Proceedings of DET2011
7th International Conference on Digital Enterprise Technology
Athens, Greece
28-30 September 2011

LIFE CYCLE ORIENTED EVALUATION OF FLEXIBILITY IN INVESTMENT DECISIONS FOR AUTOMATED ASSEMBLY SYSTEMS

Prof. Dr.-Ing. Achim Kampker
WZL, Laboratory for Machine Tools and Production Engineering, RWTH Aachen University
a.kampker@wzl.rwth-aachen.de

Dipl.-Ing. Peter Burggräf
WZL, Laboratory for Machine Tools and Production Engineering, RWTH Aachen University
p.burggräf@wzl.rwth-aachen.de

Dipl.-Ing. Cathrin Wesch-Potente
WZL, Laboratory for Machine Tools and Production Engineering, RWTH Aachen University
c.wesch@wzl.rwth-aachen.de

Dipl.-Wirt.-Ing. Georg Petersohn
WZL, Laboratory for Machine Tools and Production Engineering, RWTH Aachen University
g.petersohn@wzl.rwth-aachen.de

ABSTRACT

Due to fast changing market requirements and short product life cycles, flexibility is one of the crucial characteristics of automated and partly automated assembly systems besides purchasing and operation costs. Since the life cycle of an assembly system is longer than the one of the assembled products, flexibility enables an assembly system to adapt to future product requirements as well as production scenarios. The approach proposed in this paper strives for a systematic and economic measurement of flexibility in investment decisions. It offers methods and key-figures supporting the investment decisions for automated assembly systems. The right levels of flexibility and automation of an assembly system are evaluated by using a set of potential future scenarios of the system's life cycle. Based on two new key-figures called Return on Automation and Return on Flexibility, the approach allows comparing different configurations of an assembly system and therefore makes well-informed investment decisions.

KEYWORDS

Assembly System, Flexibility, Decision Making, Life Cycle

1. INTRODUCTION

Companies in manufacturing industries are confronted with the challenges of an increasing market dynamic, an increasing competition and an uncertain environment, caused by globalisation of the markets and economic crises. Shorter product lifecycles, more product variants and volatile product demands and a concurrent increasing product complexity are characteristic consequences for companies in this market environment (Schuh et al, 2004; Schuh et al, 2005; Seidel and Garrel, 2011).

In this context, the ability to adapt to the changing requirements is becoming an important competitive factor. A continuous adaptation of the manufacturing system to the market requirements is necessary. Since the future requirements for the manufacturing system cannot be forecasted exactly, a proactive adaptation of the system is rarely possible and the manufacturing system is not optimally configured for the upcoming situation. Therefore, manufacturing flexibility is an important goal to achieve in the early planning phases of the system (Schuh et al, 2004; Schuh et al, 2005). In addition low production costs are an important factor for competitiveness. The automation of manufacturing systems is one solution to reach this goal. While automation usually effects a reduction of the flexibility of the manufacturing system, a trade-off has to be made between these two goals.

The approach proposed in this paper, attempts to give support in finding the right trade-off between flexibility and automation in investment decisions for automated assembly systems. Automated assembly systems are one example of a system with high investment costs on the one hand and the need for flexibility over the systems life cycle on the other hand. The approach is supposed to be used in the early planning phases of automated assembly systems. Chapter two of this paper illustrates the required types of flexibility of assembly system. Challenges in the economic evaluation of flexibility and existing approaches are summarized in chapter three. In chapter four the approach to a life cycle oriented evaluation of flexibility in investment decisions for automated assembly systems is introduced. In chapter five an industry case is presented. Chapter six concludes this paper.

2. FLEXIBILITY OF ASSEMBLY SYSTEMS

The economic and life-cycle oriented evaluation of flexibility in investment decisions requires a clear definition of the necessary types of flexibility provided by assembly systems. As there are numerous approaches on the description and measurement of manufacturing flexibility, a common definition of manufacturing flexibility and its various types in literature is not available (De Toni and Tonchia, 1996).

