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Life Cycle Cost Estimation of Robot Systems in an Early Production Planning Phase

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Abstract

Cost estimation is necessary for comparing manufacturing systems. Because of simultaneous engineering this approximation should take place in an early planning stage with uncertain information. However traditional calculation methods do not concern the possibility to use robot systems in different scenarios along their life cycle.

Due to a high diversity of these systems, the costs can vary in a large range within an application. This paper introduces a cost estimation method for robot systems in an early planning phase also regarding future scenarios. Therefore the presented methods for product cost estimation are linked with a developed DMM (Domain Mapping Matrix).

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Keywords: Robotics; Economics; Production Planning; Life Cycle Costing

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1. Introduction

Automation gets more and more important. Robots as one possibility for flexible automation are gaining most attention, because of the decreasing lot sizes and the increasing degree of customization [1]. The benefit of robot systems concur with the costs. The initial investment in such a system is much higher than the costs for changes of the system for example to use the robot for other applications. Therefore the costs along the life cycle are more important for them than for other investments, because the economy increases over years. [2]

Furthermore the planning of manufacturing systems is shortened while simultaneous engineering is finding its way into enterprises. This leads to a demand for cost estimation in an early phase with only uncertain information available [3]. While such methods do not exist yet for robot systems, some methods for the cost estimation of products are available.

This paper describes a method to estimate the life cycle costs of robot systems based on the known methods for products. At last the quantification of qualitative aspects is important regarding robot systems and needs to be incorporated into the method. The method itself is split into three sections. First of all the estimation of investment is introduced. Afterwards two qualitative aspects, complexity and flexibility, are quantified to enable weight alternatives. Finally, future developments like Plug & Produce need to be taken into account, as they might change the life cycle.

Nomenclature

Ω	basic set
μ_M	membership value to the set M
M	fuzzy set
C	degree of complexity
m	multiplicity
d	diversity
A	ambiguity
t	income tax rate (including other taxes)
s_n	average number of part revisions in the nth year
c_1	average cost required for alteration of tooling
n	planning horizon in months
r	minimum attractive rate of return
N	project or product life
F_j	jth element of realizable flexibility
τ	number of flexibility elements
P	fuzzy present worth
F	fuzzy future worth

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2. Economics in robotics

The calculation of costs has been studied a long time. There are several methods and models how to calculate costs in an early planning stage. These models are clustered in various groups regarding their basis method. Also for the evaluation of flexible manufacturing systems methods exist. These methods are often based on simulations and expert knowledge is needed to use them. [4]

For cost models it is important that they are easy to use with minimal inputs and provide understandable results. It is also important to do a calculation over the whole life cycle in an early planning stage. At last uncertainties have to be considered. [5]

The method developed by the authors should observe all these requirements to ease the calculation of costs and make it useful for small and medium sized enterprises. This section describes the basic elements of life cycle costing. Moreover methods for quantifying qualitative aspects and for estimating costs are explained.

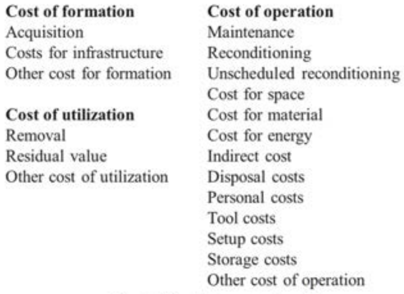
2.1. Life cycle costing

Life cycle costs include the costs of products and systems from the raw material to their recycling. [5] gave a review on models for life cycle costing. They state that there is no unique model that can be adopted to a specific use case. Therefore universal models of different organisations like VDMA or VDI have been built to calculate the life cycle costs. [3] These models are meant to be matched and so they are used in this paper.

