INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED'09
24 - 27 AUGUST 2009, STANFORD UNIVERSITY, STANFORD, CA, USA

TOWARDS LIFE-CYCLE AWARENESS IN DECISION SUPPORT TOOLS FOR ENGINEERING DESIGN

Henrik Nergård[1], Marcus Sandberg[1], Tobias Larsson[1]
(1) Luleå University of Technology

ABSTRACT
In this paper a decision support tool with the focus on how to generate and visualize decision base coupled to the business agreement is outlined and discussed. Decision support tools for the early design phases are few and especially tools that visualize the readiness level of activities throughout the product life-cycle. Aiming for the sustainable society there is an indication that business-to-business manufacturers move toward providing a function rather than selling off the hardware and providing separate services. This increased responsibility for the function provider implies that early phase development needs intensified life-cycle awareness to minimize cost and maximize customer satisfaction. The main contributions from this paper are the outline of the decision support tool, the presented example scenario and aspects to consider when developing a multi-disciplinary decision support tool for the early design phases.

Keywords: Decision support, product life-cycle, early phases, collaborative engineering

1 INTRODUCTION
In an objective for product success in the sustainable society, business-to-business manufacturers move toward providing a function rather than selling hardware and providing separate services. Concepts such as Total Care [1], Product Service Systems (PSS) [2, 3], Integrated Product and Service Engineering [4], Functional Products (FP) [1] and Functional Product Development (FPD) [5] are areas where research is ongoing. The vision is that the customers only pay for what is needed in a resource effective manner. This implies increased risk for the function provider being the owner of the physical artifact, which also may include having the life-cycle responsibility. Life-cycle responsibility means increased opportunities as well as risks and companies organize them self in extended enterprises to reduce the risk and also to gain knowledge. By aiming for integration of the industries in the product development consortium, the extended enterprise, there is a need for win-win solutions, as companies need to collaborate closer and share company specific knowledge. This early development is known as functional product development and it has been recognized that one enabler for FPD is the use of more integrated computer support tools to support the product development process during the products lifecycle [1, 6]. However, the earlier in the development process the fewer support systems are available due to the uncertainty and ambiguity of conceptual design [7]. Focusing on computer-based design decision support for life-cycle awareness Gu and Asiedu [8] state that most support systems concentrate on design and manufacturing functions. But to enable a true GO/NO-GO decision to be made, the decision base needs to simulate or automate technical feasible and practical viable life-cycle components. Thus, the purpose in this paper is to describe and discuss a suggestion for a decision tool aiming to support a multidisciplinary functional product development team.

2 DECISION SUPPORT FOR PRODUCT LIFE-CYCLE ANALYSIS IN EARLY PHASES
In early design, uncertainty is high and the cost impact of design decisions is often seen too late in downstream product development [9]. Barton et al. [9] also emphasize the importance to evaluate the actual state and a predicted future state of a company, rather than an idealized view. Therefore life-cycle analysis concentrates on how to provide comprehensive decision bases for design. *From the point of view of the product manufacturers, the product life cycle starts with product design, followed by product manufacturing, product servicing and product remanufacturing whereas from the point of*

view of the industrial customers it consists of product purchasing, usage and disposal [10](pp.2). A review of state of the art in product life-cycle cost analysis has been done by Asiedu and Gu who report that most approaches tend to concentrate on design and manufacturing [8] Asiedu and Gu also stretch the need for design decision support tools that can provide understandable and usable information in a timely manner. The state is also that the earlier the design the fewer design decision support systems [7]. Wang et al. also identifies the importance of capture and re-use of earlier design and the challenge of agreeing on an ontological commitment to enable in depth communication. Nergård et al. [5] outline the requirements for a knowledge intensive decision base in functional product development in general and emphasize the need for business and engineering integration both internally in each company but also between partners in the extended enterprise. A research gap for further detailing the decision support requirements for a design phase that is moving towards functional product development is evident.

3 RESEARCH APPROACH

3.1 Future workshop

A workshop following the Future workshop methodology, a workshop model intended for participative software development, was done to find needs of a Swedish aerospace company regarding decision support in early design [11]. A total of 12 persons participated where 8 were company staff with design, manufacturing, business and marketing positions. Four PhD students represented the academia with research topics covering knowledge integration, knowledge management, knowledge engineering and manufacturing within engineering design. The synthesising of the team was influenced by the Tiger team approach [12]. Several months after the workshop, two telephone interviews with two company participants from the workshop were made with the intention to initially validate the findings.