Flexibility acts as a “counterbalance” to uncertainty (Newman et al, 1993). It describes the ability of a manufacturing system to cope with unforeseen changes. The two main types of unforeseen changes which necessitate flexibility are external changes (demand, supply) and internal changes (system breakdown, lack of material, delay). Manufacturing systems with a high degree of flexibility adapt to new situations caused by external and internal changes quickly and without significant, new investments (Chryssolouris, 1996; De Toni and Tonchia, 1996). Chryssolouris (1996, 2005) suggested that flexibility of a manufacturing system should be evaluated by the expected costs necessary for the adaptation of the system. There are numerous approaches to classify flexibility into different types (e.g. Browne et al, 1984; Sethi et al, 1990). In the next step the main types of flexibility for assembly systems are derived from the external and internal requirements for the assembly system.

As in most industrial sectors, the life cycle of an assembly system is longer than the one of the assembled products. Thus, the necessity for flexibility of automated and partly automated assembly systems is evident. Furthermore, the necessity intensifies by an increasing frequency of product changes caused by shorter product life cycles. These challenges can be met by a type of flexibility, which allows the set of products to be changed easily (Schuh et al, 2004).

Frequent product changes result in a mass of different variants of the same product type. In addition, the complexity of the product variants increases. Thus, the assembly system has to assemble different variants and types of products at the same time to remain competitive (Schuh et al, 2004).

Volatility of the demand during a product life cycle is typical for most markets. To enable profitable assembly at different volumes, this challenge has to be counterbalanced by flexibility (Schuh et al, 2004).

With regards to these requirements three main types of flexibility seem to be adequate for the classification of the assembly system flexibility (Figure 1) (Browne et al, 1984; Suarez et al, 1991):

- *Product flexibility* describes the ability of the production system, to produce a changed set of products without serious updates and replacements of the present resources.
- *Mix flexibility* describes the ability of a system to produce a number of different products at the same time.
- *Volume flexibility* describes the ability of an assembly system to vary the volume of products without remarkable consequences on production costs.

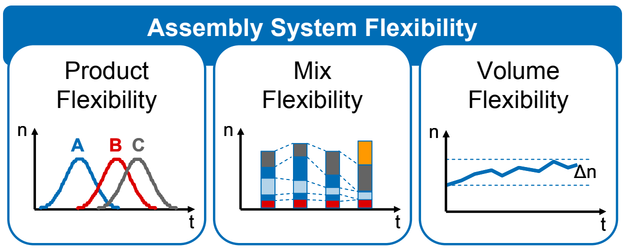

Figure 1 – Main types of assembly system flexibility

3. CHALLENGES IN ECONOMIC EVALUATION OF FLEXIBILITY

The fact, that no commonly accepted approach to the evaluation of the flexibility of manufacturing systems exists, shows the need for new decision support methodologies in industry (Rogalski et al, 2009). The multi-dimensionality of flexibility and the lack of direct measures of flexibility make an evaluation of manufacturing flexibility difficult (Cox 1989). This is particularly true for the financial or economic evaluation of flexibility. While the investment in a flexible manufacturing system is easy to quantify, the financial benefits of an increased manufacturing flexibility are hard to determine (Zäh et al, 2006). Based on a review of existing approaches to the evaluation of manufacturing flexibility, the necessity for a life cycle oriented evaluation of assembly system flexibility in investment decisions is going to be derived.

Schuh et al (2004) developed a system of key figures for the evaluation of product, mix and volume flexibility. The system is able to measure the flexibility on different organisational levels (workstation, production line and production system or production networks). A detailed monetary evaluation of flexibility is not possible.

Abele et al (2006) extended in their approach the net present value method by the real options analysis for the evaluation of flexibility. The approach considers the temporal structure of the decision relevant cash flows. The approach by Zäh et al (2003) is another example for using the real option analysis in flexibility evaluation. Since the real option analysis presupposes the existence of a market traded financial option with the same cash flows offer time, the usage of the approaches is very restricted.

