Assessment of Life Cycle Impacts and Integrated Evaluation Concept for Equipment Investment

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Abstract

Industrial companies are nowadays confronted with both economic challenges regarding cost efficiency based on the globalization and shortened product life cycles as well as societal and ecological challenges to support a sustainable development. The paper will present the results of life cycle assessment studies for assembly equipment and industrial robots. A simulation based approach for the estimation of the energy consumption during the use phase will be demonstrated on a case study. A concept for the evaluation of assembly equipment combining both a triple bottom line and flexibility is proposed and explained.

Keywords

Life Cycle Assessment, Investment Decision, Sustainable Manufacturing, Simulation

1 INTRODUCTION

Industrial companies are nowadays confronted with both economic challenges regarding cost efficiency based on the globalization and shortened product life cycles as well as societal and ecological challenges to support a sustainable development. Wiendahl et al. define flexibility and changeability as the key enablers for meeting the market challenges [1]. Facing sustainable development, defined as a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [2], companies have to evaluate their business activities no longer only on economic criteria. Elkington coined the term triple bottom line accounting for expanding the traditional reporting framework by taking into account ecological and social performance in addition to financial performance [3].

Currently no methods and tools are known to the authors which integrate economic, ecologic and social attributes in the evaluation and at the same time are able to evaluate flexibility and changeability. This evaluation can be performed from a top down or bottom up approach. The latter will be followed in this paper. A bottom up evaluation of industrial value creation would start on the equipment or work station level. The focus will be on automated and hybrid assembly equipment.

The decision on assembly equipment with the factory planning process is performed in the dimensioning phase, where different equipment alternatives are developed and evaluated. Thus, starting point for a bottom up evaluation are technically defined assembly equipment alternatives, which have to be evaluated relatively.

The economic evaluation is traditionally carried out by static and dynamic investment calculation methods. Most common used is net present value (NPV), where future cash flows are discounted with a risk adjusted discount rate. The drawback of these methods is the insufficient consideration of the equipments flexibility. Decision tree analysis or real options overcome these deficiencies and consider active decision making during the equipments life cycle [4]. Cost models based on life cycle costing or total cost of ownership further integrate in the cost evaluation all costs e.g energy or maintenance costs which occur during the equipment’s life cycle in the investment calculation.

The only international standardized (ISO 14040 and 14044) and widely accepted method for product based ecologic evaluation is life cycle assessment (LCA). LCA is a comprehensive, life cycle based, system analytic method which is performed in four steps: goal and scope definition, life cycle inventory analysis based on a model of input and output flows, life cycle impact assessment and interpretation. The disadvantage of LCA is its time consuming inventory analysis. Streamlined LCA approaches are facing this disadvantage by reducing the evaluation effort with simplified models and additional assumptions. Material Input per Service Unit (MIPS), developed by the Wuppertal Institute in Germany [5], reduces the inventory analysis on the input materials. Jungbluth or Mori propose modular or component based LCA approaches [6, 7].

So far life cycle assessment studies are mainly restricted on consumer product and production processes of semi-finished products e.g. sheet metal or chemicals. Studies on production equipment are rarely published. Considering assembly systems or industrial robots as product with embodied materials and energy as well as consumer of energy, consumables and supplies open a promising field for ecological improvement. The industrial sector of assembly and handling systems in Germany achieved in 2008 a turnover of 5.5 billion Euros jointly with robotics of 8.9 billion Euros and employ a 30,000 people work force [8].

The hardest challenge is the social evaluation. In the last years several social indicators on global, national and local level have been proposed. A dominant evaluation approach is still missing. An adaptation of LCA for social aspects names social life cycle assessment (SLCA) is still under development [9]. However, there are often conflicts between ecological improvements and social impacts. Sometimes there are trade-offs, an activity which improves the social impacts may worsen the ecological impacts and vice versa which demand for consistent analytical methodologies [10]. Further developed are ergonomics methods and tools focusing on the evaluation of workplace to fit the worker. National statistics in Germany relate 30 percent of the lost working days to skeleton and muscle diseases. The Automotive Assembly Work Sheet is a simple paper based evaluation method mainly designed for assembly workstations in the automotive industry which summaries the results based on traffic light [11].