3.2 Findings from the workshop

The main finding is that there is a need for an extensive decision base to make the right decisions in early development, especially when moving toward functional product development and the increased company responsibility thereby created. Ideally this decision base needs to, among others, generate a design decision base that is coupled to the business agreement, knowing when information is valid, outline company capacity, process status, swift requirement break down from business contract to engineering feature and prediction of material cost on long term basis, i.e., five years. The overall finding from the workshop, namely how to generate and visualize a design decision base that is coupled to the business agreement is the focus for this paper.

4 APPROACH FOR LIFE-CYCLE AWARENESS IN DESIGN DECISION SUPPORT SYSTEMS

The presented approach, total offer readiness level (TORL), builds on an idea that it is possible to visualise the life-cycle readiness level of a design and the involved life-cycle activities and use this readiness level for decision-making. An example scenario based on the findings from the Future workshop is given to further elaborate the approach. The vision for TORL is that it should be a computer based decision support tool, yet not finalized. In the study presented here a number of demonstrators have been developed and has served as ‘teasers’ in workshops to progress the research. The discussion here is based on those demonstrators.

4.1 Readiness level

Technology readiness level is metrics some companies use as a measure of the risk of launching new technology, see [13, 14]. The approach presented here, TORL, is based on the belief that it is possible to visualise more aspects of the readiness level than only technological by creating a life-cycle readiness level of the total offer. A network of all company activities connected to the design can be visualised as well as additional activities from subcontractors involved in the extended enterprise.

The TORL for a certain company is suggested to have a general structure that is intended to suit most of the company product life cycles. When starting a development project the general TORL structure, of a known structure for a similar design, can be used to write or edit information for all activities known by the user. The fields where information is lacking or a problem arises, alerts the user and thereby affects the readiness level negatively. This information is based on the customer requirements and also company processes. If partners in the extended enterprise are involved in the development process the partner information and processes that are used also have to be visible in the TORL.

To enable swift prediction of the activities in the life-cycle deterministic couplings can be used through e.g. solving mechanistic equations or using rule-based algorithms or logic. Sometimes the input cannot be described as discrete values and may then be expressed as a range of possible values, thereby increasing the uncertainty compared to validated discrete values.

The first thought was to disseminate the TORL at gate-reviews where GO/NO-GO decisions are made. However the TORL can be disseminated at any time due continuous update of its parameters. There can also be different levels of readiness to be evaluated at each gate in the stage gate process. A design team that have decision power and competence to understand the TORL output does the GO/NO-GO decision. An example of how a main level visualisation could look is shown in Figure 1. Here three readiness levels (Curve 1 – Maturity profile for Decision, Curve 2 – Maturity profile for Gate 1 approval and Curve 3 –Component readiness level) are used and a number of parameters are plotted as columns against the readiness levels. The readiness levels represent the least readiness level that a life-cycle activity needs to have in order to, i.e. pass the gate in a stage-gate process (Curve 2). Also observe that each curve have different readiness level values for different Offer Components. As an example some of the parameters in the Extended Enterprise parameter group have reached a sufficient readiness level to pass gate 1 (Curve 2) but have not reached a sufficient level of readiness in order to take the decision to offer it as a Total Offer (Curve1). The intention with the example shown in Figure 1 is to show that a TORL could include many parameters and a lot of information rather than making it possible to read all details of the figure. A simplified view coupled to a scenario can be seen in the next section.

