in terms of its principles, methodology and architecture. Ultimately, a exemplar validation exercise was carried out. The developed solution delivers a key contribution from both a theoretical and practical perspective by enabling an integrated approach to performing process-based cost modelling supported by traceable, verifiable and reliable knowledge. More specifically, this solution makes it possible to:

- Manage cost modelling knowledge bases in tandem with operational use.
- Manage model and legacy tool complexity.
- Manage risk associated with current business processes.
- Provide an easier, more user-friendly cost modelling capacity that can consequently be understood and used by more end users, enabling a better and more distributed capacity for cost modelling in early-stage design.

The solution has advanced both research and business interests by addressing functional needs in enabling: a) the ability to manage the evolution of the knowledge from a life-cycle perspective; b) the ability to exploit cost modelling knowledge by fitting it into the existing business process and through seamless transfer of knowledge elements into a working cost model; and c) high visibility to the knowledge used in the cost model. The developed solution has been functionally validated as shown in the application example (Section 5.2) and has been accepted and validated by a world class industry lead as a distinct improvement upon the previous cost modelling solution.

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In its current incarnation, the knowledge-based cost modelling solution is limited in several aspects. First, the whole process is at best semi-automatic. Composition of a cost model still requires some non-productive steps that don't add value, though the overall time spent on model composition is greatly reduced through the presented approach which produces something of great impact in a procedural and controllable manner.

Another limitation is the fact that the spreadsheet results from generated cost models and subsequent user manipulations are not yet stored into a central repository for the company; which is typical. The research has shown that it is advisable that these results are stored in such a repository for better understanding of the evolution of designs during the design process; this aspect will also be addressed in future research. A final limitation of the research that will addressed in future research is that the overall cost modelling capacity has not yet been fully addressed in informal terms: whereas the individual knowledge articles do feature informal knowledge, the higher-level process does not.

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Acknowledgments

The authors would like to thank the various involved partners in the Next Generation Composite Wing – Multi-Disciplinary Optimization of Wing project for their financial support of this research; we would like to thank Airbus UK in particular. We would also like to thank our EADS IW and Airbus UK collaborators, in particular Simon Astwood, Alistair Dare-Edwards, Kiran Krishnamurty, Dave Gore and Tom Gibbs, for their support.