Alexopoulos et al (2007) developed the DESYMA approach for the determination of the flexibility of a manufacturing system by statistical analysis of the estimates of the manufacturing system's lifecycle cost. The estimates are calculated with discounted cash flows over a time horizon and for different market scenarios using a linear program. The approach does only consider possible adaptations caused by different demand volumes. Georgoulias et al (2009) integrated the DESYMA approach into a toolbox approach for flexibility evaluation.

The approach for the flexibility evaluation by Reinhart et al (2007) is divided into three steps (definition of alternatives to evaluate, modelling the future with uncertain states of the environment, determination of the most economic alternative). Using discounted cash flows for the economic evaluation the approach just considers the volume flexibility.

Rogalski and Ovtcharova (2009) developed the ecoFLEX approach for the comparison of different manufacturing systems regarding their flexibility. The comparison is based on a linear program, calculating "flexibility areas", considering the mix and volume flexibility of a system. Monetary parameters are not considered in detail.

The approach developed by Rühl (2010) strives for the economic evaluation of manufacturing in the design phase, considering the flexibility and risk criteria. The approach is not life cycle oriented and just considers volume and mix flexibility.

Table 1 – Summary of the relevant approaches

- ● Characteristics fulfilled
- ◑ Characteristics partially fulfilled
- ○ Characteristics not fulfilled

Approach	Life cycle oriented	Detailed monetary evaluation	Product flexibility	Mix flexibility	Volume flexibility
Schuh (2004)	○	○	●	●	●
Abele (2006)	●	◑	◑	◑	◑
Zäh (2003)	●	◑	○	◑	●
Alexopoulos (2007)	●	◑	◑	◑	●
Reinhart (2007)	●	●	◑	◑	●
Rogalski (2009)	●	○	○	●	●
Rühl (2010)	○	●	○	●	●

Table 1 summarises the characteristics of the relevant approaches introduced in this chapter. None of these approaches totally fulfils all necessary requirements for a life cycle oriented evaluation of flexibility in investment decisions for automated assembly systems. The following chapter introduces a new approach for an economic evaluation of flexibility based on two main key-figures.

4. LIFE CYCLE ORIENTED EVALUATION OF FLEXBILITY IN INVESTMENT DECISIONS

As the future flexibility of assembly systems is determined within the investment decision and therefore at the beginning of the life cycle, the approach to a life cycle oriented evaluation of flexibility aims to supply support in investment decisions for assembly systems in the early phases of the systems design. The approach bases on two main key-figures. The first key-figure is the Return on automation (ROA) and the second key-figure is the Return on flexibility (ROF). These key-figures and the approach itself will be detailed in the following paragraphs.

4.1 RETURN ON AUTOMATION AND RETURN ON FLEXIBILITY

The ROA measures the cost and benefits of the assembly system with regard to its automation and the ROF measures the cost and benefits of the assembly system with regard to its flexibility level, especially considering the three types of flexibility defined in chapter 2. So, the ROF is an economic measure for the ease with which an automated assembly system can adapt to new situations.

Both key-figures, ROA and ROF are based on the definition of the return on investment. The return on investment (ROI) is the top key figure of the DuPont-System of Financial Control, developed by the company DuPont de Nemours in 1919 (Meyer, 2006). The ROI is the ratio of the earnings of a system and the total investment within a system. The earnings are the sales of the system minus the cost of sales within a period. The total investment is the sum of the permanent investment and the current assets. The ratio of the earnings and the total investment is the basis of the definition of the ROA and ROF.

The calculation of the "earnings" of the assembly system for n years is based on the net present value (NPV) approach. The NPV as a dynamic investment analysis considers the temporal variability of the Revenues and Expenses by discounting them with the required rate of interest. By using the NPV a life cycle oriented evaluation of the assembly system is possible.