The model published by [6] was made with the motivation of creating a universal standard for the engineering and plant engineering industry. Therefore the degree of standardization and the possibility of expansion and adaption are high [7]. The model consist of three phases with different types of costs: formation, usage and recycling. The formation mainly includes costs for invest and start up, but also costs for generating the needed infrastructure. The phase of usage is characterized by the production process. This can be a value-adding process like welding or an auxiliary process like handling. Moreover personal cost, energy costs and maintenance costs have influence on the costs of usage. The costs in the recycling can include income from disposition and costs from removal. [6, 8]

The costs during life cycle can be described in three levels of detail. While in the first level of detail only the overall costs of each phase are displayed, the third level is a detailed calculation based on assembly groups. The middle level includes specific cost elements for every phase that can be considered, neglected or added. Fig. 1 shows the cost elements of the middle level. [8]

Based on the level of detail, a specific procedure is passed through. An important step at the beginning is the specification of the relevant cost elements. On the second and third level the description of the use case follows. This includes for example the production volume and the availability of the machine. The period under consideration starts with the acquisition and ends after a given useful life. After collecting the data, the calculation of the costs is done. To simplify this step, a constant distribution of the products manufactured with the system is supposed. Finally the results are validated and displayed. [8]



Cost of formation
Acquisition
Costs for infrastructure
Other cost for formation

Cost of utilization
Removal
Residual value
Other cost of utilization

Cost of operation
Maintenance
Reconditioning
Unscheduled reconditioning
Cost for space
Cost for material
Cost for energy
Indirect cost
Disposal costs
Personal costs
Tool costs
Setup costs
Storage costs
Other cost of operation

Fig. 1. Cost element after [6].

2.2. Cost estimation

A fundamental element of cost management is a concurrent calculation with an early detection of and influence on the costs close to constructive decisions. Bases are the enterprise specific calculation structures that enable a constant cost comparison. For this reason quick calculation techniques based on decision relevant parameters were developed. [3]

The greatest challenge within this calculation is the incomplete database. Ideally the costs are known for specified requirements [3]. Another problem is the different quality of the given data. The accuracy of the data should be noted within the calculation to estimate the risk during the planning phase [9].

Before explaining a few methods for estimating the costs in an early planning phase, important aspects need to be considered. As this calculation is done with uncertain information, the output is not as exact as for normal pre or post calculation. For the comparison of different alternative robot systems the quality has to be similar for all variants to compare the systems in a proper way. Furthermore, the most calculation methods are based on known input from earlier projects. [3]

[3] devide the cost evaluation methods in an early planning phase in:

- Cost estimation
- Similarity calculation
- Determination of the costs based on main parameters
- Identification of the costs with equations
- Short calculation with more influence values
- Calculation with the help of cost growing rules

The procedures for short calculation with more influence values, as used in this paper for the estimation of the investment for robot systems, can be divided into the development of calculation equations with regression analysis, with optimization procedures, while using neural networks or while using fuzzy logic. [3]

For robot systems the single components are influenced by various parameters that partly interact. Also the information about earlier investments in the existing components of robot systems is available. Therefore the calculation equations developed from the author are built with a regression analysis for each component (group).

2.3. Quantifying qualitative aspects

For robot systems two quantitative aspects are important to evaluate – flexibility and complexity – because they represent their possibilities and problems. Procedures that allow a comparison based on quantitative and qualitative aspects are called multi-criteria evaluation and decision procedures [10]. For the comparison of different robot systems only finitely many solutions are given. Thus this paper focuses on Multi Attribute Decision Making (MADM) methods [11].

One possibility to integrate qualitative aspects is using the cost-benefit analysis or the Analytic Hierarchy Process (AHP). This method summarizes the evaluation of different, also weighted, factors to a utility value. The cost-benefit analysis is easy to use and transparent [12]. But there is the danger of mixing quantitative and qualitative aspects [12, 13].

Also for quantifying qualitative aspects neural networks and fuzzy logic can be used. For neural networks input from training is necessary. This data doesn't exist in practice. Therefore neural networks are not applicable for robot systems. [15]

Fuzzy logic includes the fuzzy-set theory. This theory allows a flowing or fuzzy affiliation of elements to a set [16]. Lately this theory, having its origin in control theory, finds its way into production management [17]. Within fuzzy sets a specific element can be a member of a set fully, only partially or not at all [18]. This characteristic is given by a so called membership function (eq. 1). This function allocates a membership value μ to all elements of a basic set Ω [19], with μ being a rate for the degree of membership [20].

$$\mu_M : \Omega \rightarrow [0,1] \qquad (1)$$

A membership value of 1 expresses a full membership. A membership value of 0 shows elements with no membership to the set M [21]. Within fuzzy-set theory linguistic terms are used to reproduce qualitative knowledge with all its fuzziness and allow the integration in mathematical models [22]. Some possible membership functions are shown in Fig. 2.