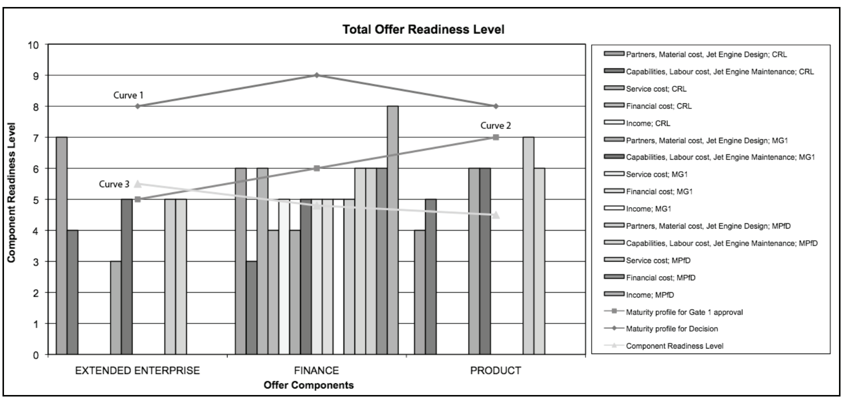

Figure 1. An example of a total offer readiness level view

4.2 Aerospace example scenario

An example scenario based on the findings from the workshop is here created to further explain the proposed approach for the TORL. A designer's view TORL visualisation in both 3D and 2D is shown in Figure 2. Each block and column represents separate life-cycle activities. The connections between blocks represent relationships between activities. The relationships can be hierarchical in a top-down structure but might as well be interrelated and/or dependent of each other. The different shades of grey in Figure 2 represent the range of how much of the set readiness levels have been achieved. White represent that the activity have met the set readiness level and black the least achieved level. Using 2D charts of the activities and their relationships give an increased understanding of which upstream or downstream activities are affected if a set level of readiness in an activity is not achieved. Also note that in the 3D chart the different columns can have different heights although having same level of readiness (i.e. same colour). This is explained that each activity can have different GO/NO-GO readiness levels as seen in Figure 3, that is, one activity can have a value of 5 as a GO-value while another have 8 but both can have the colour grey to show that none of the activities have reached a sufficient level of readiness.

In the scenario a design team is using computer-aided design (CAD) software to generate concepts for a design feature during the early design phases. Knowledge and information as well as a TORL model regarding a similar feature from previous projects are available as a first start.

The team uses the feature from the previous project and changes the material from e.g Inconel 18 to Titan 64 finding that the purchase activity in the TORL alerts (see the grey 2D boxes in the design view of a TORL in Figure 2. A live coupling to the purchase function shows that component cost is OK but the availability of Titan 64 cannot be met (thereby the black Availability block). In an attempt to cope with the lack of material the team changes the manufacturing method of a specific geometry in a way that has not been performed before, e.g. small forgings or castings are welded together. This can be seen due to the lower readiness level of the manufacturing function. Although it is not the welding and heat treatment activities that affects the lower level of readiness of the manufacture activity, it is due to that the geometry that now will be fabricated have to be machined in way that haven't been fully investigated. Simulations have to be created and performed in order to verify the process thus increasing the total lead-time. Also, the recycling activity is affected by the shift to Titan 64.

It is now up to the design team to decide whether the material availability and increased lead-time can be accepted or if there is a way to change the geometry to overcome these issues.

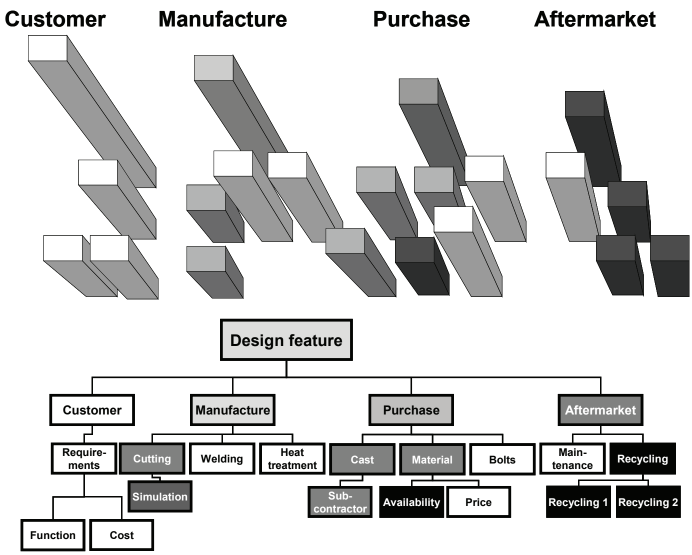

Figure 2. Example of both 3D and 2D TORL design feature breakdown.

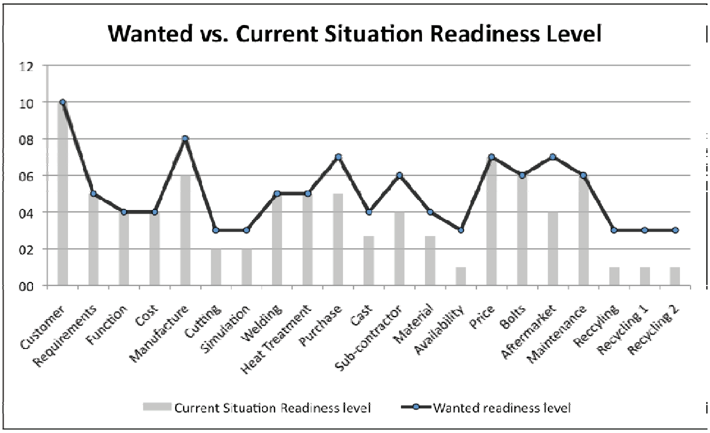

Figure 3. Wanted vs. Current Situation Readiness Level 2D chart

5 DISCUSSION REGARDING ASPECTS TO CONSIDER

An approach to visualize the readiness level of a design has been outlined to spur the ongoing research work on product life-cycle decision tools. There are a number of aspects to consider creating a working TORL. Here issues of setting the readiness level, enabling technology, business function coupling, visualisation, business aspects and knowledge management are discussed.

