INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN
ICED 03 STOCKHOLM, AUGUST 19-21, 2003

A GENERATIVE MODELING APPROACH TO ENGINEERING DESIGN

Ola Isaksson

Abstract

This paper describes an approach at Volvo Aero to systematically develop and use design and evaluation support systems, using Knowledge Based Engineering (KBE) generative modeling techniques. Product and process knowledge derived from product strategies and experiences from previous design projects have to be organised into a successful generative model. These generative models support both the synthesis stages of design and the analysis stages, allowing design alternatives to be compared with each other. The designs are described in product models with a full 3D solid and shell representation, together with material and manufacturing information. The organisation of these models uses ideas from well-known theories in engineering design to meet the requirement of flexibility in updating and reorganisation of the generative models. An example of how these generative design and evaluation systems have been used for a jet engine component conceptual design study is presented. The lead-time for a design and evaluation loop was shortened by more than 90%, which allowed multiple candidates to be evaluated and presented at the design review following the design study. The design study also required updating of the design system, which was included in the lead time for design.

Generative Modeling, Engineering Design, Aircraft Engine, Methodology, Knowledge Based Engineering

1 Introduction

Profitability and competitiveness are classical driving forces for most industries. The way by which companies improve these capabilities cannot easily be summarised. Improvements, both continuous and more radical are being made from individual level to corporate level. For manufacturing companies, such as Volvo Aero, the cost (in time, quality and money) of satisfying the customer by delivering the desired product is in focus. Due to the competitive nature of doing business, Volvo Aero has chosen to specialise developing and producing certain parts of jet engines – a product specialisation strategy. This is a common way to strengthen a company's competitiveness and can, as we shall see, guide the development of the engineering design and evaluation systems used in product development.

The classical route of generating ideas, defining conceptual descriptions, modeling these and finally evaluating these from scratch is time-consuming. Since products most often inherit a significant amount of structure from previous designs, why not make use of this knowledge? Despite the fact that Computer Aided modeling tools have become more flexible, the lead-time to conduct design studies including analysis and evaluation activities is likely to take weeks, whereas the time available from a project point of view is shorter.

The objective in this paper is to describe an approach to systematically develop and use design and evaluation support systems, using Knowledge Based Engineering modeling environments. The question is if the concepts steaming from engineering design theory are suitable to design the design system itself? An integrated design and verifications system has been developed following a framework for design systems design.

1.1 A view of engineering design

First, there is a distinction made here for the following discussion between product development and engineering design.

Product development is the company process that takes the business requirements as a start and transforms these into a product. *Engineering design* is the general process of transforming design requirements to verified solutions. See Figure 1. The engineering design process in product development is thus restrained by the business environment that gives some unique conditions. These conditions may restrain the engineering design process, such as lead-time and cost, but also enrich the product knowledge since the product development process can use experience and strategies to provide information about the product to be designed.

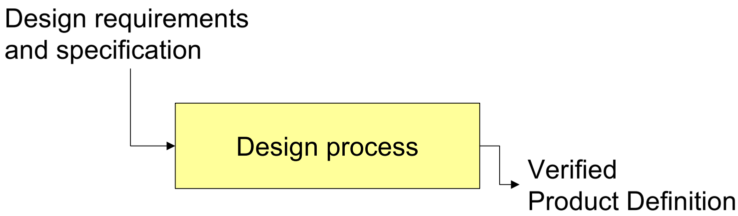

Figure 1 A simple top view of the design process

The design process contains activities to both generate and evaluate the design object. The design process have been described by many authors, but a high level process may comprise of high level steps such as,

1. Problem clarification and design specification
2. Concept generation and evaluation
3. Detailing and optimisation
4. Verification

Through research conducted over the latter half of the previous century, theoretical approaches to engineering design have been suggested [1], [2]. The terminology for design science has been suggested to be “an ordered, categorized and co-ordinated set of knowledge about designing (including knowledge about designers) and the objects being designed”[4]. Highlighting merely two important distinctions being made is worthwhile here;

- The differentiation between the design object (*What* is being designed) and the transformation process (*How* the object is being designed). Methods development focuses on improving the means used in the process to gain knowledge about the design object.

- The fact that knowledge of the forthcoming product is limited in the early phases of design and increases along the design process suggests that design methods in early phases tend to be more abstract that methods used when the product has been detailed. See Figure 2.