A configuration of an assembly system is beneficial with regard to its automation level, if the ROA is positive and vice versa. Using the ROA, different configurations and automation approaches of an assembly system can be compared to each other. The most beneficial configuration of the assembly system is the configuration with the greatest ROA. A fair comparison of the different configurations is only possible if the comparison is based on the same basic future scenario. The basic future scenario describes the most probable future demand of products and the product range which is going to be assembled in the assembly system. For the comparison of the different configurations and their automation approach a realistic basic future scenario has to be defined (see next paragraph). Equation 1 in Figure 2 shows the input parameters necessary for the calculation of the ROA. The ROA is only a measure for an economic automation of the assembly system for the most probable scenario not considering the systems flexibility.

$$ROA = \frac{\sum_{t=1}^{T} \frac{(AS_t - OE_t - AC_t)}{(1+i)^t} - I_0}{I_0} * 100\% \qquad (1)$$

With:

- ROA = Return on Automation [%]
- ROF = Return on Flexibility [%]
- AS = Adjusted sales [€]
- OE = Operating expenses [€]
- AC = Adaptation costs in year t [€]
- I_0 = Investment in the assembly system [€]
- i = Required rate of interest [-]
- T = number of years [-]
- t = Index for the year [-]
- BS = Index for the basic future scenario [-]
- OS = Index for the optional future scenario [-]

$$ROF_{OS} = \frac{\sum_{t=1}^{T} \frac{(AS_{OS,t} - AS_{BS,t}) - (OE_{OS,t} - OE_{BS,t}) - (AC_{OS,t} - AC_{BS,t})}{(1+i)^t}}{I_0} * 100\% \qquad (2)$$

Figure 2 – Equations of the ROA and ROF

To be able to measure the facility of the assembly system to adapt to new situations at least one optional future scenario has to be defined. These optional future scenarios describe the changes of the future demand of products or the changes of the product range, which is going to be assembled in the assembly system. The optional future scenarios represent the uncertain future, which the assembly system should be able to adapt to. Examples for these changes are the introduction of a new product or product variants to the assembly system or a change in the demand of the products. The ROF measures the changes of the revenues and expenses of the assembly system in comparison to the basic future scenario, if the optional future scenario becomes real. Using the ROF, the different configuration of the assembly system can be compared with regard to their facility to adapt to the new situation. The ROF of an assembly system which is able to adapt to new situations very easily will be greater than the ROF of an assembly system which is not able to adapt to the new situation as easily. The most beneficial configuration of the assembly system with regard to the flexibility is the configuration with the greatest ROF. Equation 2 in Figure 2 shows the ROF for a specific optional future scenario.

Both key-figures are measured as the percentage of the initial investment at the beginning of the system's life cycle. The *initial investment* (I_0) includes all necessary expenses to enable the assembly system to start with the assembly process.

The revenues of the assembly system are termed as *adjusted sales* (AS). The adjusted sales are the Sales of the products assembled in the considered assembly system minus the expenses for the products which are not caused by the considered Assembly System. Expenses which are not caused by the considered assembly are for example material costs, expenses for up- and downstream production processes or selling and administrative expenses. The adjusted sales can be interpreted as the value added which the assembly system contributed to the products and the margins which can be achieved.

The expenses of the assembly system are separated into two categories, *operating expenses (OE)* and *adaptation costs (AC)*. Operating expenses include all cost categories necessary for the daily operation of the assembly system:

- Labor costs
- Energy costs
- Costs for the workspace
- Tooling costs
- Costs of maintenance
- Logistics costs
- Costs of operating supplies
- Quality costs.

