Supporting the sharing and reuse of modelling and simulation design knowledge

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Abstract

Modelling and simulation is used to support a number of engineering processes including product design, testing and maintenance. However, knowledge management support for modelling and simulation is currently poor. Here we present technological and methodological support for knowledge sharing and reuse in the modelling and simulation domain. The Clockwork approach has three key aspects. First, knowledge management support focuses on key stages and transitions in the design process. Second, rationale is integrated with work activities and engineering models to minimise additional effort on the part of the designer. Third, support is provided for knowledge formalisation and generalisation to increase the value of explicated knowledge. The Clockwork methodology and toolkit have been tested and deployed in two industrial case studies. Preliminary trials suggest that the Clockwork approach effectively supports reuse, expediting the modelling and simulation process.

Keywords

Knowledge management, modelling and simulation, design rationale capture, collaboration, knowledge reuse.

1 Introduction

Modelling and simulation is the development and testing of models to solve complex problems that cannot be tackled directly due to factors such as cost, inaccessibility, complexity and safety. Engineering companies build and use simulation models to support various engineering business processes including product design, testing, manufacturing and maintenance.

The modelling and simulation process is becoming increasingly collaborative comprising distributed design teams incorporating different stakeholders and expertise. For example, modelling and simulation is often undertaken by dedicated service companies. Here there is a need for the service company to negotiate requirements with the customer and appropriately hand over the findings of the modelling and simulation process.

There is also increased pressure to reuse modelling and simulation work in order to reduce costs and expedite and improve the design process. Modelling and simulation often comprises an important stage in the design process of a product. The speed, efficiency and quality of the results gained from modelling and simulation can significantly impact on the lead time for the resulting product.

Despite these trends, and the significant role played by modelling and simulation in many design processes, there is still little in the way of knowledge management support. In terms of collaboration there have been some studies of how synchronous communication technology can be used to support modelling and simulation [Taylor, 2000], but this has yet to make and impact in industrial contexts. From a knowledge reuse perspective, modelling and simulation is poorly supported. It is common for companies to archive the final modelling and simulation code, but little or none of the reasoning or assumptions that led to this code, significantly restricting its reuse potential. The work reported here, conducted in the EU IST funded Clockwork project aimed to provide technological and methodological support for knowledge sharing and reuse in the modelling and simulation domain.

The rest of this paper is structured as follows. Section two describes selected previous work relevant to this research in areas including modelling and simulation, design rationale, engineering design and ontologies. Section three outlines the Clockwork approach. Section four describes the use of the Clockwork approach in an industrial setting.

2 Previous work

Much previous research on providing knowledge management support for design has focussed on providing tools and methods for the engineer to record their design rationale. Tools and methods supporting the explication of design rationale can overburden the designer [Gruber, Russell, 1996). [Ball, Evans, Dennis, Ormerod, 1999] argue that in industrial contexts design rationale may be rejected because the designers cannot envisage the rationale providing sufficient value to justify the additional effort involved. *Resolving the burden of design rationale is a key aim of the Clockwork approach.*

Similarly to accounts of design problem solving [Cross, 1989; Hubka, Eder, 1995], the simulation and modelling process can be characterised as comprising a number of stages or phases. Each stage of the modelling and simulation process contains its own concepts for expressing the design. For example, in an early stage of the design of a simulation model of a car, the concepts used by the designer may be expressed as a sketch or CAD drawing comprising wheels, suspension, road surface and steering. At a later stage in the process, the concepts used by the designer may comprise equations or program code and be expressed using a particular modelling and simulation software package. The transition between stages in the design process is non-linear. A designer may have to backtrack to a previous stage and elaborate and alternative design route. Unless each transition to the next stage is right first time, the design history eventually takes the form of a hierarchy of design alternatives, with a one to may relationship between each design stage and its subsequent stage.