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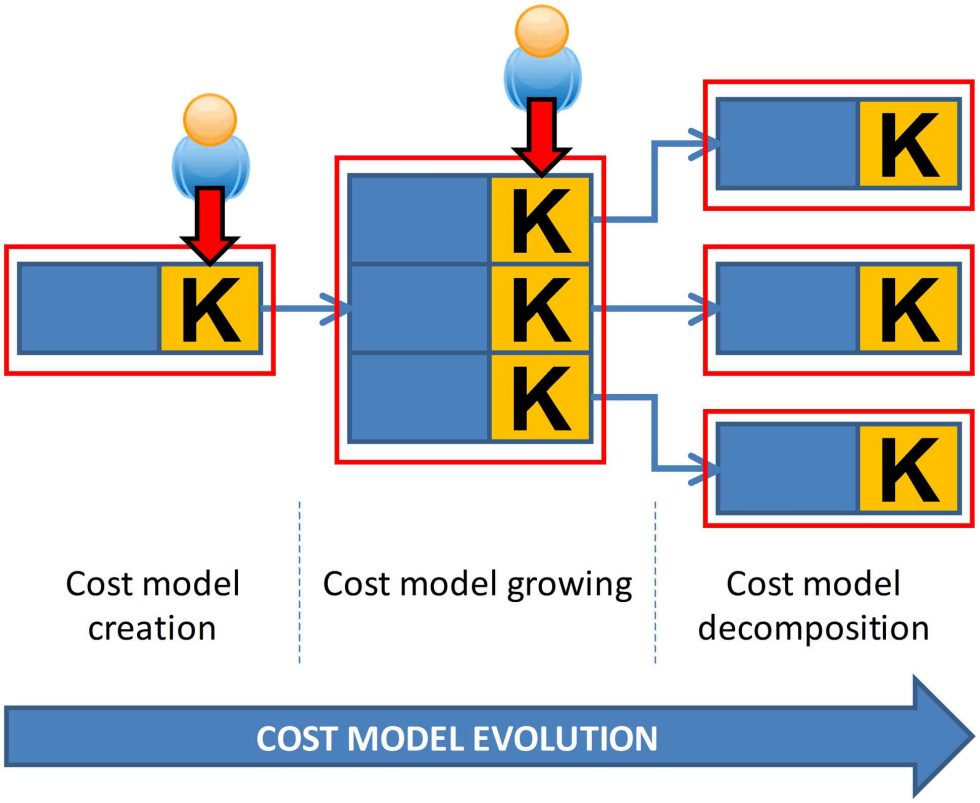
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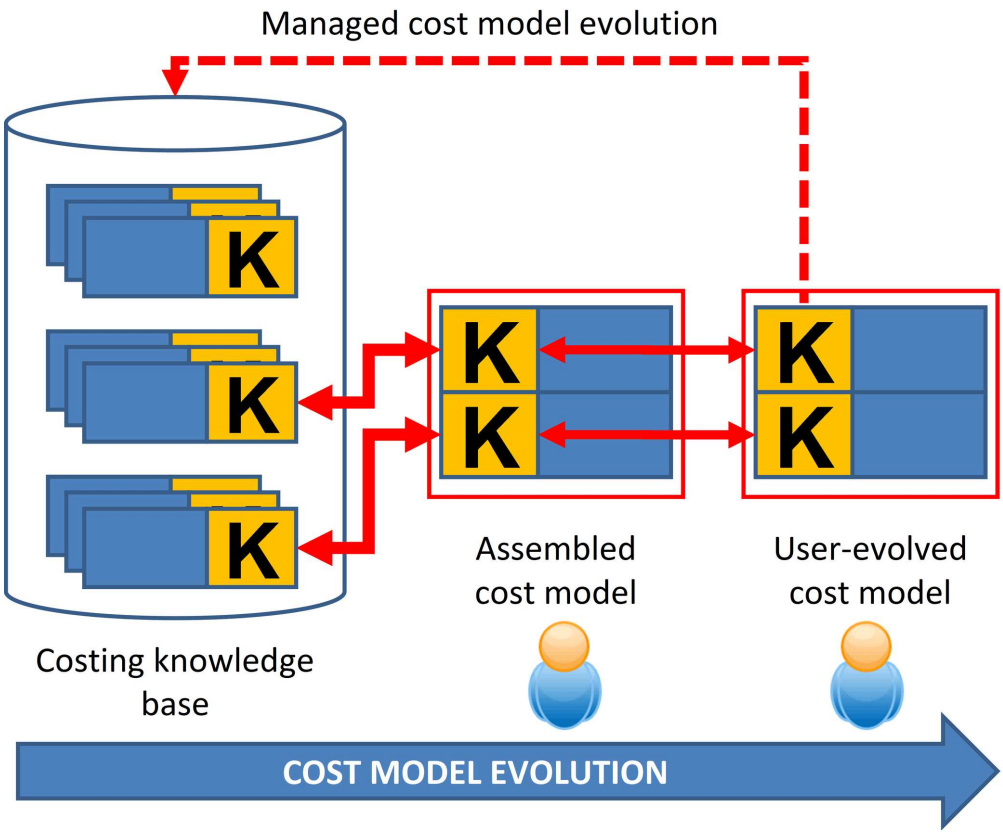