While the operating expenses describe the regular expenses for the daily operations of the system, the adaptation costs describe the irregular expenses necessary for adapting the system to a new situation caused by future incidents. Examples for future incidents are the introduction of a new product or a new product variant to the assembly system. The adaptation costs are the main indicator for the flexibility of the considered assembly system. The adaptation costs are low, if the assembly system is flexible and vice versa. For the basic future scenario the adaptation costs should normally be near to zero, since the possible configurations of the assembly system have to be able to produce the demand of the basic future scenario. Cost categories within the adaptation costs are:

- Project costs
- Engineering costs
- Ramp up costs
- Adaptation investments.

4.2 METHOD FOR EVALUATING FLEXIBILITY IN INVESTMENT DECISION

The method for evaluating flexibility in investment decisions is separated into four steps (see Figure 3). The steps of the method will be detailed in the following paragraphs.

4.2.1 Definition of future scenarios

As already mentioned in the paragraph above, the ROA and ROF are calculated on the basis of different future scenarios. Thus, the first step of the method for evaluating flexibility in investment decisions is the definition of the different future scenarios. These scenarios have to be developed by experts with intense knowledge of the market in question, concerning the market development and the product strategy of the company (e.g. marketing department). The scenarios have to provide the demand of all products and product variants, which are going to be produced on the considered assembly system. Different scenarios may be a certain rise in demand or the introduction of a new product at a specific point in time. It is also possible to construct certain scenarios to specifically test the potential of only one of the types of flexibility. Different scenarios for a specific test of the volume flexibility are for example scenarios, in which only the demand of the product changes and nothing else.

In addition to the arrangement of the future scenario, the probability or likelihood of its occurrence also has to be estimated by the experts. The scenario with the highest likelihood is the basic future scenario. All other scenarios are the optional future scenarios.

4.2.2 Calculation of the ROA

The only scenario of concern for the calculation of the ROA is the basic future scenario. The calculation of the ROA needed the variables in equation 1 to be obtained. The revenues and expenses which are included in these variables have to be collected and calculated for the different configurations of the assembly system. Possible data basis for these figures are the controlling of the company and external quotations for the resources, equipments, etc. for the specific configuration of the assembly system. Based on the collected data the ROA can be calculated for the different configurations of the assembly system and an evaluation of the configurations of the assembly system concerning their automation approach is possible.