5.1 Setting the readiness level

One aspect to consider is how to "set" the readiness level. If the readiness level is based on previous projects the previous goal and how well the final product suited that goal can be found. If the goal was met or exceeded the readiness level can be raised or kept at the same level. The readiness level is also dependent on the visions and goals of the company and can be affected by new laws, policies etc.
The readiness levels as seen Figure 1 (Curve 1 to Curve 3) are represented as somewhat straight lines, however these lines can be functions that vary in amplitude. Thus the readiness level can vary between different activities in the company as seen in Figure 3.

5.2 On the issue of enabling technology

To make an exhaustive description of enabling technology is out of the scope for this paper, yet based on the findings from the workshop, some areas are identified as useful.

The information of the TORL could be collected into a spreadsheet to allow for intuitive interaction between user and computer as shown in Figure 1. But to integrate all life-cycle components the architecture for the information backbone system has to be defined. Pejryd and Andersson [15] make a comparison of using either an Enterprise Resource Planning (ERP) system or a product life-cycle management (PLM) approach as an information backbone system for 3D-CAD-based development and state that PLM systems are currently more suitable for early stages. Another addition is that the information, not only, becomes available for different kinds of users but also become visible in their "native" view or language thus increasing the life-cycle awareness throughout the company or enterprise. This calls for company ontology to promote knowledge communication.

A major information-generating source is projects, why project portals need to be integrated with the CAD environment of the company. If project team sites can be updated with design rationales it is possible that information can be found and used in other projects. Techniques to find the appropriate information, for instance data mining or data harvesting, may be suitable to integrate.

Models need to be created for swift and overarching predictions of for example performance, manufacturability, maintainability, cost in general and other life-cycle activities related to the design as well as the wanted business agreement. Methods such as finite element analysis, knowledge-based engineering and case-based engineering can drive design activities [16] [17]. For knowledge and experience transfer the use of ontology [18] is seen as essential if companies are going to be able to handle the increasing amount of information and to guarantee that it is updated and valid. Design concepts generated by using TORL need to be chosen among and this can be done using other design decision support tools used in product development [19].

5.3 Visualisation

One of the main issues in the TORL is how to make an intuitive visualisation of the life cycle. How can a designer see that the product life cycle is acceptable, excellent or unacceptable? Colours are not used in the figures presented here otherwise using the colours of a traffic light may be useful. The activity with lowest readiness level can shine in bright red and the change of colour could be done continuously as the columns move closer to the highest readiness level.

It would also be beneficial if the rate of change in the affected factivity could be visualised in order to see not only that it is affected, but also how it changes over time. This also introduces that the TORL need to take time aspects into consideration. Examples of this could be how long time it took in the last project to achieve the readiness level and if the curve showed continuous smooth behaviour or if it takes “leaps”. This can show where in the design process things run smoothly in a fast manner or where problem or time-consuming activities occur.

5.4 Business aspects

The design needs to be anchored in the business agreement. When making a business agreement often several plausible subcontractors are asked for prices and their companies’ capacity need to be assessed to make a GO/NO-GO decision. If connections between design and business agreement can be created in a TORL, plausible subcontractors from the business agreement can be evaluated by assessing the costs for e.g. manufacturability.

The ongoing discussion of making information available earlier to make better decisions can gain from looking at using the TORL in the offering phase before development starts. The TORL starts from the design and seek to visualise the life-cycle impact of design decisions. To allow a business view of the TORL business, the staff need to contribute to the structure and information.

The closer the business offers is a traditional offering, e.g. a physical artefact transaction, the more likely it is that the TORL will give correct results as the TORL idea is initially based mostly on knowledge from working with traditional product development. Therefore, it seems beneficial for companies to develop product derivatives, i.e. products that to a large extent are similar. However, moving towards functional product development there may be larger differences between product generations, but also more elements of innovation. The TORL is suggested to be vital here, due to that it can visualise the activities that have not reached the readiness level. It can then be used as a strategic tool focusing on what areas to improve.