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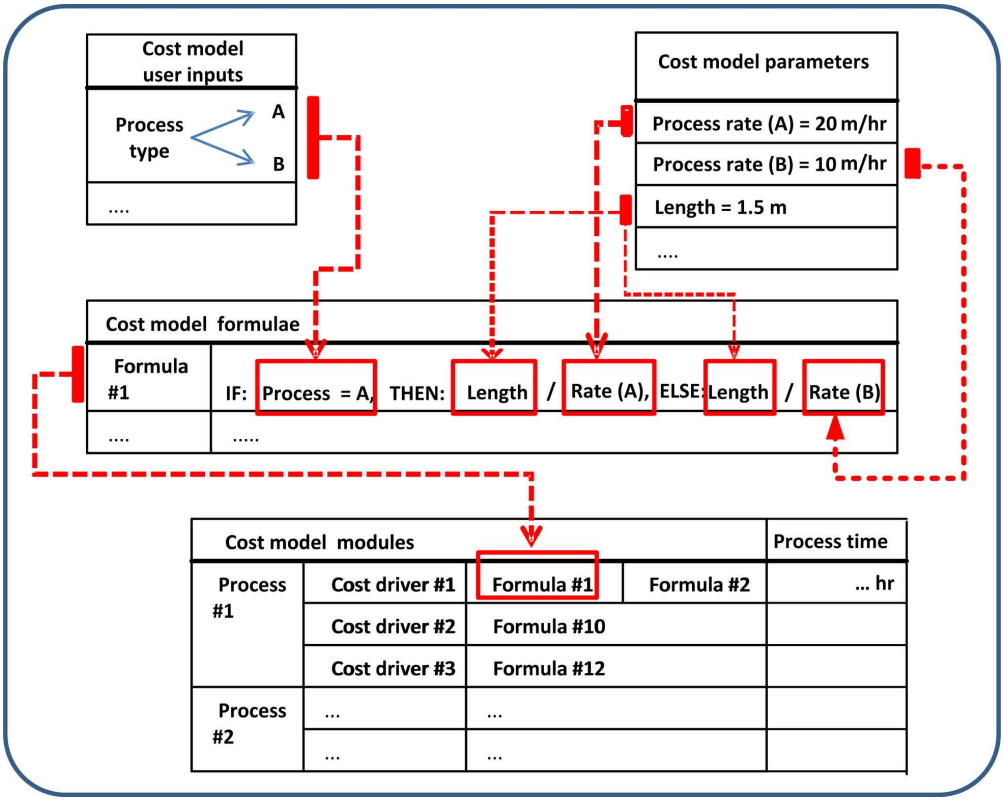
Cost model evolution
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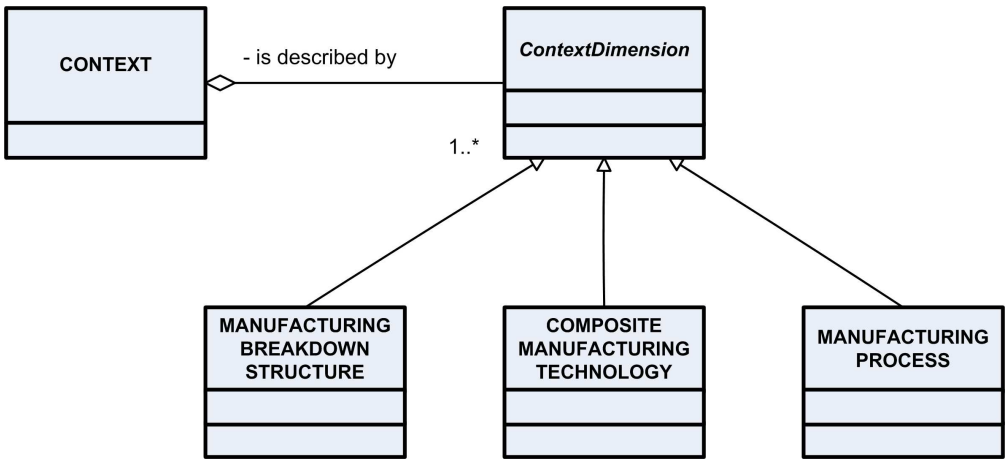
Managed cost model evolution