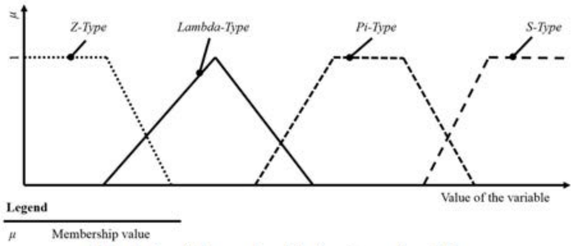


Fig. 2. Possible membership functions after [15].

For further information on fuzzy set theory see [23] and [24]

3. Method for estimating the costs of robot systems

This chapter explains the three main parts of the estimation model for life cycle costs of robot systems: the assessment of the investment, the evaluation of complexity and flexibility and the consideration of future developments.

3.1. Estimating the investment

As stated in section 2.3 for the investment of robot systems the influence parameters are analysed, checked for correlations and finally a regression analysis identifies the relation between the significant parameters and the investment. This paper explains the procedure using the example of the robot. The data is shown for two applications (handling and welding) to see an influence of the application on the investment. The difference may occur because of special equipment, e.g. internal wires.

For robots the important characteristics are velocity, accuracy, load, reach, application, number of axes, type of kinematics. For a first examination only articulated robots with 6 axes were analysed. Therefore number of axes and type of kinematics aren't necessary parameters. The velocity depends on the process and the type of kinematics. Therefore this parameter is also not important. The other characteristics are now analysed regarding correlations.

The correlation diagrams (Fig. 4) show, that there is no correlation between accuracy and another factor. Between load and reach there can be a linear correlation. But the significance of the correlation varies regarding the application. The load shows no explicit correlation with the price. Here a linear or a polynomial correlation is possible. The reach shows a clear linear relation to the price. Therefore the regression analysis is done for load and reach. The correlation diagrams are shown in Fig. 4. The result of the regression analysis can be seen in Fig. 3.

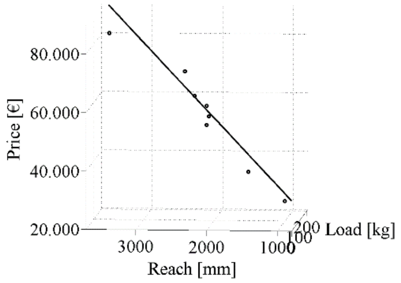


Fig. 3. Price of robots and result of regression analysis.

The cost function for robots shows, that the procedure to get them can be used for calculating the investment with less information of the system. While the data for the analysis is from one manufacturer, future work will compare the results with other manufacturers. Also other kinematics and numbers of axes should be added to the analysis to get a more precise cost function. Finally this procedure is done for the most common peripheral components to calculate the investment of the robot systems without asking for quotations.

3.2. Evaluation of complexity and flexibility

To quantify complexity and flexibility straight forward procedures were used. First of all **complexity** is defined by Reis [25] with four parameters – diversity, multiplicity, ambiguity and variability – whereas variability and sometimes also multiplicity can be knowingly excluded. While variability is considered in another aspect, it is chosen not to be part of the quantification of complexity in this method. The other parameters are defined regarding robot systems as follows:

- Multiplicity is the number of interfaces within the robot cell and to the environment.
- Diversity is the number of kinds of interfaces. There are five kinds: pneumatic, mechanic, hydraulic, electric and informatics interfaces.
- Ambiguity is a factor between 1 and 5 describing the required effort for developing the interface.

First, all components of the robot system have to be listed to determine the multiplicity. To do so, the system has to be broken down into its single components to examine the connections and interfaces. After defining the multiplicity diversity has to be described.