Equipment life cycle problems are limited not only by technological issues, but also by economic, ecological and social issues. Decision making in social systems is deeply interdependent [12]. The integration of multiple attributes in a decision can be supported by multi attribute decision making method (MADM) e.g. cost utility analysis or PROMETHEE [13].

The paper is structured as follows: chapter 2 will present the results of two exemplary LCA studies of an assembly automat and an articulated robot. Chapter 3 will propose a simulation based approach to predict the energy consumption of equipment resulting of production schedules. Chapter 4 will describes an equipment evaluation concept integrating both economic, ecologic and social aspects and flexibility.

2 ECOLOGICAL ASSESSMENT WITH LIFE CYLCE ASSESSMENT (LCA)

In order to estimate the ecological impact of assembly equipment two representative systems have been evaluated exemplarily: an articulated industrial robot and an assembly automat. Table 1 shows a simplified bill of material of both systems. The evaluation is conducted using the LCA method defined in ISO 14040 and ISO 14044.

Material	Unit	Amount	
		Articulated Robot	Assembly Automat
Aluminium	kg	219,0	338,6
Copper	kg	250,0	8,7
Electronics	kg	20,0	5,0
Plastics	kg	85,0	7,0
Plexiglas (PMMC)	kg	-	50,5
Stainless Steel	kg	63,0	9,0
Steel	kg	828,0	336,9
Sum	**kg**	**1.465**	**756**
Electricity	MWh	60,0	10,0

Table 1: Simplified bill of materials

The estimation is based on a standard articulated industrial robot with a possible pay load of 120 kg e.g. the KUKA KR 120. The embedded materials and their contribution to the overall weight of 1.5 tons can be seen in the first two columns. The estimation of the energy consumption is based on measurements for standard movements with 3250 Watt during operation and 630 Watt during standby.

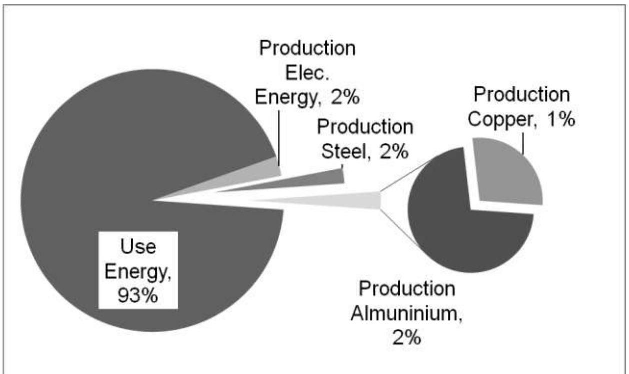

Figure 1: Global warming potential of articulated industrial robot: most contributing components

Figure 1 shows with the contribution to the global warming potential a result of the LCA study performed with the GABI software of PE International, Stuttgart. The LCA study is based on the life cycle inventory of the whole product life cycle and the results or calculated based on the estimated impacts of this inventory. In order to model a product or system the processes during the production, use and recycling of the system are modelled with the respective resource in- and outputs. The results are based on international accepted impact categories by the Centre for Environmental Studies (CML), University of Leiden, 2001. These impact categories categorize and characterize the single in- and outputs to e.g. global warming potential or eutrophication. The results show that the energy consumption during the use phase is the dominant resp. the only driver for the global warming potential.

Figure 2 shows the respective results for the automated assembly station with half a shift use per day over four years. The evaluated assembly station is a packaging machine consisting of two conveyer belts, four pneumatic pick and place handling devices and two pneumatic centring devices. The calculations are based on the bill of material and energy resp. compressed air field measurements. In contrast to the robot, the energy consumption during the use phase only represents 20 % of the overall global warming potential in the LCA study. Thus the composition of the station and the embodied materials mainly aluminium and steel influence the life cycle ecological impact.