Within engineering design in general, and modelling and simulation specifically, prescriptive methods can help support collaboration and reuse. [Zeigler, Praehofer, Kim, 2000] propose a generic modelling and simulation methodology defining the stages, processes and components of the modelling and simulation task. A set of designers subscribing to the approach are facilitated in decomposing the task in a consistent way and adopting and using a similar vocabulary of the modelling and simulation process. *Clockwork aims to build on the above work by providing knowledge management support that structures the modelling and simulation task and focuses on key stages and transitions in the design process where it has greatest impact.*

One successful approach to lowering the demands of describing work in order to facilitate its reuse is to make the process of description an integral rather than additional part of work. [Mulholland, Zdrahal, Domingue, Hatala, Bernardi, 2001] provided knowledge management support for planning and maintenance activities incorporating collaboration support tools. This integrated support was used to capture knowledge concurrently, therefore reducing additional burdens for the workers involved. Also, in engineering settings, although the reuse and comprehension of design models can be enhanced by associated rationale, models themselves can communicate a great deal of knowledge when used collaboratively. [Schön, 1988] describes how within a design community, design classifications emerge, which he terms "design types". Designers use these as a communal method for talking about particular types of design, without ever defining precisely what they mean. In this context, a team of designers who regularly work together develop a shared conceptual scheme, and shared artefacts can be used communicatively to refer to these concepts. *Clockwork aims to integrate rationale with work activities and engineering models in order to reduce the additional effort required for design rationale explication.*

The capture and archiving of knowledge always imposes costs. For knowledge management to deliver a return on investment, archived knowledge has to pay back these costs in terms of, for example, reduced product lead time. It is therefore important that captured knowledge has a maximal impact on future design processes. Knowledge that has been formalised or generalised can have a greater value within the organisational memory. A number of research projects have focussed on the development of ontologies to support the formal description and reuse of engineering models. For example, [Borst, Akkermans, Top, 1997] developed the PhysSys ontology for describing models in terms of their functional and physical decomposition. The Design Repository [Szykman, Racz, Bochenek, Sriram, 2000] provides a formal language for the description of engineering designs in order to support their retrieval and reuse. Other work has used ontologies within a web-based environment for the sharing of modelling and simulation knowledge among undergraduate students. [Zdrahal, Mulholland, Domingue, Hatala, 2000] describe a web-based tools allowing students to semantically retrieve, reuse and discuss structured modelling examples from a shared repository. *Clockwork aims to provide support for knowledge formalisation and generalisation to increase the value of explicated knowledge.*

3 Clockwork approach

In this section will we consider three key features of the Clockwork approach:

1. The task is structured, and rationale explication is focussed, on key stages and transitions in the design process where it has greatest impact.
2. Knowledge management support is integrated with work activities and outcomes to reduce additional effort.
3. Support is provided for knowledge formalisation and generalisation in order to increase the value of explicated knowledge.

3.1 Focus on key stages and transitions

Our analysis of engineering modelling and simulation cases has shown that a typical modelling process consists of four well-defined stages (see figure 1). First, the engineer defines the problem, i.e. restricts the part of reality which he/she wants to investigate and defines the objectives of the modelling experiment. In the second stage he/she simplifies the problem by selecting objects which will be further considered and those which will be omitted. The third stage consists of expressing the selected objects in terms of interconnected ideal physical objects. Finally, the behaviour of the ideal objects is encoded in a selected simulation language (e.g. Matlab/Simulink) as a simulation model. Each stage has an associated set of assumptions under which the step from the previous stage has been made. Eventually, the simulation model is executed, results are validated against the assumptions and interpreted in terms of the original engineering problem. In Clockwork, these four stages are called *worlds*. Each world incorporates its own objects and has a specific engineering representation language. The modelling process can be viewed as a sequence of re-representation steps i.e. transformations between the worlds. For a typical application, the four worlds are named as follows:

- *Real world* is essentially a requirements analysis for the resulting model usually as informal text and sketches.
- *Conceptual world* specifies the type of model to be developed and its core components, in the form of diagrams or text.
- *Ideal model world* breaks the problem down into more fine-grained ideal modelling elements, represented for example as a topological diagram.
- *Simulated world* represents the problem in a simulation code such as MATLAB/SIMULINK™ or SIMPACK™.