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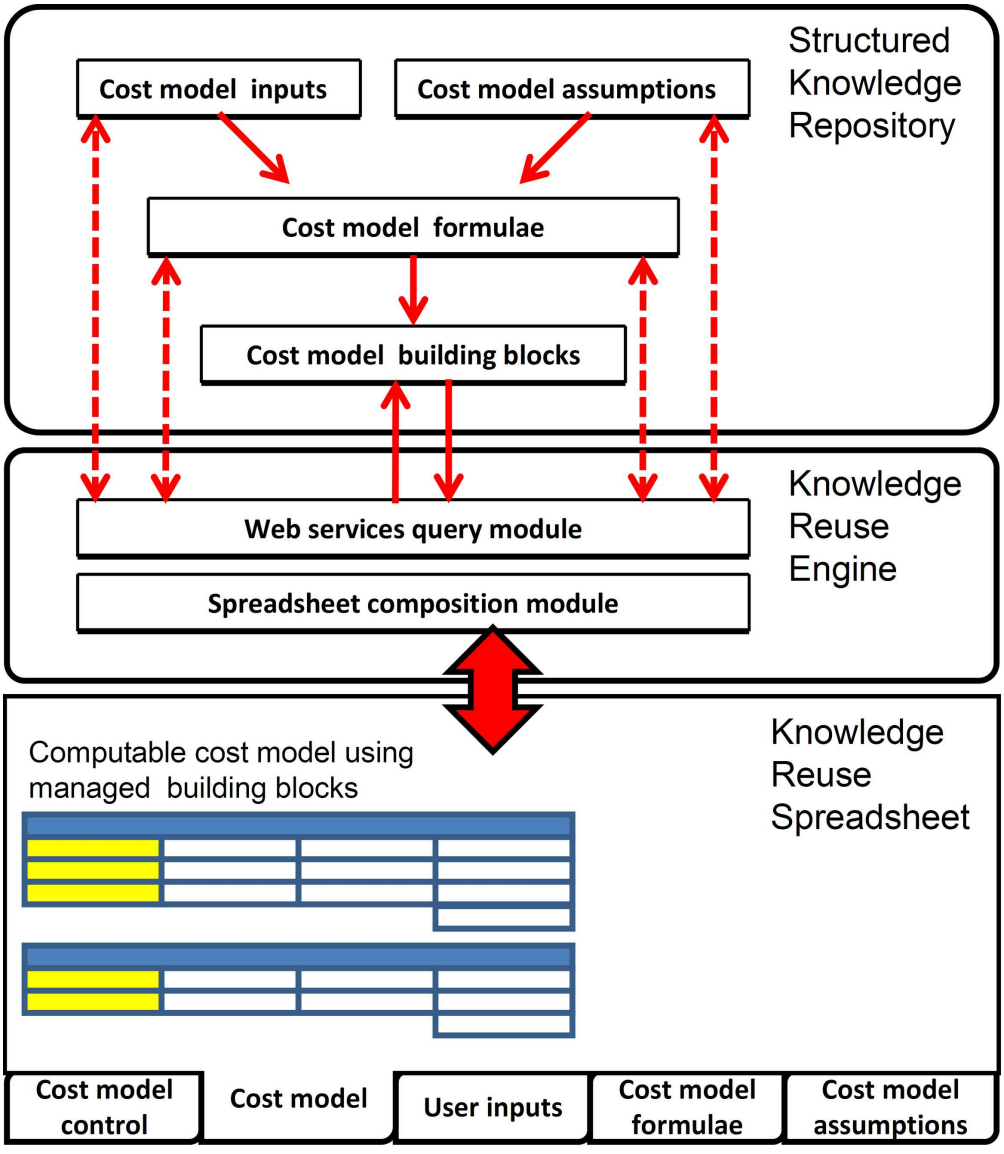
Cost model - generic process
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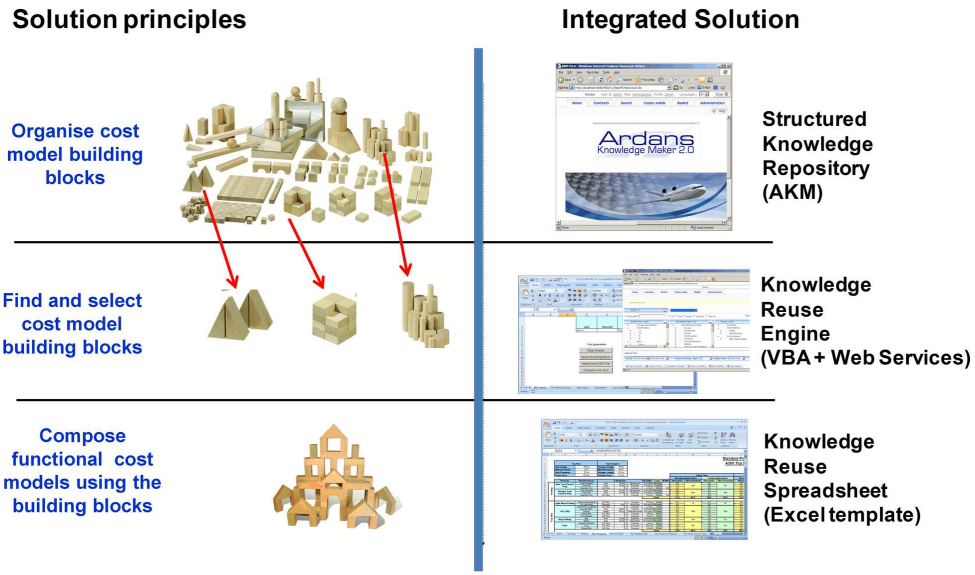