The idea of integrating every function of the company connected to design can be seen as a daunting task, and is also not the intentions with TORL. The TORL can be swiftly developed on the highest level, and the potential for a life-cycle overview is created. When only developed for the highest level there will probably be few, if even one, activity that is ready for a GO-decision as the underlying connections are not defined. The TORL can then guide the company through the network to find the gap of maturity and seek to fill the gap.

5.5 Knowledge management

Workflow systems, e.g. [20] can be an enabler for maintaining the dependencies described in the TORL. To always have the latest information coupled to the TORL several persons need to be able to edit the information instead of just one knowledge engineer, which sometimes is mentioned as beneficial in knowledge-based engineering situations, [21]. The idea of the internet dictionary Wikipedia, [22], where everyone can change the information and discuss the contents with other users, may lead to a constantly updated information database. Yet, not totally adapting the Wikipedia way, it can make it possible for individuals at each company function to edit the information, and can be a feasible approach. For example, in the aerospace example there is a need for at least one person from the purchase function to manage the updating of material availability and price. This connection between design and purchase might be realised by connecting engineering and resources activities as discussed by Pejryd and Andersson [15].

5.6 Static vs. dynamical models

Creating static models that only show snapshots of the current situation can give a faulty view of the examined scenario due to that interaction and behaviour between life-cycle activities are left out. This means that scenarios including the affected life-cycle activities should be modelled and simulated to examine their interaction and behaviour over time in addition to what level of readiness they have. This suggests that models of activities should incorporate descriptions of their behaviour from a process-level perspective. Creating Agent-Based models to examine and understand dynamical behaviour of different business scenarios have been examined by Buxton et al. [23]. Using a similar approach to create models of the TO scenario where strategic R&D activities, the design and manufacturing processes, business, sale and aftermarket activities can be simulated over time and examined in the same strategy (or scenario) can give an understanding which scenario suits the company best or how the proposed business can be adapted to fit the product development processes and start-up of new technologies from R&D.

6 CONCLUSIONS

This paper proposes an approach to make design teams aware of life-cycle issues during early design. These issues become even more important as manufacturers move towards increased life-cycle responsibility. The contribution from this paper is the outlining of a TORL that can provide a decision base visualisation from which a GO/NO-GO decision can be made. The TORL have been discussed from a designer’s point of view, however, the TORL is thought of as being used by many different roles and from different point of views. This paper provide an initial description of the approach as a part of the intentions to enhance it further and develop a prototype to enable field test and validation. It has been discussed that aspects to consider when realizing the TORL is the need to visualize the different life-cycle activities used to realize the TO. Modelling approaches that enables dynamic simulation of life-cycle activities is needed in order to examine behaviour of interacting activities. Workflow systems seem to be able to support the enabling of a TORL as well as support multiple users to update information, instead of specific knowledge engineers. Using PLM or ERP systems also enable structuring and organization of CAE models and information through the enterprise. The readiness level or maturity for each activity in the life-cycle have to be decided upon in order to have some reference to how far from the wanted Total Offer Readiness level each activity is. It have to be remembered that the TORL is a decision and a design support tool based on information and knowledge about life-cycle activities at a certain point in time.

REFERENCES

[1] Alonso-Rasgado, T., Thomson, G., and Elfström, B.-O. The Design of Functional (Total Care) Products. *Engineering Design,* 2004*,* 15(6), pp.545-540.
[2] Mont, O.K. Clarifying the Concept of Product-Service System. *Cleaner Production,* 2002*,* 10(3), pp.237-245.
[3] Morelli, N. Developing New Product Service Systems (PSS): Methodologies and Operational Tools. *Cleaner Production,* 2006*,* 14(17), pp.1495-1501.
[4] Lindahl, M., Sundin, E., Öhrwall Rönnbäck, A., Ölundh, G., and Östlin, J. Integrated Product and Service Engineering – the IPSE Project. In Changes to Sustainable Consumption, Workshop of the Sustainable Consumption Research Exchange, Copenhagen, Denmark, April 20-21,
[5] Nergård, H., Ericson, Å., Bergström, M., Sandberg, M., Törlind, M., and Larsson, T. Functional Product Development - Discussing Knowledge Enabling Technologies. In *9th International Design Conference, Design2006*, Vol. 1, Dubrovnik, Croatia, May 15-18, pp.587-593 (Faculty of Mechanical Engineering and Naval Architecture, University of Zagreb, The Design Society, Glasgow).
[6] Ericson, Å. *A Need-Based Approach to Product Development*. 2007, Doctoral Thesis, Division of Functional Product Development, (Luleå University of Technology, Luleå)
[7] Wang, L., Shen, W., Xie, H., Neelamkavil, J., and Pardasani, A. Collaborative Conceptual