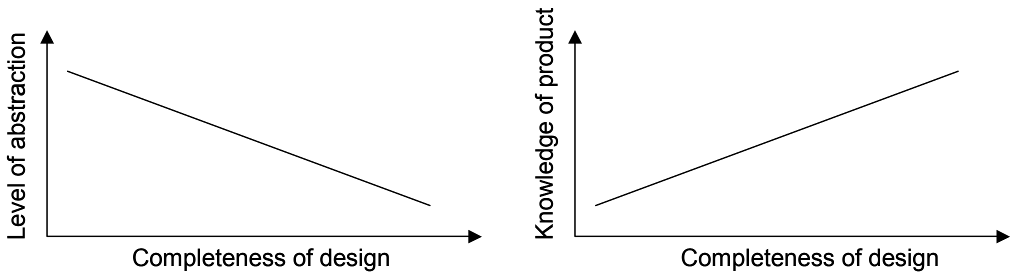

Figure 2 Abstraction vs. product knowledge along the product design process

Despite the efforts in establishing a firm theoretical basis for engineering design, the way engineering design is carried out in industry is still based on experience and relative simple, yet effective, tools and techniques. Eder [4] provided several possible explanations to this inertia for industry to adopt theory and stressed the importance of training and education in engineering design. A plausible explanation may be the difficulties in defining structured and organised methods supporting the creative synthesis activities compared to the analytical activities. Where practical methods for synthesis often are limited to various brainstorm approaches, the methods used for definition (CAD) and analysis are significantly more developed. As one example the analysis of strength of a product may readily be used using e.g. Finite Element Analysis. One theory for the creative activities in engineering design that has gained some interest is the Theory of the solution of Inventive Problem Solving (TIPS), for which there also exist computer support [5].

1.2 Some observations affecting engineering design practice

Below are some elements of interest that will be used in more detail in the remaining part of the paper.

1. The theories describing and prescribing how to do engineering design are slowly being formed and possible adopted [1]. Since the design support systems should support design work there must exist a theoretical support for systems development. *This states that there exists a theory that can be used.*

2. The computer aided tools and techniques have seen a dramatic evolution over the last years. Today it is not only possible to model the product, but also model the processes in which the product information is being transformed from one state to another. These systems are to some extent capable of supporting both synthesis and analysis stages of the design process. *This states that computer tools may be used in a new way.*

3. Many companies have a product strategy. The implication is that rather than inventing new products every time, new products rely on knowledge gained from previous products, strategic technology development and market. *This states that the information about the forthcoming product exists already from the earliest stages of design.*

4. The lead-time pressure in product development has made engineering design in product development a means to meet and verify requirements coming from a business situation. The innovative parts of engineering design are transferred to R&D activities. Innovation in product development often implies a risk that can be too expensive to take, especially in the aerospace industry where safety and reliability are quite high. *This states that innovations are difficult to motivate in product development.*

Comparing alternatives often require analysis of product models and these models can be time consuming to define. Consequently, the lead-time required to define models for candidate design is a bottleneck. There is a need to define and evaluate candidate designs, despite the effort required to generate models and conduct analysis. A complete design support system must support both generation and evaluation of designs. The importance of CAD system functionality integrated with the knowledge models is obvious, and due to lead-time pressure, there must be a better support when generating these models – a generative modeling support!

Some questions may be formulated at this stage

1. How can we make use of the fact that we have information upfront about the forthcoming product based on experience, product strategies and marketing research? If so, can we develop a flexible computer model that covers the design space needed?

2. Can a generative KBE model be designed flexible enough to allow both updating and actual use in a design study in the short time frame available in a design project?

2 Generative modeling and evaluation

Generative models can generate a solution based on combinations of alternatives given in an hierarcical product structure. The possible alternatives are created by a combination of user selections and rules defining the relationships in the hierarchy. The generative modeling provides a logically closed set of possibilities based on standard hierarchical operations for predefined objects. This distinguishes the generative approach found in KBE from modeling using reasoning mechanisms, similarity etc. that are found in Artificial Inteligence (AI) applications and Case Based Reasoning (CBR), [6].

2.1 Trends in product modeling

One of the prime objectives of a product model is to make application specific data available for each of the different phases and activities in the development process. It is no longer sufficient to represent merely the geometric definition, but also material information, manufacturing information, maintenance information and more. A broad definition of a product model is that it should be able to represent all information that defines the product during its life cycle. The relation how the product model relates to the design process is seen in Figure 3.