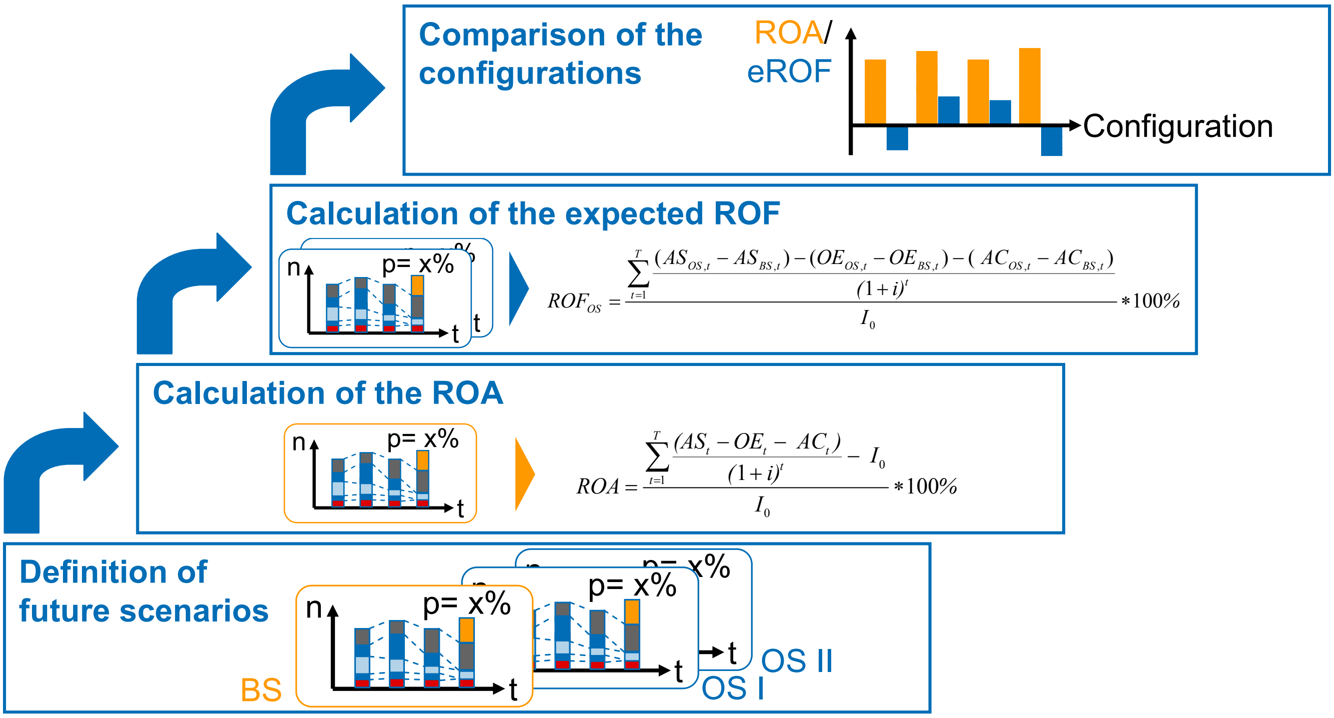

Figure 3 – Method for evaluating flexibility in investment decisions

4.2.3 Calculation of the expected ROF

The calculation of the expected ROF for the configurations of the assembly system is divided into two steps. In the first step a flexibility check of the assembly system verifies if the assembly system is capable to produce the demand of the different future scenarios. Based on the flexibility check the ROF for every optional future scenario and configuration will be calculated. In the second step the expected ROF for one scenario will be calculated by taking the average over all optional future scenarios.

First of all, it is necessary to find out whether the configurations of the assembly system are capable of producing the customer demand of the future scenarios. Therefore, a comparison between the needed product requirements of the optional future scenario and the provided capabilities of the configurations of the assembly system is made. The flexibility check compares the requirements and the capabilities regarding process accuracy, product size, tooling possibility, process time and volume capacity. The outcome of the flexibility check provides a detailed account of aspects of the assembly system, which would have to be adapted to meet the requirements of the optional future scenarios. Examples for these aspects are fixtures, tools or human capacities.

If an adaptation of the assembly system is needed the examination of the revenues of an adapted system with regard to the expenses needed to adapt the assembly system is necessary. Based on the detailed account of aspects of the assembly system, which would have to be adapted, the required adaptation costs can be calculated. Using the information from the optional future scenario and the account of aspects to be adapted, the adjusted sales and the operating expenses of the configuration of the Assembly System in the specific optional future scenario can be calculated. The investment has not changed in comparison to the basic future scenario and the adjusted sales, operating expenses and adaptation costs of the configuration of the assembly system in the basic future scenario are also established from the calculation of the ROA. Using equation 2, the ROF for the option of an adaptation of the specific configuration of the assembly system in the specific optional future scenario can be calculated. If no adaptation is necessary, the ROF for the specific optional future scenario is zero.

Finally, the expected ROF can be calculated with regard to the ROFs of the different optional future scenarios. The ROFs of all scenarios are weighted with their individual estimated likelihoods (step 1 of the method), by multiplying the ROF_{OSX} with the probability of the optional future scenario X.

Afterwards, the weighted ROFs of all scenarios are added to result in the expected ROF of one configuration of the assembly system (Equation 3).

$$eROF = \sum_{X=1}^{N} P_X \times ROF_{OSX} \quad (3)$$

With:

eROF = expected ROF [€]

P_X = Likelihood for optional future scenario X [-]

ROF_{OSX} = ROF for the optional future scenario X [€]

4.2.4 Comparison of the configurations

Based on the calculated ROA and expected ROF a comparison of the different configurations of the assembly system is possible. Within the following chapter the method is going to be applied to an industry case.