Design - State of the Art and Future Trends. *Computer-Aided Design,* 2002*,* 34(13), pp.981-996.
[8] Asiedu, Y., and Gu, P. Product Life Cycle Cost Analysis: State of the Art Review. *International Journal of Production Research,* 1998*,* 36(4), pp.883-908.
[9] Barton, J., Love, D.M., and Taylor, G.D. Design Determines 70% of cost? A Review of Implications for Design Evaluation. *Engineering Design,* 2001*,* 12(pp.47-58.
[10] Aurich, J.C., Fuchs, C., and Wagenknecht, C. Life Cycle Oriented Design of Technical Product-Service Systems. *Cleaner Production,* 2006*,* 14(pp.1408-1494.
[11] Kensing, F., and Madsen, K.H. Generating Visions: Future Workshops and Metaphorical Design In *Design at work: Cooperative design of computer systems*, 1991, pp.155-168, J. Greenbaum and M. Kyng Eds., (Lawrence Erlbaum Associates, UK).
[12] Ashley, S. DARPA Initiative in Concurrent Engineering. *Mechanical Engineering,* 1992*,* 114(4), pp.54-57.
[13] Mankins, J.C. *Research & Development Degree of Difficulty (R&D^3)*. 1998, March 10, pp.1-3, http:www.hq.nasa.gov/office/codeq/trl/.
[14] Mankins, J.C. *Technology Readiness Levels - a White Paper*. 1995, pp.1-5, http:www.hq.nasa.gov/office/codeq/trl/.
[15] Pejryd, L., and Andersson, P. Information Back Bone Systems for Virtual Manufacturing, a Comparison of ERP and Engineering Based PLM Systems. In *39th CIRP International Seminar on Manufacturing Systems*, Ljubljana, Slovenia, p.6
[16] Chapman, C.B., and Pinfold, M. The Application of a Knowledge Based Engineering Approach to the Rapid Design and Analysis of an Automotive Structure. *Advances in Engineering Software,* 2001*,* 32(12), pp.903-912.
[17] Sandberg, M., and Larsson, T. Automating redesign of sheet-metal parts in automotive industry using KBE and CBR. In *International Design Engineering Technical Conferences & Computers and Information in Engineering*, Philadelphia, PA, USA, September 10-13, p.9
[18] Kamsu Foguem, B., Coudert, T., Béler, C., and Gensete, L. Knowledge Formalization in Experience Feedback Processes: An Ontology-Based Approach. *Computers in Industry,* 2008*,* 59(7), pp.694-710.
[19] Krishnan, V., and Ulrich, K.T. Product Development Decisions: A review of the Literature. *Management Science,* 2001*,* 47(1), pp.1-21.
[20] Derks, W., Weston, R., West, A., Harrison, R., and Shorter, D. Role of Workflow Management Systems in Product Engineering. *International Journal of Production Research,* 2003*,* 41(15), pp.3393-3418.
[21] Stokes, M. *Managing Engineering Knowledge - MOKA: Methodology for Knowledge Based Engineering*, 2001, (Wiley Chichester).
[22] http://www.wikipedia.org/, Last Accessed 2009-05-27.
[23] Buxton, D., Farr, R., and MacCarthy, B. The Aero-Engine Value Chain Under Future Business Environments: Using Agent-Based Simulation to Understand Dynamic Behaviour. In *8th International Conference on the Modern Information Technology in the Innovation Processes of the Industrial Enterprises, MITIP*, Budapest, Hungary, 11-12 September 2006.

Contact: Henrik Nergård
Luleå University of Technology
Division of Functional Product Development
971 87, Luleå
Sweden
Phone: +46 (0)920-49 29 76
Fax: +46 (0)920-49 13 99
Email: henrik.nergard@ltu.se
URL: www.ltu.se/tfm/fpd

Henrik Nergård is a research assistant at the division of Functional Product Development at Luleå University of Technology. He coaches students in Computer-Aided Design, Knowledge-Based Engineering, Engineering Design and Multi-Body Dynamics. He conducts research within the area of Functional Product Development (PSS) where he has specialized in methods and tools to support Experience Feedback within Engineering Design.