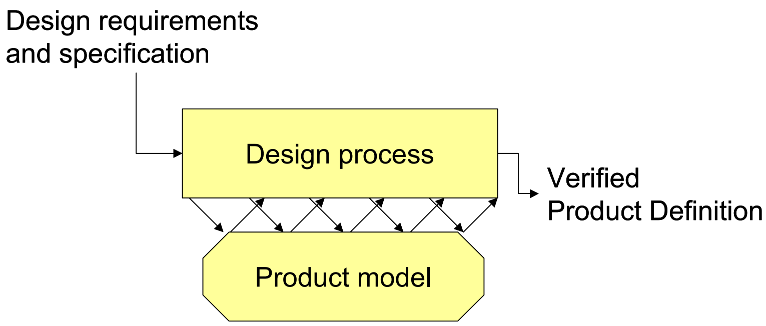

Figure 3 The product model as the carrier of all product information.

Many companies spend significant efforts into establishing a learning organisation. One way is to take care of experience gained in running projects and transfer the knowledge to the next in a systematic way. The single most important "storage" of experience is of course in the personnel, but there is also a driving force to be able to define product models so that these can more easily be reused in new product programs. KBE, Knowledge Based Engineering, has increasingly being used as a way to "store" knowledge and automate routine design work [8],[9]. Vajna and Freisleben [10] have also described an approach to modelling the engineering design process using KBE. Tang and Wallace further emphasised the need for careful organisation of knowledge models [11] and that the knowledge should be defined independent of the implementation [3]. The knowledge acquisition process is crucial for such programs and methods and international projects have started to give results in how this knowledge acquisition can be carried out [9]. The effect of using KBE is that the often cumbersome product and process modeling efforts can be more or less eliminated for at least the standard products. The challenge of KBE models is that these are predefined and leaves little room for innovation. It may be argued that this is a limitation and the design space covered is too narrow in a conceptual design study. The counterargument is that in practice, the room for innovation is no longer there in product development. The conceptual design work in product development is merely to adopt and combine pre-existing conceptual solutions to a design proposal, here called a Design Case.

One important consequence is that it is technically possible to define product models with an increased degree of detail already in early stages of design. Someone may ask – to what use, since the information of the product still is too limited to make any difference, and that detailed models in early stages merely are of cosmetic and possible marketing use. The degree of detail may give an illusion of a fairly complete product. Here is where the knowledge from product strategies and experience from previous product developments must be used.

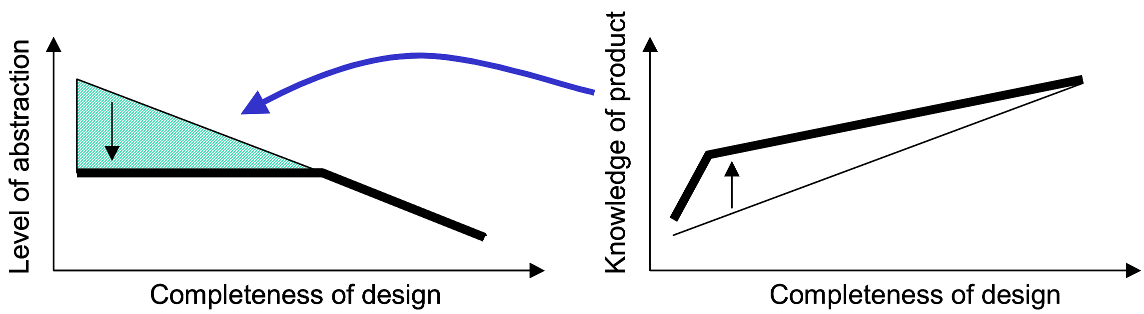

Figure 4 Reduced level of abstraction in early stages of design

Figure 4 illustrates that the knowledge required to reduce the working level of abstraction in the early phases of design can exist if experience and product strategy can be used.

The generative models need to be prepared, taking the engineering best practice together with rules and restraints into an engineering model that can be used more or less executable in a design situation. The approach to define generative models is described, bringing the knowledge of engineering into the generative models.