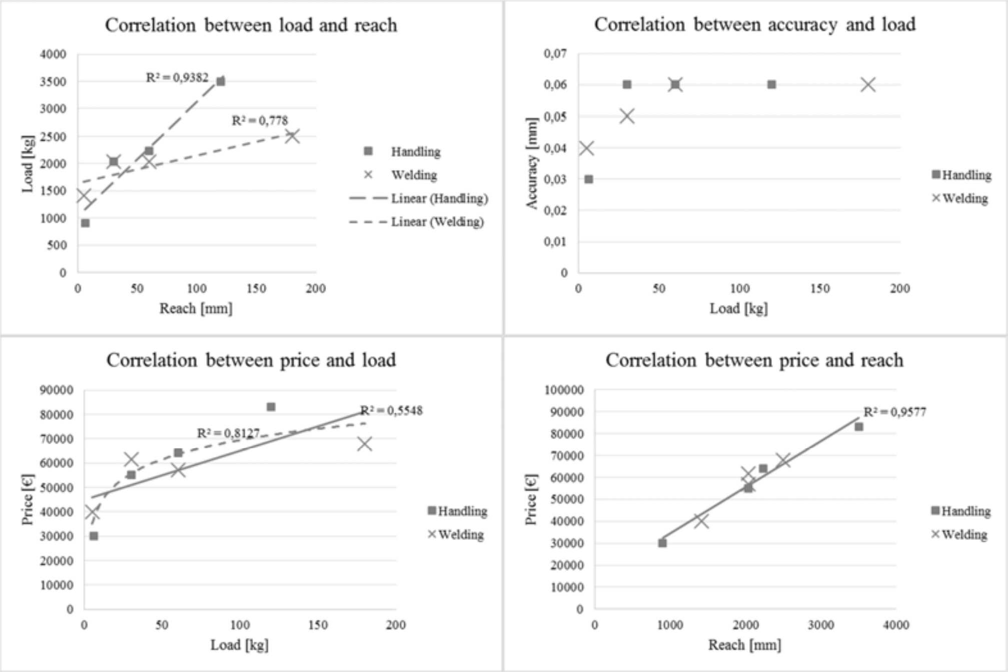


Fig. 4. Correlations between price, load, reach and accuracy.

At last ambiguity has to be considered. One possibility for doing this is a classification in less complex to highly complex based on the influence of the ‘Size Driver’ developed by [26]. A ’Size Driver’ contains system requirements, number of main interfaces, criticality of algorithms and number of use cases, in summary the capabilities of the interface. Every ‘Size Driver’ can be evaluated as easy (1), nominal (2) or difficult (3). Table 1 lists the rate of ambiguity according to the evaluation of the ‘Size Driver’.

Table 1. Evaluation of ambiguity.

Ambiguity	Evaluation Size Driver
1	4
2	5/6
3	7/8
4	9/10
5	11/12

Thereby complexity can be calculated as the sum of ambiguity over diversity and multiplicity (eq. 2).

$$C = \sum_{i=1}^{m} \sum_{j=1}^{d} A_{ij} \qquad (2)$$

Flexibility is mostly defined as the ability to match a system to changing requirements [27]. [28] differentiate between 8 kinds of flexibility.

Flexibility regarding:

- Machines
- Processes
- Products
- Interruptions
- Amount
- Extensions
- Cycle time
- Production

Flexibility depends on response time, adaptation time and modification effort. In this context reaction time is the time from detecting the necessity for a change until deciding the implementation. Adaptation time includes setup and implementation time. Fig. 5 shows the parameters considered while calculating flexibility. The marked area is indirectly proportional to flexibility. Therefore high flexibility is the result of short reaction and adaptation time with less amount of necessary changes. [27, 29]

The versatile dimensions of flexibility prohibit a total mathematical description and require expert knowledge, which is often fuzzy. Thus fuzzy set theory is used to describe flexibility. [30]

[31] evaluate flexibility using fuzzy set theory based on present worth analysis. Their results are shown in the following section. According to [32] no changes in the estimation of parameters, like the number of part revisions in the nth year (s_n), occur. [31] define these parameters as triangular fuzzy numbers $s_n = (s_{n0}, s_{n1}, s_{n2})$. The discount rate during time n is $r_n = (r_{n0}, r_{n1}, r_{n2})$. The income tax rate t is a fixed value. With this input the equation for the fuzzy present worth of the flexibility for continuous improvement (PWoCI) with no inflation is given in eq. 3. [31]