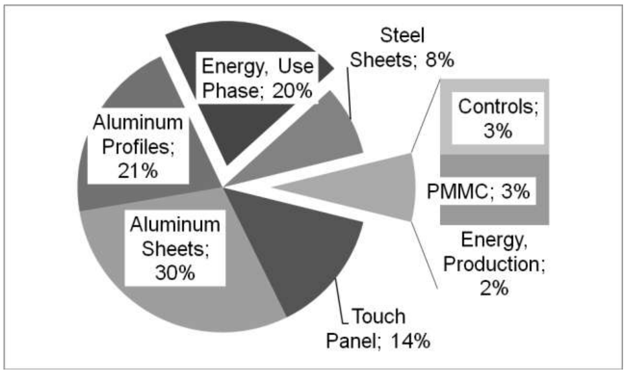

Figure 2: Global warming potential of automated assembly station: most contributing components

Following conclusion can be drawn of the two case studies. The evaluation of the robot shows, that the energy consumption during the use phase has to be investigated more in detail in order to evaluate the ecological impact more precisely. The following chapter will present a simulation based study in order to predict the energy consumption of equipment e.g. industrial robot.

3 ENERGY CONSUMPTION STUDY WITH SIMULATION SOFTWARE

There are several ways in studying and estimating the energy consumption for assembly equipment and industrial robots during the production operation. Explosive growth in IT technology making simulation is one of the potential tools that can be use. Not only providing a simple estimation data, but energy consumption regarding to several scenario and random failure can be the outcome of the simulation. Simulation based approach to predict the energy consumption for a case study is going to be explained.

A part of door assembly processes has been taken as a case study. Models are developed and simulated by using 3DCreate, commercial software from Visual Components Oy. The simulation model consists of 12 KUKA 125 industrial robots with a payload of 125kg, a common belt conveyor and a turntable.

In order to minimize the differences with a real system, the simulation is developed with push strategies operations with each equipment have their own operation and life cycle data. This makes all the assembly equipment and industrial robots have their own behaviour and independent from each other.

Figure 3 shows the simulation layout. There are three applications of robots; handling, spot welding and MIG