Contextual description model for cost modelling of composite structures
100x45mm (600 x 600 DPI)

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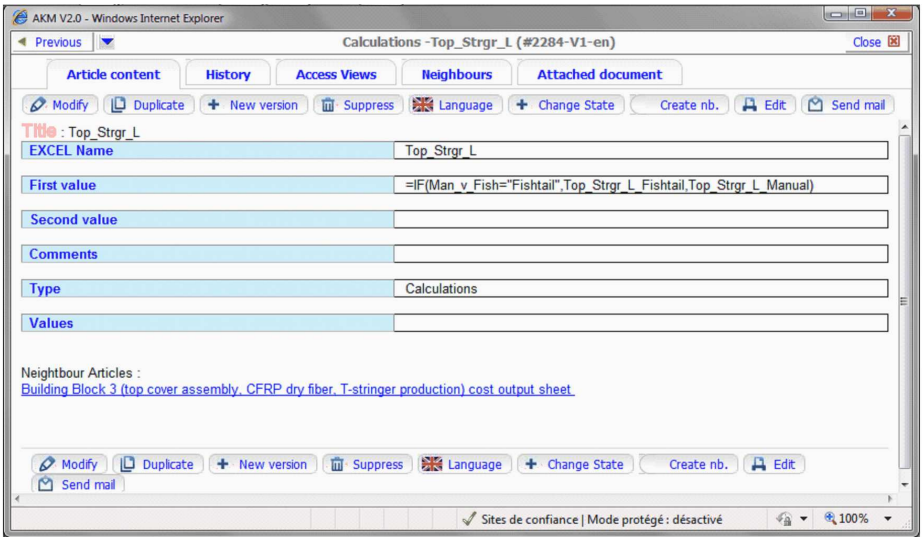