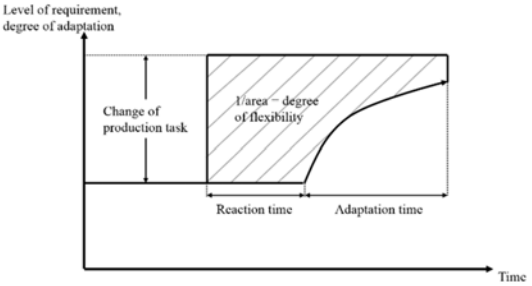


Fig. 5. Parameters for calculating flexibility after [27, 29].

$$PWoCI = \left[(1-t)\sum_{n=1}^{N}\frac{s_n^{l(\alpha)}c_n^{l(\alpha)}}{\prod_{n'=1}^{n}\left(1+r_{n'}^{r(\alpha)}\right)},\right. \left.(1-t)\sum_{n=1}^{N}\frac{s_n^{r(\alpha)}c_n^{r(\alpha)}}{\prod_{n'=1}^{n}\left(1+r_{n'}^{l(\alpha)}\right)}\right] \tag{3}$$

$s_n^{l(\alpha)}$ is the left side and $s_n^{r(\alpha)}$ the right side representation (of the triangle of the membership function) of the average number of parts revisions. $c_n^{l(\alpha)}$ is the left side and $c_n^{r(\alpha)}$ the right side representation of the average cost required for alteration in the nth year. The fuzzy flexibility value (FFV) according to [32] is calculated considering also the triangular fuzzy numbers stated by [31] with eq. 4.

$$FFV = \sum_{j=1}^{\tau} PWoF_j \tag{4}$$

F_j is the jth element of realizable flexibility and τ the number of flexibility elements. Combining this with the formula for the membership function of [33] and [34] (eq. 5) the fuzzy present worth of flexibility $\widetilde{P_n}$, eq. 6 [31], can be built. For eq. 6 there is no inflationary condition.

$$f_{ni}\left(y\middle|\tilde{P}_n\right) = f_i\left(y\middle|\tilde{F}\right)\left(1+f_k(y|\tilde{r})\right)^{-n} \tag{5}$$

$$f_{ni}\left(y\middle|\tilde{P}_n\right) = (1-t)c_1\sum_{n=1}^{N} f_i(y|\tilde{s}_n)(1+f_k(y|\tilde{r}))^{-n} \tag{6}$$

With eq. 6 the present worth can be calculated with the knowledge of the number of part revisions, the discount rate and the constant average costs for alteration. Also the membership function has to be known. The next step for describing flexibility is to investigate the correct form of the triangular fuzzy set for robot systems and to ease the calculation to make it more useful for the early planning phase. If necessary inflation can be considered accordingly.

3.3. Consideration of future developments

The last part is the consideration of future developments. Based on a research on current trends in robotics a Domain Mapping Matrix (DMM) was set up. First of all a situation analysis of robot systems was done. There are 3 stakeholder: customer, integrator and producer. The centre of the model are the costs. The values included in the DMM can be costs, a stakeholders, future developments like Plug & Produce, hardware components and characteristics of the system. Table 2 lists the values within their groups.

At first, some basic presumptions were made. There is no market power of one manufacturer, so that he will not increase its benefit and pass his savings to the customer. The model considers learning effects which means that production time and costs decrease over time. Enterprises that already use robots normally invest in the same robot manufacturer and robot type. The last presumption is that the variance of products depends on the demand. Thus it is a pure active element, that isn't influenced by other parameters.

Table 2. Elements of DMM.

Customer/ Integrator/ Manufacturer	Costs
Robot/ Periphery	Amount in one system
	Complexity of interfaces
	Number of changes
	Scheduled downtime
	Commissioning/ Configuration time
	Not-scheduled downtime
Development effort	
Product variance	
Potential Plug & Produce	

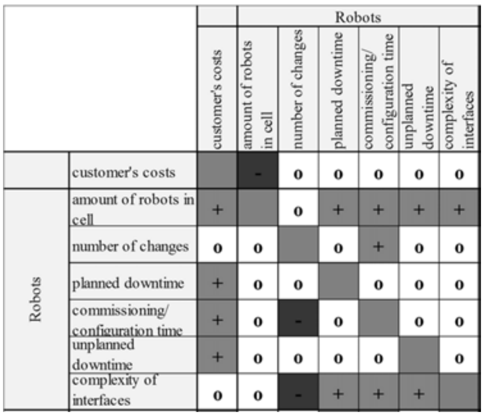
Next, the single elements of the model are described. Initial operation time means the time for setting up the robot the first time. It includes physical set up, configuration and programming. The time to reconnect is also called reconfiguration time. There are two cases. First, the robot can stay at its position and only the tools are changed. Second, the robot moves to another site of operation. As setup and reconfiguration time include the same tasks, they are grouped to one value.