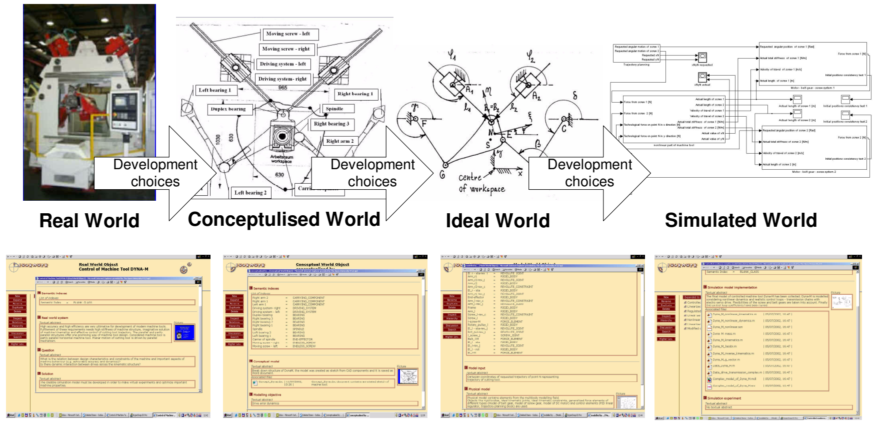

Figure 1: The four-world modelling and simulation structure.

A modelling and simulation process characterised according the four world structure is shown in the top half of figure 1. The Clockwork Knowledge Management Tool (CKMT) provides support for the description, archiving and retrieval of models for each world defined in the modelling and simulation process. The CKMT interface used to organise, capture and describe each world is shown in the bottom half of figure 1.

The above four world structure is typical for many modelling and simulation applications however, the CKMT can be customised according to any adopted modelling and simulation methodology that can be expressed in terms of worlds. It can then be represented in an ontology referred to as the *backbone ontology* for the application. The backbone ontology is then used to generate the CKMT application (see figure 2). The world ontologies contain the concepts that can be used to formally describe each world. The specific appearance and functionality of the tool can be further altered by the selection or modification of JSP (Java Sever Pages) templates in the library.

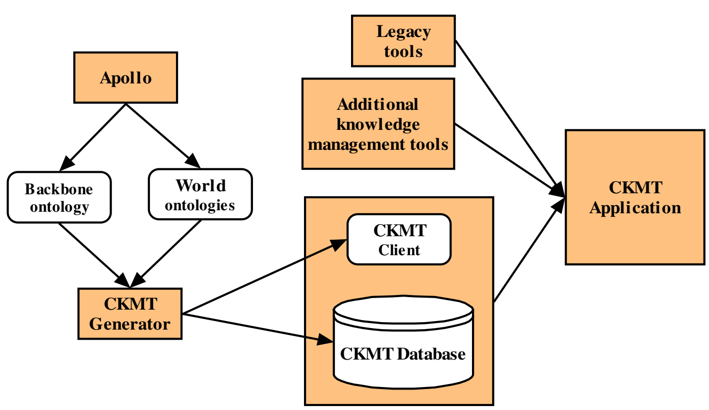

Figure 2: Generation of a CKMT application from ontologies.

3.2 Integrating knowledge management with work process and engineering models

One successful approach to lowering the demands of describing work in order to facilitate its reuse is to make the process of description an integral rather than additional part of work. This is achieved in Clockwork in two ways. First, asynchronous collaboration tools within the Clockwork toolkit support distributed design. The collaboration is captured and associated with the relevant modelling and simulation design process. Second, Clockwork provides support for the integration of formal and informal design rationale with the models at key stages of the design process. Here we will focus on the second of these issues.

The worlds of any specific modelling and simulation process comprise engineering models, composed of modelling components. Depending on the specific world, the engineering models may take the form of text, sketches, topological diagrams or program code. These engineering models can be described in two ways, either informally or formally. Informal descriptions, which we refer to as *annotations*, may take the form of natural language or sketches. Formal descriptions, which we refer to as *semantic indexes*, are associated with an ontology of concepts related to that world. As each world comprises its own concepts, each world has its own ontology or ontologies associated with it.

The interface to a specific world in the CKMT is shown in figure 3. The CKMT has the following key features:

- Models can be semantically searched and retrieved using the formal description of models and model assumptions, as well as the keyword searching of textual resources.
- Files developed locally can be uploaded and organised according the adopted modelling and simulation world structure.
- A forms interface can be used to supply informal annotations to each world of the modelling and simulation task and its associated objects.
- Semantic indexes can be associated with each model, its components and assumptions.