Implementation architecture
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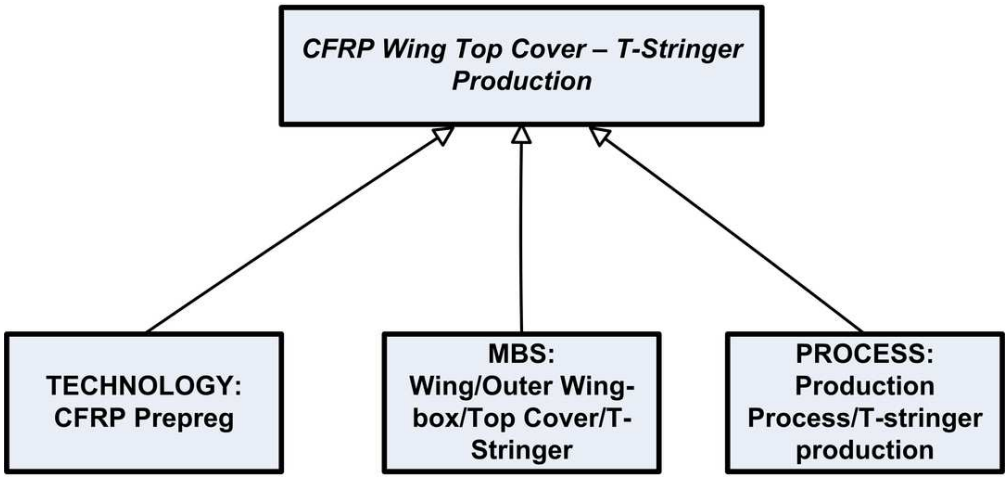
Overview of solution principles (left) and integrated solution (right)
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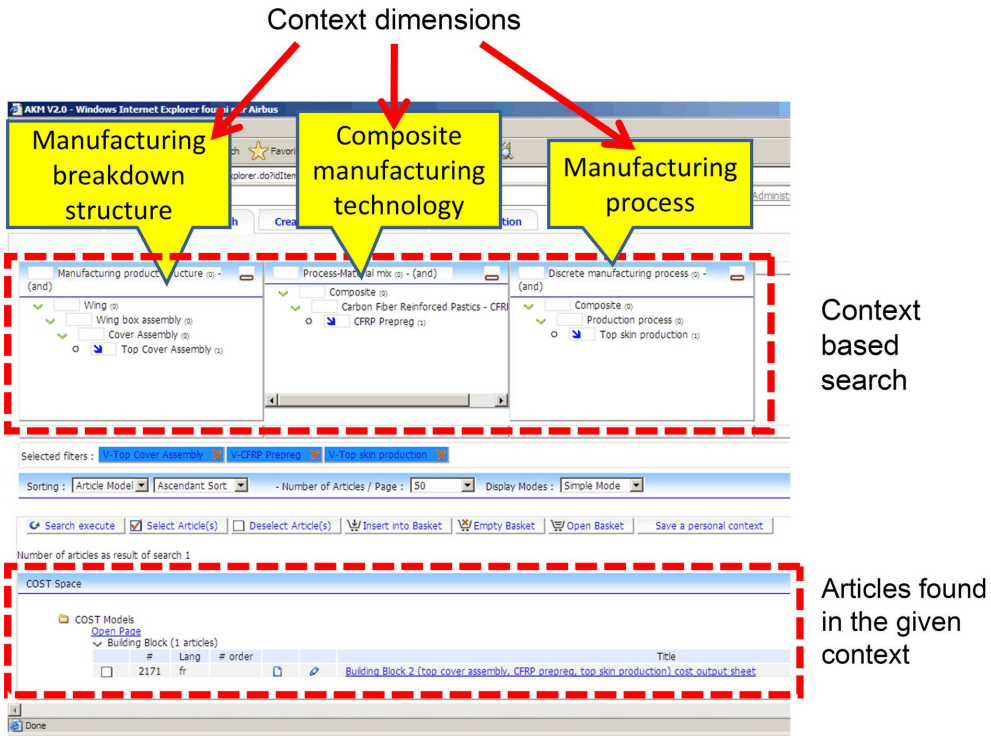
AKM knowledge article example
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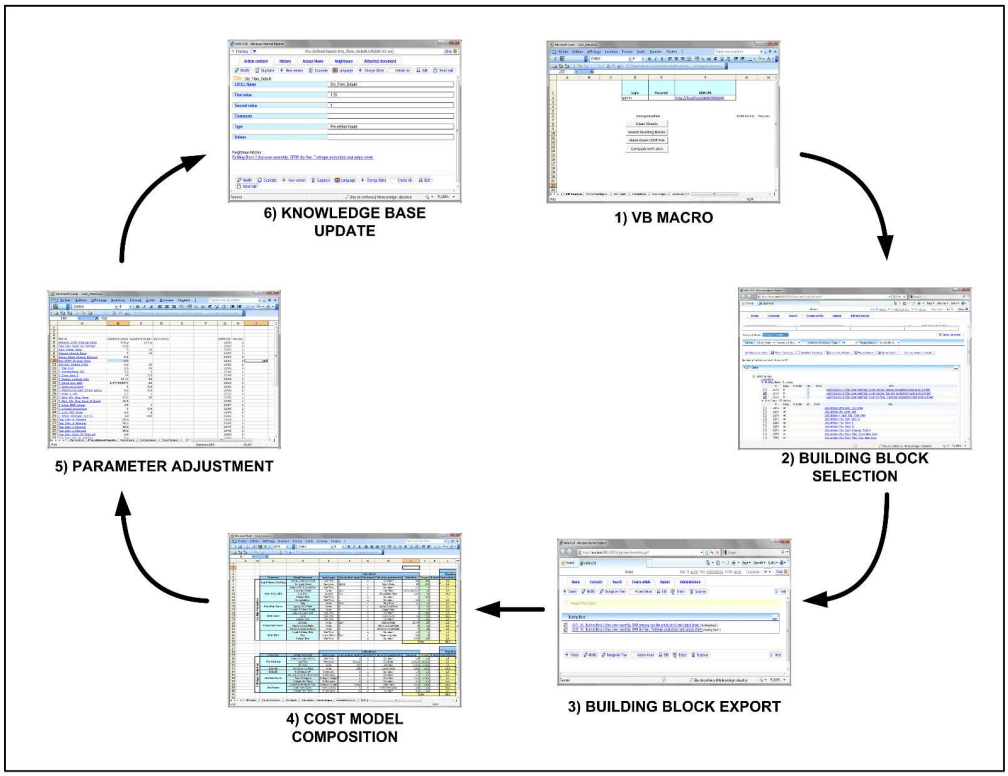
Contextual model – CFRP Wing Top Cover: T-stringer production
45x21mm (600 x 600 DPI)