The generative models can generate instances consisting of geometric models as well as evaluation methods. The evaluation models, that are a part of the generative model, can be defined to cover both numerical analysis, such as FEA analysis, cost models and geometric inspections.

In the particular example of jet engine components, there is still a degree of innovation needed in new engine designs to fulfil the requirements, especially on the detail level. Therefore, there is often a need to complement the strategically based generative models. The well known 80/20 rule is applicable in this respect, and stresses the flexibility requirement on a design system.

3 KIDS - Knowledge based Integrated Design and evaluation System

The generative approach being developed at Volvo Aero has been given the name KIDS – Knowledge based Integrated Design and evaluation System. In short it is a framework for development and use of a knowledge based generative design applications. Application models are being developed for strategically important products. The application models are being developed following the same methodology and have the same organisation and uses the same generic building elements. This approach is chosen to enable flexibility and scale ability of the design system to meet the always-present changes in prerequisites for design work.

3.1 The use of KIDS

The approach relies on the fact that knowledge of the forthcoming product design pre-exists and generative models can be defined in advance. There are three different stages for the application model – Strategic Development, Updating and Use, see Figure 5.

1. <u>Strategic development</u> of an 80 % application model. This model can capture the immediate needs in early phases (quotations etc) and later serve as a reference model. This phase requires application model development and validation.

2. <u>Updating</u> the 80% model with the additional requirements expected once entering a new product development project. This phase requires updating and validating the application model.

3. <u>Use</u> of the application model. The model is used to carry out design studies in run time mode.

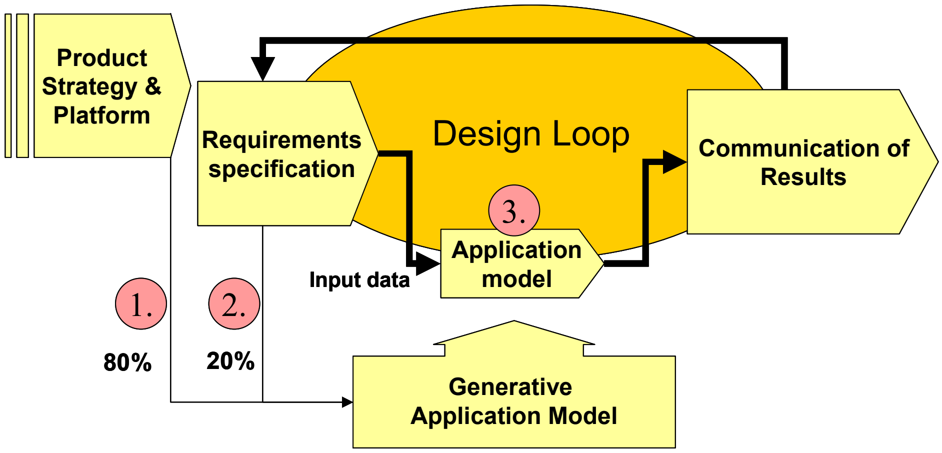

Figure 5 Modeling and using generative models

When an application model is in place, and has been validated the benefits are clear. The lead-time to generate and evaluate design alternatives is dramatically reduced compared to a traditional interactive modeling and evaluation design iteration. Many more design alternatives can be treated in short time.

3.2 The KIDS framework

The architecture of the application models have to be carefully designed. A framewok, Knowledge based Integrated Design and Evaluation System (KIDS) is for any application model. The different levels of KIDS are shown in Figure 6, and described in the following sections.

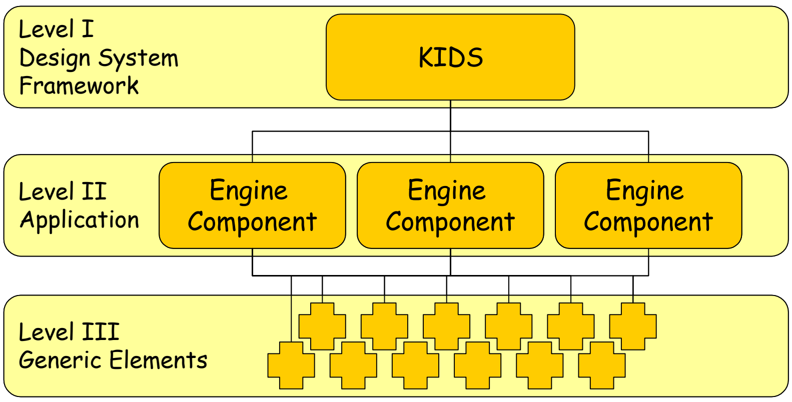

Figure 6 The three different levels of KIDS

Level I Design System Framework

At Level I the guidelines for development and the norms and regulations for the application models are defined and described, taking an object oriented approach. The framework is based on a modular description of the product, an activity based description of the actual design process and evaluation process and a skeleton for the computer application models. In KIDS, all models have a project level and a design case level. Parameters defined on project level are by default valid for all design cases. This principal hierarchy is shown in Figure 7.