The complete toolkit developed to support sharing and reuse comprises further tools including specialised graphical annotation tools for adding in-line comments to models locally during model development, and the Apollo tool (http://apollo.open.ac.uk) that supports the editing and browsing of ontologies.

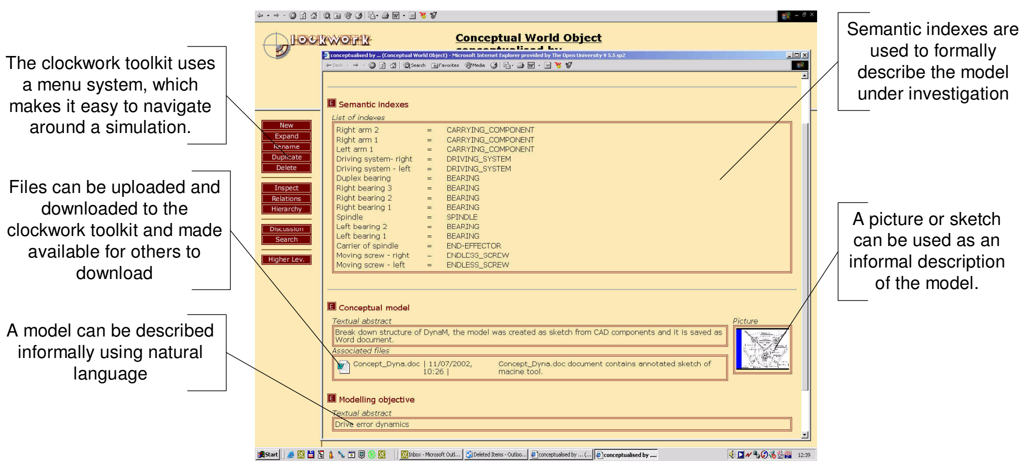

Figure 3: A modelling and simulation world as represented in the CKMT.

The process of re-representation from one world to another involves adopting a set of *assumptions*. Different kinds of assumption can be made. An assumption may relate to all components within a world. Generally such assumptions specify properties that should be included or ignored. For example, a simulation engineer may assume that some property (e.g. friction) can be ignored in the re-representation of a world into a new world. An assumption may also apply to a specific object or group of objects within a world. For example, the simulation engineer make assumptions that allow a shaft in the conceptual world to be represented as a three mass model in the ideal model world. Additionally, a single object in one world may be substituted by a number of objects in the next world, or vice versa.

Support is provided to describe transformations both formally and informally. In terms of formal knowledge, *mapping ontologies* are provided to allow the simulation engineer to describe how a world and its objects are transformed into the next world. Each mapping ontology uses two world ontologies, essentially mapping objects of one world into objects of the next. Formal descriptions of assumptions are referred to as *mapping semantic indexes* or *mapping SIs*. Assumptions can also be described informally as plain text. Informal descriptions of assumptions are referred to *assumption annotations*.

3.3 Support for formalisation and generalisation

Support is provided in the Clockwork toolkit and methodology for the informal and formal description of models. Over time, the formalisation of informal knowledge enhances the organisational memory and increases the usefulness of provided knowledge services such as the semantic search of resources for reuse. Within Clockwork, knowledge formalisation can occur in two ways:

- Informal model descriptions in the form of model annotations can be formalised into Model SIs.
- Informal assumption descriptions in the form of assumption annotations can be formalised into mapping SIs.

It is vital that Clockwork provides support for informal descriptions. However, support should also be provided for the formalising of knowledge where appropriate. Knowledge that is later formalised is often initially expressed informally. This is for two reasons:

Demands on the simulation engineer – Describing knowledge formally places additional demands on the engineer which may detract from undertaking the modelling and simulation task itself. In such situations the formal description of knowledge therefore cannot be done in parallel with the modelling and simulation task.

Evolution of the domain – Knowledge of the domain within any discipline or community evolves over time. New concepts within a community are often initially ambiguous and become more formal over time. Such new concepts therefore cannot initially be expressed formally until the knowledge of the community has further evolved.