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AKM search environment – hierarchical knowledge representations
81x60mm (600 x 600 DPI)

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Knowledge-based cost modelling solution – user process
134x111mm (600 x 600 DPI)

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Approach	Advantages	Disadvantages
Bottom-up costing	Cause and effect understood Very detailed estimate	Difficult to develop and implement Substantial, detailed expert data are required Requires expert knowledge
Analogous costing	Cause and effect understood More easily applied than bottom-up method	Appropriate baseline must exist Substantial, detailed data are required Requires expert knowledge
Parametric costing	Easiest to implement Non-technical experts can apply method Uncertainty of the forecast is generated Allows scope for quantifying risk	Can be difficult to develop Factors might be associative but not causative Extrapolation of existing data to forecast future products including new developments might be unwarranted

Assessment matrix for traditional cost estimation methods (Curran et al., 2004)
73x42mm (600 x 600 DPI)

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		Analysis Discipline						
		Aerodynamics	**Structures & weights**	**Noise**	**Geometry**	**Cost**	**Manufacturing**	**Maintenance**
Fidelity	**Low**	Empirical methods (e.g. EDET)	Empirical methods (e.g. FLOPS)	Empirical methods (e.g. FLOPS)	Vehicle Sketch Pad (VSP)	Piano, SEER, Price	**GAP**	**GAP**
	Medium	Vortex Lattice (e.g. WINGDES)	Basic structures (e.g. ELAPS)	Basic Noise (e.g. ANOPP)	**GAP**	**GAP**	**GAP**	**GAP**
	High	CFD (e.g. FUN2D, Fluent)	FEM (e.g. NASTRAN)	Advanced Noise (e.g. AVATAR)	High-end CAD systems (e.g. CATIA)	**GAP**	Virtual Factory Simulations (e.g. DELMIA)	**GAP**

Disciplines versus fidelity (modified from Price et al., 2006)
54x20mm (600 x 600 DPI)

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	Process	Detail Process	Calculation				Baseline	Target
T Stringers production	Strgr ATL (2D)	Setup ATL & Load Tool	Set Time		x	Constant		
		Lay Slab	Weight		/	Deposition Rate		
		Unload ATL	Set Time		x	Constant		
	Strgr ATL (2D) Cut & Kit	Cut Slab into Planforms	Slab Perimeter		/	Cut Rate		
		Kit Planforms	N Stringer pieces		x	Constant		
	Strgr Hot Roll Form	Setup & Soak Hot Roll Form	N Stringers		x	Constant		
		Feed Stringers	Stringer Weight		/	Roll Rate		
		Unload Hot Form	N Stringers		x	Constant		
	Strgr Hot Form	Load Planforms to Tool	Stringer Length		/	Load Rate		
		Hot Form Cycle	Form Cycles		x	Hot Form Cycle		
		Unload Hot Form	N Stringers		x	Constant		
	Stringer Profile Shape	Position Blade	N Stringers		x	Constant		
		Make Final Profile	N Stringers		x	Constant		
		Insert Noodle	Length		/	Rate		

Predefined Manufacturing Process: T-stringer Production – Initial Parameters
70x35mm (600 x 600 DPI)

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Number of figures/tables/illustrations	
Format	both print and electronic
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No	
Order reference number	
Title of the article	Knowledge-Based Cost Modelling of Composite Wing Structures
Publication new article is in	International Journal of Computer Integrated Manufacturing

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Author of new article	W.J.C. Verhagen
Expected publication date	Dec 2010
Estimated size of new article (number of pages)	18
Elsevier VAT number	GB 494 6272 12
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