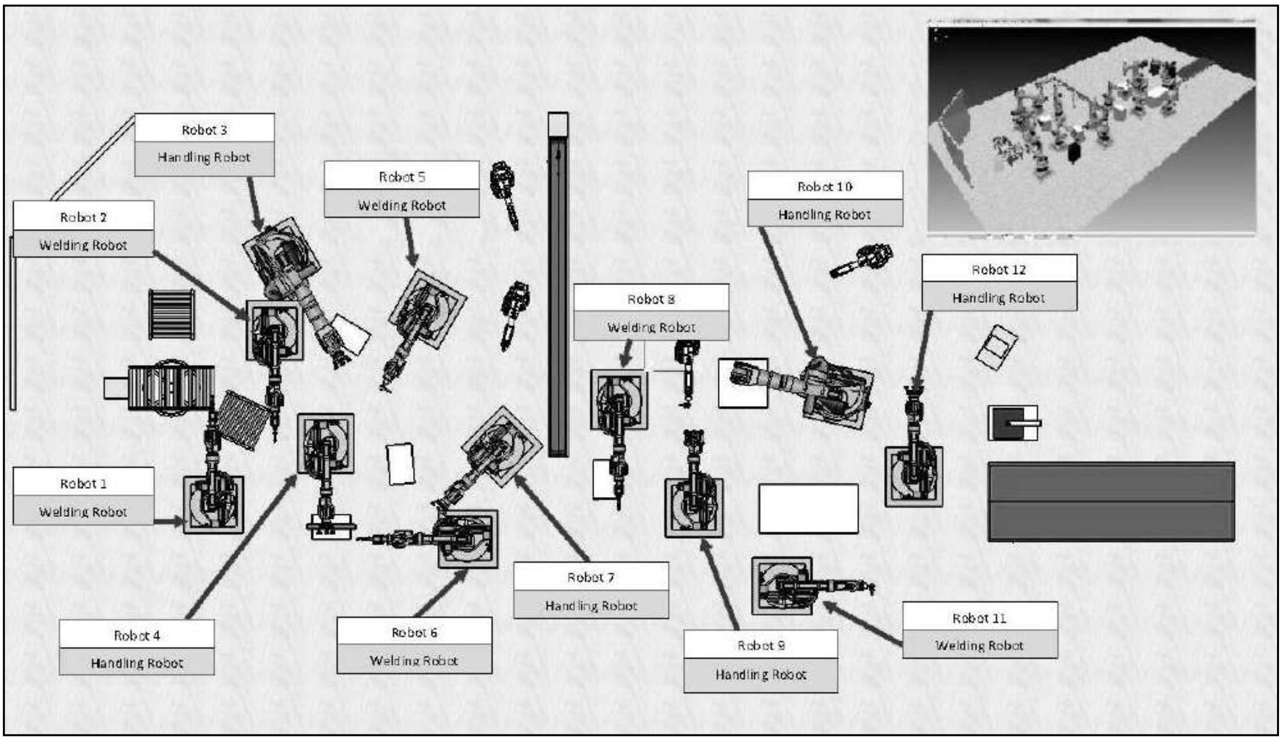

Figure 3: Simulation layout and screenshot of the selected case study

welding. However, only the energy consumption of the robot movements is estimated in this study without taking into account its end effector movement and consumption.

The energy consumption of the KUKA 125 for this simulation is based on measurements in the laboratory with 3.25kW/h during operation and 0.63kW/h during standby as below;

$$\Sigma_{Energy} = 0.63(^{kW}/_{h}) \times \Sigma t_{idle}(h) + 3.25(^{kW}/_{h}) \times \Sigma t_{operate}(h) \quad (1)$$

t_{idle}: Standby time (time during idle)

$t_{operate}$: Operation time

The products enter the assembly line from the turntable as two preassembled components and leave the line as a door frame after going through ten processes such as stamping, spot welding, arc welding, MIG welding and cleaning. It is a fully automated process which has to be stop if one of the equipment is fail and will continue after it has been repaired.

The model was simulated for one year. By integrating 3DCreate with Microsoft Excel, the outcome is recorded for each two month. The result from this simulation is presented in Table 2.

The first column is the name of the robots and follows by its operating hours in the second column. The operating hours is consisting of idle time, (t_{idle}) and operation time, ($t_{operate}$) without taking into account failure and repair time. The next column is the estimated energy consumption for each two month; second month, fourth month, sixth month, eighth month, tenth month and twelfth month. The last column is the number of failure that appears during one year operation.

The result shows that the performed operations of similar robots in one workstation strongly influence the energy consumption of the respective robot. Four robots consume more energy (≥20MW) than others even the operating hours for each robot are about the same. These four robots are Robot 1, Robot 2, Robot 4 and Robot 7. Two of the robots are operated as spot welding robots and another two robots are handling robots as shown in Figure 3. The simulation analysis manifest that these robots have been operated with more kinematics movements during operation times and only small amount of idle times which allow robots to be in its standby mode. Even though the tasks are different, the amount of kinematics movement required for each robots operation makes the energy consumptions for these four robots higher. By assigned operations, these robots consumed about 2MW in a month of operation and almost 100% more energy compared to the other eight robots in one year operation time. For instance, Robot 10 consumes only 10MW in a year of operation.