Evolution of an organisational memory involves generalisation as well as formalisation. Within Clockwork this particularly applies to assumptions, formally represented as mapping SIs. Within the Clockwork knowledge base, a mapping SI can be defined as having a particular scope. When initially expressed, a mapping SI applies to a particular modelling and simulation problem. For example, a mapping SI describing how an object in the Real World can be conceptualised as another object in the Conceptual World would be expressed using the relation "is-conceptualised-as". If this SI where generalised to a set of cases within a particular scope, it can be generalised using the relation "can-be-conceptualised-as" which specifies the scope within which the assumption applies. The scope of a generalised mapping SI is described in terms of the components and function of the models of the two worlds. The generalisation process is illustrated in figure 4. Generalisation extends the reuse potential of the modelling and simulation worlds and their associated transformations.

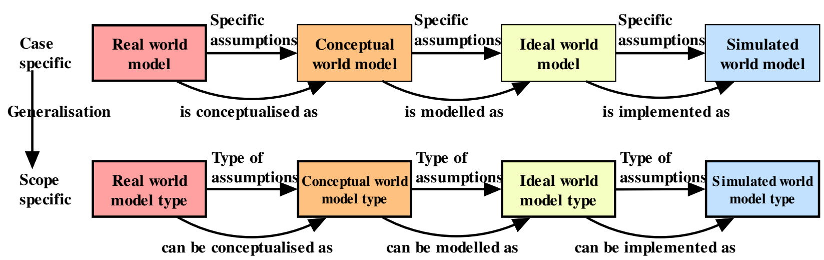

Figure 4: The generalisation of formal assumptions.

4 Case studies

The Clockwork toolkit and methodology has been successfully deployed in two industrial settings. In ELOTHERM GmbH, a thermal machinery manufacturer, the tools and methodology are being used to support the effective reuse of machine designs developed using modelling and simulation, and collaboration within the design team. In INTEC GmbH, a simulation software and engineering service company, the methodology and tools are being used to support in-house design reuse, and also support virtual design teams incorporating designers from client engineering organisations. INTEC use the Clockwork tools and methodology with SIMPACK™, their own simulation software package. Here we will focus on the work of INTEC.

INTEC adopts the four world simulation and modelling process as described in section 3.1. Figure 5, shows the real, conceptual and ideal world models for a specific car suspension problem. This is illustrative of the design tasks undertaken at INTEC. At the real world stage, in collaboration with the customer, requirements are specified in terms of what is to be modelled, and the questions to be answered by the modelling exercise. For example the real world model may be defined as a 5-link and double wishbone suspension of a car for testing the car traction control system (TCS). The simulation model may have to operate in real time for integration with the car hardware (hardware-in-the-loop, HIL). The INTEC simulation engineers may then develop the conceptual model as a structural model of the suspension, in terms of springs, dampers, levers, links, wishbones, wheel carriers, wheels, chassis and the road. In developing the conceptual model, the designer needs to make assumptions that can be expressed as informal or formal annotations. For example, the designer may assume the chassis as a rigid body and symmetry of the road shape.

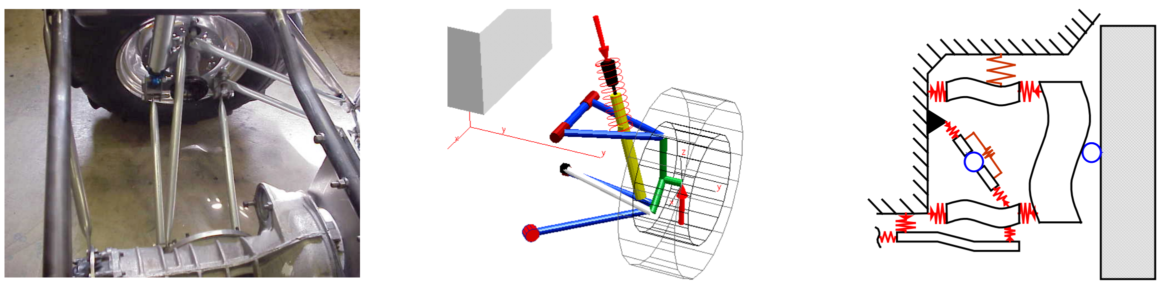

Figure. 5: Real, conceptual and ideal world models.