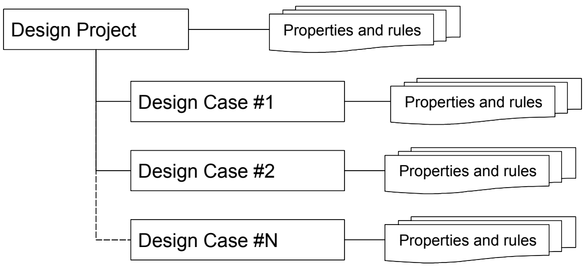

Figure 7 A Design Project with multiple Design Cases

Level II Application

This is the level where the actual generative models are defined, here called application models. The product is described to the level of detail needed for the purpose. Ideally, the allowable design space must be covered. Configuration variants for the constituent product modules are defined. Each variant may have a unique set of design parameters, and the configurations are not limited to geometrical variants. See Figure 8.

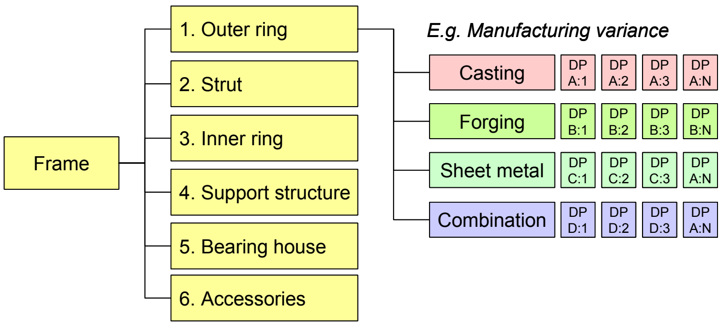

Figure 8 Modular structure of a frame with manufacturing alternatives

Level III Generic Elements

The generic elements are the building blocks in the KIDS system framework. Re-useable sub sets of information are defined in generic classes that are used in several positions. An example is the definition of a Ring. A single engine component may have several ring structured defined. In the same generic Ring definition can be used in the Outer Ring module as for the Inner Ring module. The same is true for other, possible not yet defined application models for other products. The same Ring definition can be reused.

4 Example of a conceptual design study

The scenario was a situation where a conceptual design study for a jet engine component was needed. The design review was only two weeks ahead, and the question was how the weight and structural stiffness of a jet engine frame, shown in Figure 9, depended on the number of struts in the design. The evaluation of the weight and stiffness required geometrical models of the design. Normally, there was time to model only a couple of design alternatives, since traditional parametric CAD modeling techniques was difficult to cover the design space.

By the time, a strategically developed “80 %” model existed. The unique requirements in the underlying design project required some modifications of the model. The task was to update the existing model to a level where the alternative design study could be carried out. Then the actual design work had to be conducted as well.

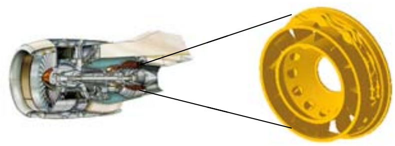

Figure 9 A structural frame in a jet engine

The model was updated, since not all configuration variants were supported in the pre-defined model. The core interface parameters were defined on Project Level in the application and a number of alternative Design Cases were defined having different number of struts. In the two week period about 15 different designs were generated and analysed using Finite Element Analysis. At the Design Review the design team could base their answer to the design questions on investigations of several different alternatives. An example of how alternative design alternatives were presented at the design review is shown in Figure 10.