Robot	Operating Hours (1000h)	Energy Consumption (MW)						No. of Failure
		2	4	6	8	10	12	
1	8.36	4.65	9.07	13.50	17.99	24.47	27.15	4
2	8.21	4.42	8.81	13.23	17.61	21.99	26.67	5
3	8.41	1.92	3.91	6.03	8.00	9.91	11.91	4
4	8.36	4.60	8.89	13.14	17.56	22.13	26.61	4
5	8.23	3.02	5.91	8.81	11.73	14.65	17.71	6
6	8.32	2.13	4.14	6.18	8.20	10.33	12.47	4
7	8.39	3.78	7.56	11.31	15.05	18.79	22.71	5
8	8.30	1.84	3.64	5.48	7.32	9.14	11.06	7
9	8.29	2.33	4.51	6.77	9.15	11.43	13.78	6
10	8.30	1.65	3.21	4.99	6.77	8.45	10.10	5
11	8.39	1.95	3.76	5.62	7.52	9.47	11.47	4
12	8.34	2.62	5.06	7.62	10.19	12.89	15.58	4

Table 2: Estimated energy consumption for one year by simulation

From this study, robot operations that require more energy can be identified and thus the assessment of the life cycle impacts can be predicted dependent on the planned operations. Different operations assigned will give different energy consumption for the same type of robot. As comparison to the LCA of section 2 the global warming potential of the robot 1 and robot 10 is shown in Figure 4.

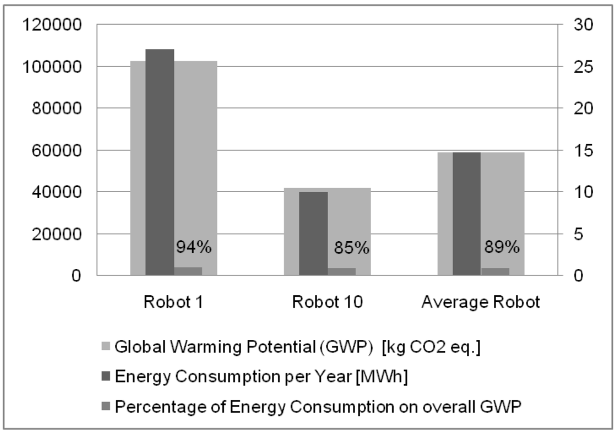

Figure 4: Global warming potential of articulated industrial robot with different energy consumption

4 INTEGRATED EVALUATION CONCEPT

Currently no evaluation method for equipment investment decisions is known to the authors which considers both the equipment's impact in all three sustainability dimension and the ability of the equipment to adapt to future developments. In the following paragraph a concept for the integration of ecological and social criteria in the economic investment evaluation process is proposed. In order to include as well the changeability of the equipment the basis for the evaluation is a decision tree (Figure 5). The method consists of six phases, which can be applied in an iterative manner in order to detail the result (Figure 6).

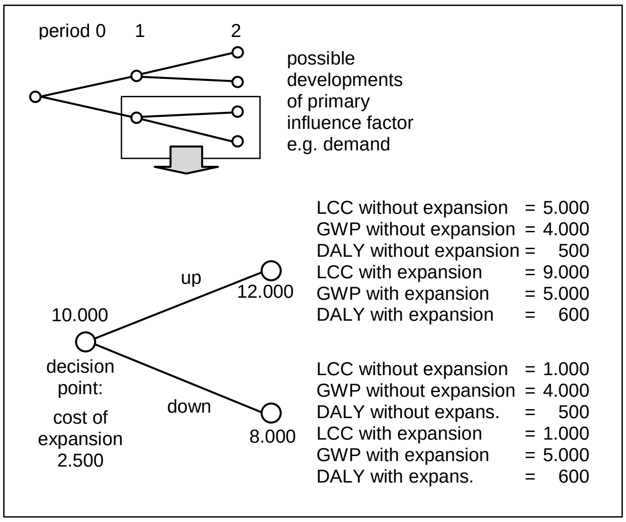

Figure 5: Decision tree

The first phase of the method is dedicated to the development of the decision tree for the designated product. Applying the scenario method by [14] key influence factors will be identified and future developments will be estimated. In adaptation of [15] a primary influence factor e.g. demand will be selected and a decision tree will be modelled based in the future developments of this factor. The figure shows a binominal not recombining tree which allows an up and down movement of each note from one period to another.