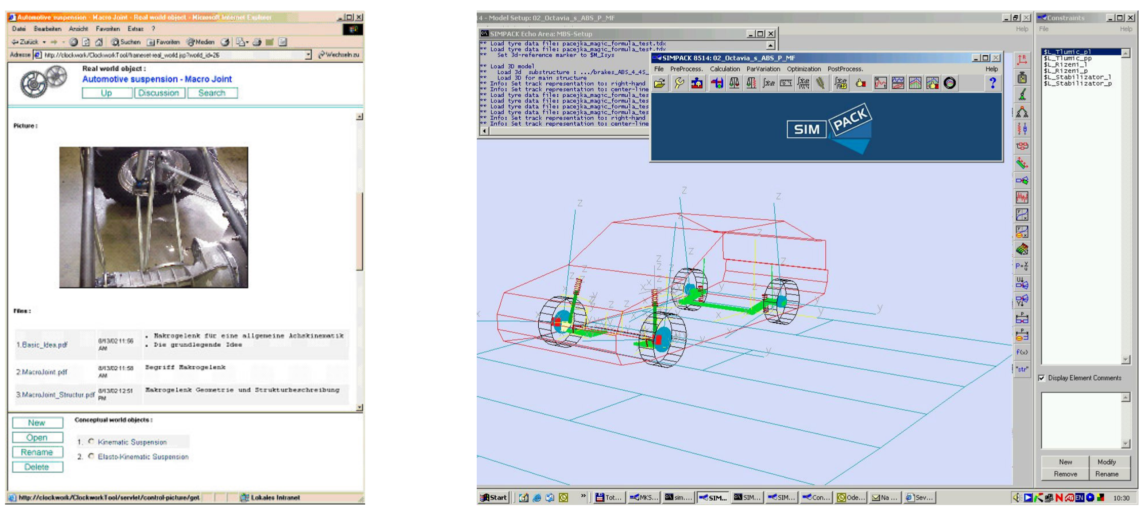

Figure 6: CKMT interface used at INTEC (left) and a SIMPACK™ model (right).

In the model world, components of the conceptual model are expressed as ideal modelling elements. They are for example rigid bodies, kinematic joints, tyre-force models, linear spring models and damper models. Additional assumptions are also made at this stage. For example the spring model may be assumed to be linear and the tyre force model will take a specific form such as Pacejka's "magic" formula. Finally, the ideal model with the corresponding inputs and outputs is encoded as a simulation model. The first version may be a standard model of suspension. As this is too slow, the designer may opt for modelling the 5-link suspension as a macro-joint. This technique allows the simulation to work in real time but makes further assumptions about the model, such as ignoring the dynamics of bodies with negligible mass.

After implementing and tuning up, the macro-joint based simulation model satisfies the real-time response requirements and can be handed over to the customer. As can be seen, the simulation and modelling process involved making certain key assumptions that can be captured within the CKMT. Assumptions provide essential context for the reuse of an example. Figure 6 shows the CKMT interface used at INTEC (left) and a simulation model of car suspension in SIMPACK™ (right), archived in the simulation world of the CKMT.

Initial results from use of the CKMT at INTEC indicate significant expedition of the design process. In the first set of trails, INTEC reported in some cases a five fold reduction in the task-to-result time. This was explained as being due to the model reuse capabilities provided by CKMT. However, further more extensive tests are being undertaken to more precisely establish the impact of the Clockwork approach.

5 Conclusions

The Clockwork approach characterises the modelling and simulation process as comprising a number of stages, called worlds. Modelling and simulation involves making transformations across worlds in order that the initial problem can be eventually solved. Clockwork provides knowledge management support for simulation and modelling according to this world structure. The informal and formal annotation of simulation models is focussed around this world structure. Annotations can be added to models at each stage of the process and also describe the transformation process to the next world. Further support is provided to formalise and generalise explicated knowledge. The approach has been tested and deployed in two industrial settings.

Acknowledgements

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