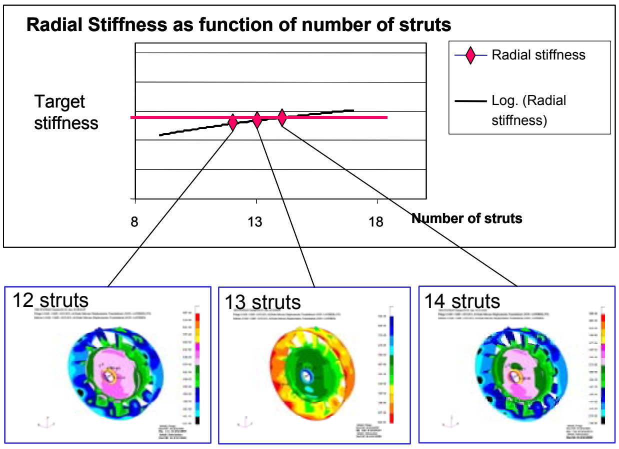

Figure 10 Presentation of FEA supported alternative design evaluations

Through the alternative design study, it was shown how the application model could be updated to meet the additional requirements in the product development project. The actual use of the application model allowed generation and evaluation of more than ten different design concepts within the two-week period. This would not have been possible using traditional modeling techniques to the same degree of resolution.

5 Conclusions and discussion

It is possible to use pre-existing knowledge to define flexible conceptual engineering models with a level of detail normally reserved for later design stages. The generative KBE technology can be used to provide enough flexibility to capture early phase design studies, something that has been difficult for traditional parametric design. In addition, KBE models are not limited to geometric features of the product. The design decisions are multi disciplinary and especially manufacturing and maintenance questions are important already at the conceptual design stages.

The requirement on updating of the application models in a development project can be met only if the design system is well organised. Since the generative models captures both the design object and its corresponding design process, the structure provided through design theory should be a good candidate to bring structure to the complexity in generative design and evaluation models. If generative models can be successfully updated to meet the shifting design requirements "on the fly" real usefulness in a design situation increases significantly.

Product models tend to become increasingly content rich. For real engineering value any computer aided design system must communicate information as needed. CAD and CAE integration is utterly important and the coupling to PDM will increase even further since the information base for decisions need to be traceable.

Acknowledgements

The object oriented development environment in which KIDS was implemented and used was in this case AML – Adoptive Modeling Language from Technosoft Inc.

References

[1] Hubka V. and Eder W.E., "Design Science: introduction to the needs, scope and organization of engineering design knowledge, London, Springer Verlag, 1996

[2] Suh N.P. "The Principles of design", Oxford university press, 1990

[3] Lindeblad M., Isaksson O. and Abrahamsson, H. "Utilisation of common IT-technology for Multidisciplinary Engineering", 6th International Conference on Concurrent Enterprising, Toulouse, 2000

[4] Eder W.E., "Design Modeling – A Design Science Approach (and Why Does Industry Not Use It?), Journal of Engineering Design, Vol 9, 1998, pp. 355-371

[5] Altshuller G.S. "Creative as an Exact Science – The Theory of the Solution of Inventive Problems", Gordon and Breach Science Publishers (translated by A Williams), 1988

[6] Rosenfield, L.W., "Solid Modeling and Knowledge-Based Engineering", in Handbook of Solid Modeling , McGraw Hill, 1995

[7] Isaksson O., Fuxin, F., Jeppsson P., Johansson, H., Johansson P., Katchaounov T., Lindeblad M., Ma H., Malmqvist J., Mesihovic, S., Sutinen, K., Svensson, D., Törlind, P. "Trends in Product Modelling; an ENDREA perspective". In Proceedings of Produktmodeller ,Linköping 2000, pp 65-86

[8] Dutta S., "Strategies for Implementing Knowledge-Based Systems", IEEE Transactions on Engineering Management, Vol 44, February 1997, pp. 79-90

[9] Stokes M. (Ed.) "Managing Engineering Knowledge – MOKA: Methodology for Knowledge Based Engineering Applications", ASME Press, 2001

[10] Vanja S. and Freisleben D., "Knowledge Based Engineering Process Model", In proceedings of ICED 97, Tampere, 1997, pp 181-184

[11] Tang M. X. And Wallace K., "A Knowledge-Based Approach to CAD System Integration", In proceedings of ICED 97, Tampere, 1997, pp 185-190

For more information please contact:
Ola Isaksson Volvo Aero Corporation, 461 81 Trollhättan Sweden
Tel: Int +46 520 93987 Fax: Int +46 520 98584 E-mail: ola.isaksson@volvo.com