5. INDUSTRY CASE

The proposed approach is applied to an industry case of the electronic industry in this chapter. Three different configurations of an assembly system have been proposed for the production of electronic parts. The required type of flexibility for the assembly system is the volume flexibility. The assembly system has to be capable of producing an increasing number of products per year.

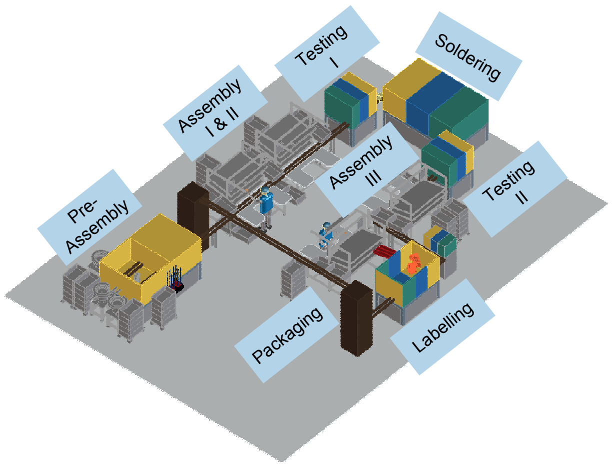

Figure 4 – Configuration A of the assembly system

Figure 4 illustrates configuration A of the assembly system. The assembly process starts with the automated pre-assembly of the products followed by two manual assembly stations, a testing rig, a soldering station, a second testing rig, a third assembly station, an automated labelling station and a packaging station. Configuration B differs from the configuration A by an automated third assembly station. Configuration C extends configuration B by an automated packaging stations. Table 2 summarizes the main information of the different configurations. Configuration A is the configuration with the lowest initial investment and capacity. Assembly station three is the first capacity constraint and the packaging station is the second capacity constraint. To extend the capacity of configuration A to the capacity of configuration C adaptation costs of 100,000 € for an automated third assembly station (capacity of configuration B) and 120,000 € for an automated packaging station are necessary. The operating expenses of the configurations can be calculated by using the variable costs per produced unit and the fix cost determined by the number of employees (labor costs are 40,000 € per employee and year). The Adjusted Sales are 3 € per produced unit for every configuration of the assembly system.

Table 2 – Configurations of the assembly system

	Config. A	Config. B	Config. C
Investment	800,000 €	900,000 €	1,020,000 €
Employees	4	3	2
Capacity/ year	305,000	320,000	330,000
Variable costs/ unit	1.72 €	1.75 €	1.82 €

While volume flexibility is the required type of flexibility of the assembly system three different scenarios with different product demands are defined in Table 3. The scenarios differ in the percentage of yearly demand growth and the likelihoods. Scenario I is the scenario with the lowest percentage growth. Because of the highest likelihood scenario A is the basic future scenario. Scenario II and III are the optional future scenarios.

Table 3 – Scenarios of product demand

Year	Scenario I (+2% / year)	Scenario II (+5% / year)	Scenario III (+10% / year)
1	280,000	288,235	301,961
2	285,600	294,000	308,000
3	291,312	299,880	314,160
4	297,138	305,878	320,443
5	303,081	311,995	326,852
Likelihood	**50%**	**35%**	**15%**

Based on the given information and on the supposition of a required rate of interest of 9 % p.a. the ROA of the configurations can be calculated.

All configurations are capable of producing the demand of the basic future scenario and adaptations of the assembly system are not necessary. Figure 5 summarizes the results of the comparison. Configuration B is the configuration with the highest ROA (5.04 %) and therefore most economic configuration for the basic future scenario. Configuration C has a low ROA because of the high initial investment and the high variable cost per unit.