Dependent on the identified key influence factors relevant technical possibilities of the equipment to adapt to the changing environment e.g. increase capacity or introduce new product variant will be determined in the second phase. To facilitate this step the method proposes generic adaptation possibilities and their relevance for standard key influence factors. The determined adaptation possibilities will be detailed regarding their impact on the cost structure of the investment and on the ecological and social target criteria.

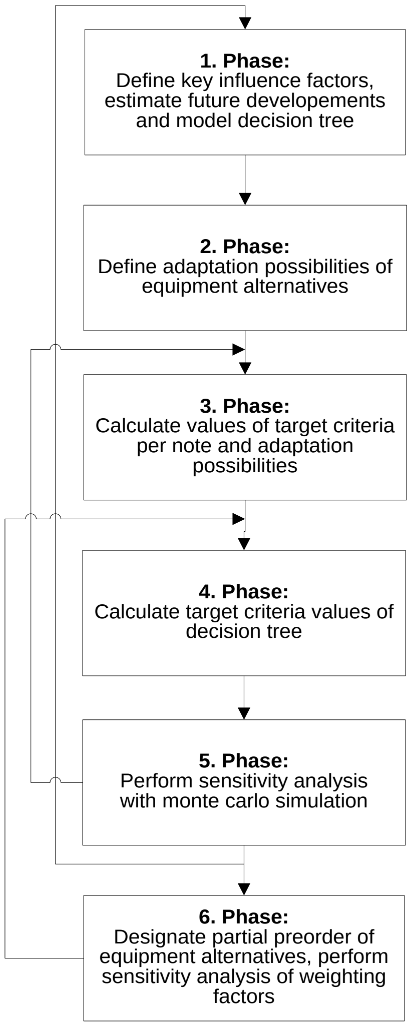

Figure 6: Structure of the evaluation method

The aim of the third step is to calculate the values of the target criteria per note of the decision tree. As economic target criteria the extended net present value (ENPV) including the option value of the adaptation possibilities is proposed. The ENPV will represent the life cycle cost of the different equipment configurations dependent on the chosen adaptation possibility. For the ecologic dimension the impact categories damage to the mineral and fossil resources and damage to the ecosystem quality of Eco-Indicator 99 are proposed. The ecological impact is estimated with a modular LCA based on type of system e.g. assembly automat or articulated robot, the weightings of the embedded materials; and the energy and supplies consumptions during production. The estimation of the energy consumption can be achieved by a simulation study as proposed in chapter 3. The social aspect could be represented by the impact category damage to the human health, measured in DALY, of Eco-Indicator 99 -

representing the social aspects during the production and end of life phase of the equipment – and the value of an ergonomic evaluation with the automotive assembly work sheet – representing the social aspects during the use phase. Figure 5 shows an exemplary branch of the tree and the effects of the adaptation possibility capacity expansion on life cycle costs, global warming potential and disability-adjusted life years – a measure of overall disease burden originally developed by the World Health Organization (WHO). The decision for the adaptation can be taken at the parent node of the branch.

During the fourth phase the calculation of the decision tree based on the real options approach is conducted similar to [16]. Based on a duplication of the evaluated investment with an inflexible comparable system the decision tree is calculated with a roll back method starting from the last period. The decision for the determined adaptation possibilities at the parent note of each branch is based on a multi attributive decision making, which allows a decision for the adaption over all target criteria values, calculated based on the development of the primary influence factor in the third step. Within this calculation process the economic, ecological and social criteria are kept separately. As a result a single value per target criteria for each equipment alternative is calculated.

The ranking of the evaluated alternatives based on a sensitivity analysis with a Monte-Carlo Simulation and a multi attribute decision making method e.g. PROMETHEE are aim of the fifth and sixth phase. Dependent on the results and iteration of the precedent phases can adapt or detail the results.