Downtime includes scheduled and non-scheduled time elements. The scheduled downtime includes organisational downtime and time for maintenance and its secondary downtime. It is split into setup and reconfiguration time and time for maintenance. The non-scheduled downtime consists of every time regarding failures. The time elements are evaluated for robots and peripheral components on their own. Otherwise the change of single peripheral components and the correlations between robot and other components cannot be investigated. Peripheral components in this context include all elements that have an active function.

The complexity of interfaces has to be evaluated for robot and peripheral components separately because of possible changes to only one peripheral component. There are also connections between robot and peripheral components that have to be considered. The complexity as one qualitative element can be described as shown in chapter 3.2.

Last but not least the potential of Plug & Produce is a pure passive element which is influenced by other parameters. It describes whether Plug & Produce has advantages compared to normal robot systems. Parts of the developed influence matrix are shown in Fig. 6.

The output of the research on future robotic applications is a DMM that can be used for evaluating different scenarios including qualitative aspects. With the model the influence of a single aspect can be predicted and a risk analysis can be done for different variants. This model completes the holistic evaluation of robot systems.



			Robots					
		customer's costs	amount of robots in cell	number of changes	planned downtime	commissioning/ configuration time	unplanned downtime	complexity of interfaces
	customer's costs		-	o	o	o	o	o
Robots	amount of robots in cell	+		o	+	+	+	+
	number of changes	o	o		o	+	o	o
	planned downtime	+	o	o		o	o	o
	commissioning/ configuration time	+	o	-	o		o	o
	unplanned downtime	+	o	o	o	o		o
	complexity of interfaces	o	o	-	+	+	+	

Fig. 6. Part of the Domain Mapping Matrix for robot system.

4. Conclusion and outlook

Evaluating robot systems in an early planning stage is very difficult. Therefore this paper introduces three parts of an evaluation method. First, the real costs have to be estimated over the whole product life cycle. For this step the influence parameters are analysed and compared with correlation diagrams. Afterwards, cost functions are built using regression analysis. Here, further work will expand the database to get more reliable cost functions. The second step is the evaluation of qualitative aspects like flexibility and complexity. This can be done with fuzzy theory and other logic relations. For the fuzzy theory the fuzzy set has to be investigated. At last, future developments like Plug & Produce have to be considered as well. This can be done using the developed DMM that can be further adopted to different circumstances.

References

[1] Bachmann E. Planungsablauf bei der Einführung eines Roboters. 1. RobotDay. Biel (Schweiz); 2004.

[2] Müller S, Schweizer M. Robotertechnik. Landsberg: verlag moderne industrie; 1987.

[3] Ehrlenspiel K, Kiewert A, Lindemann U, Mörtl M. Kostengünstig Entwickeln und Konstruieren. 7th ed. Berlin: Springer, 2014.

[4] Niazi A, Dai JS, Balabani S, Seneviratne L. Product Cost Estimation: Technique Classification and Methodology Review. Journal of Manufacturing Science and Engineering 2006; 128:563-575.

[5] Asiedu Y, Gu P. Product life cycle cost analysis: state of the art review. International Journal of Production Research 1998; 36:883-908.

[6] VDMA. VDMA-Einheitsblatt 34160. Berlin: Beuth, 2006.

[7] Bünting F. Lebenszykluskostenbetrachtung bei Investitionsgütern. In: Schweiger S. Lebenszykluskosten optimieren. 1st ed. Wiesbaden: Gabler, 2009. p. 35-50.

[8] Bode M, Bünting F, Geißdorfer K. Rechenbuch der Lebenszykluskosten. Ein Leitfaden mit Rechenmodell und Arbeitshilfen. Frankfurt am Main: VDMA-Verlag, 2011.