5 SUMMARY AND CONCLUSION

The paper presented two exemplary LCA studies of an assembly automat and an articulated robot. The results show that on the one hand for some assembly equipment the production contributes crucial to the overall ecological impact. On the other hand energy became one of the main ecological aspects that concern industrial sector nowadays. Energy consumption of assembly equipment and robot has to be optimising in order to produce a product with small embodied energy. Simulation has been proved to be a visible tool for estimating energy consumption. By this estimation, decision can be made more ecologically and systematically as proposed in evaluation method. Finally an evaluation method for investment decision in assembly equipment is proposed which is based on a flexibility evaluation with a decision tree and integrated economic, ecologic and social aspects.

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REFERENCES

[1] Wiendahl, H.P.; Elmaraghy, H.A.; Nyhuis, P.: Zäh, M.F.; Wiendahl, Duffie, N. and Kolakowski, M., 2007, Changeable Manufacturing – Classification, Design and Operation, Annals of the CIRP Vol. 56/2/2007.

[2] World Commission on Environment and Development, 1987, Our common future, Oxford.

[3] Elkington, J.; Elkington, J.; ed., 1998, Cannibals with forks_The triple bottom line of 21st century business, New Society Pub.

[4] Zäh, M.; Möller, N. and Sudhoff, W., 2005, A Framework for the valuation of Changeable Manufacturing Systems, in 'Proceedings CIRP 3rd International Conference on Reconfigurable Manufacturing'.

[5] Ritthoff, M.; Rohn, H. and Liedtke, C., 2002, MIPS berechnen: Ressourcenproduktivität von Produkten und Dienstleistungen, Ressourcenproduktivität von Produkten und Dienstleistungen. Wuppertal Spezial 27, Technical Report, Wuppertal Institut.

[6] Jungbluth, N.. 2000, Umweltfolgen des Nahrungsmittelkonsums: Beurteilung von Produktmerkmalen auf Grundlage einer modularen Okobilanz, PhD thesis, Eidgenossische Technische Hochschule, Zurich.

[7] Mori, Y.; Huppes, G.; de Haes, H. A. U. and Otoma, S.. 2000, Component Manufacturing Analysis, Int. J. LCA 5, 327-334.

[8] VDMA Verband Deutscher Maschinen- und Anlagenbau, 2009, public statistics, www.vdma.org, accessed November 20th 2009.

[9] UNEP; Andrews, E.S.; Barthel, L.-P.; Tabea, B., Benoît, C.; Ciroth, A.; Cucuzzella, C.; Gensch, C.-O.; Hébert, J.; Lesage, P.; Manhart, A. and Mazeau, P., 2009, Guidelines for social life cycle assessment of products.

[10] Hauschild, M.Z.; Dreyer, L.C. and Jørgensen, A.. 2008, Assessing Social Impacts in a Life Cycle Perspective – Lessons Learned, Manufacturing Technology, Annals of the CIRP Vol. 57/1/2008

[11] Schaub, K.. 2004, Das Automotive Assembly Worksheet, in: Landau, K. (Ed.): Montageprozesse gestalten, Ergonomia Verlag.

[12] Ueda, K.; Takenaka, T.; Váncza, J. and Monostori, L.. 2009, Value Creation and Decision-Making in Sustainable Society, Manufacturing Technology, Annals of the CIRP Vol. 58/2/2009

[13] Brans, J.; Vincke, P. & Mareschall, B., 1986, How to select and how to rank projects_The PROMETHEE method, European Journal of Operational Research 24, 228-238.

[14] Gausemeier, J.; Fink, A. and Schlake, O., 1995, Szenario-Management: Planen und führen mit Szenarien, Hanser.

[15] Sudhoff, W., 2007, Methodik zur Bewertung standübergreifender Mobilität in der Produktion, PhD thesis, Technischen Universität München.

[16] Möller, N. 2008, Bestimmung der Wirtschaftlichkeit wandlungsfähiger Produktionssysteme, PhD thesis, Technischen Universität München.