[9] Lindemann U, Stricker H, Gramann J, Pulm U. Kosteneinsparungen in Wertanalysen – Eine Systemaik zur Wirkungskontrolle. In: ZWF. München: Carl Hanser, 2001. p. 543-546.

[10] Brieke M. Erweiterte Wirtschaftlichkeitsrechnung in der Fabrikplanung. Hannover: PZH, 2009.

[11] Schuh H. Entscheidungsorientierte Umsetzung einer nachhaltigeren Entwicklung: empirische Anayse, theoretische Fundierung und Systematisierung am Beispiel der netürlichen Ressource Wasser. Berlin: dissertation.de, 2001.

[12] Hoffmeitser W. Investitionsrechnung und Nutzwertanalyse. Stuttgart: Kohlhammer, 2000.

[13] Blohm H, Lüder K, Schaefer C. Invesition. 9th ed. München:Vahlen, 2006.

[14] Götze U. Investitionsrechnung – Modelle und Analysen zur Beurteilung von Investitionsvorhaben. Berlin: Springer, 2005.

[15] Krebs P. Bewertung vernetzter Produktionsstandorte unter Berücksichtigung multidimensionaler Unsicherheiten. München: Utz, 2011.

[16] Zadeh LA. Fuzzy Sets. Information and Control 1965; 8:338-353.

[17] Wong BK, Lai VS. A survey of the application of fuzzy set theory in production and operationsmanagement:1998-2009. International Journal of Produktion Economics 2001; 129:157-168.

[18] Nauck DD, Klawonn F, Kruse R. Neurinale Netze und Fuzzy-Systeme. Braunschweig:Vieweg, 1994.

[19] Rommelfanger F, Eickemeier SH. Entscheidungstheorie. Berlin: Springer, 2002.

[20] Forschner M. Prozeßorientiertes Investitionscontrolling. Wiesbaden: Dt. Univ.-Verlag, 1998.

[21] Traeger DH. Einführung in die Fuzzy-Logik. Stuttgart: Teubner, 1993.

[22] Jasvoin L. Integration der Unsicherheitsaspekte in die Schedule-Optimierung. Wiesbaden: Dt. Univ.-Verlag, 2006.

[23] Jones A, Kaufmann A, Zimmermann HJ. Fuzzy Sets Theory and Applications. Dordrecht: D. Reidel Publishing Company, 1986.

[24] Zimmermann HJ. Fuzzy set theory – and its applications. Boston: Kluwer, 1991.

[25] Reiß M. Komplexitätsmanagement I. In: Das Wirtschaftsstudium, 1993; 22-1:54-59.

[26] Valerdi R. The Constructive Systems Engineering Cost Model (COSYSMO). Los Angeles: University of Southern California, 2005.

[27] Helberg P. PPS als CIM-Baustein. Gestaltung d. Produktionsplanung u. -steuerung für d. computerintegrierte Produktion. Berlin: Erich Schmidt, 1987.

[28] Browne J, Dubois D, Rathmill K, Sethi SP, Stecke KE. Classification of flexible manufacturing systems. THE FMS Magazine 1984; 2:114-117.

[29] Schmitz M. Flexibel automatisierte Fertigungssysteme. Bewertungsprobleme und Lösungsansätze. Wiesbaden:Dt. Univ.-Verlag, 1994.

[30] Tsourveloudis NC, Phillis YA. Manufacturing Flexibility Measurement: A Fuzzy Logic Framework. Transactions on Robotics an Automation 1998; 14-4:513-525.

[31] Beskese A, Kahraman C, Irani Z. Quantification of flexibility in advanced manufacturing systems using fuzzy concept. Int. J. Production Economics 2004; 89:45-56.

[32] Pyoun YS, Choi BK. Quantifying the flexibility value in automated manufacturing systems. Journal of Manufacturing Systems 1994; 13:108-118.

[33] Buckley JJ. The fuzzy mathematics of finance. Fuzzy Sets and Systems 1987; 21:257-273.

[34] Buckley JJ, Eslami E, Feuring T. Fuzzy Mathematics in Economics and Engineering. Heidelberg: Physica Verlag. 2002.