For the calculation of the ROFs the information whether an adaptation of the system is necessary or not is needed. In this industry case the comparison of the product demand and the capacity of the configurations shows if an adaptation of the assembly system is needed or not. In scenario II an adaptation of configuration A in year 4 is necessary. The adaptation costs are 100,000 €. In scenario III configuration A has to be adapted twice (year 2 and 4) and configuration B has to be adapted in year 4. The expected ROFs of the different configurations are also summarized in Figure 5. Because of the adaptation in all scenarios configuration A has a expected ROF of -0.14 %. Configuration C has the highest volume flexibility and therefore also the highest expected ROF with 2.88 %.

In this industry case configuration B is the most economic configuration over all scenarios. With a sum of ROA and expected ROF of 7.48 % and an ROA of 5.04 % configuration B has the best trade-off between initial investment and volume flexibility.

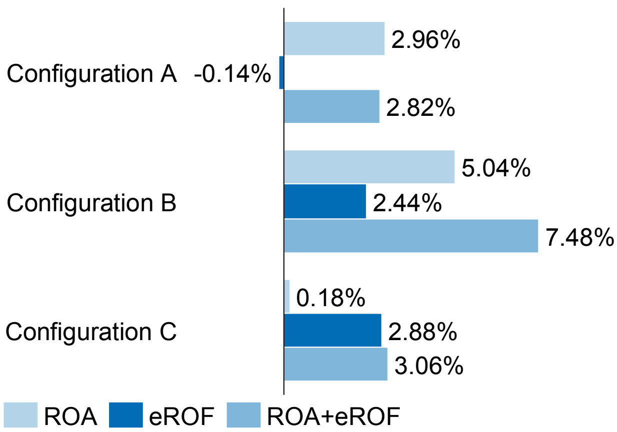

Figure 5 – Results of the comparison

6. SUMMARY AND CONCLUSIONS

Because of increasing market dynamics and competition companies in the manufacturing industries have to consider the flexibility of their manufacturing system in the early planning phases and especially in investment decisions. The approach proposed in this paper is capable of coping with the challenge of evaluating flexibility in investment decisions. This paper introduces the two main aspects of the approach:

- Definition of the key-figures Return on automation and Return on flexibility
- Introduction of the method for evaluating flexibility in investment decisions.

Further on an application in an industry case has verified the relevance and potential of the approach.

The challenges within the new approach will be on the one hand the implementation of the method within an IT-application and on the other hand the integration of such an application into the structure of existing companies decision processes. The IT-application has to provide different tools. Beside a calculation tool tools for the definition of the different scenarios and the estimation of their likelihoods as well as a tool for the flexibility check of the system are essential. To ensure an easy integration of the IT-application within a company a central sever with different front-end types is one possibility for an implementation of the approach. An efficient collection of the necessary data is very important for the integration of the application. Therefore a standardized application for the data collection is necessary. On the one hand this data collection application has to be able to cope with different data sources like ERP-systems, existing databases, or companies' experts. On the other hand the data collection application has to be able to select the data in the right quality which are essential for the evaluating approach. The data collector module suggested by Georgoulias et al (2009) is an example for a data collection application.

The proposed approach is capable of evaluating volume, mix and product flexibility of automated assembly systems and gives companies the support for a well-informed investment decision.

7. ACKNOWLEDGMENTS

The new approach is a result of the "COSMOS" (Project N. 246371-2) research and development project, which is funded by the European Commission within call FP7-NMP-2009-SMALL-3 as part of the Seventh Framework Programme (FP7). "COSMOS" is the acronym for "Cost-driven Adaptive Factory based on modular self-contained factory units". The main objectives for "COSMOS" are the design, development and implementation of a distributed control system for the management of a factory with a flexible, modular and evolvable automation (www.cosmosproject.eu).

REFERENCES

Abele E., Liebeck T., Wörn A., "Measuring flexibility in investment decisions for manufacturing systems", *Annals of the CIRP*, Vol. 55, No. 1, 2006, pp 433-436

Alexopoloulos K., Mourtzis D., Papakostas N., Chryssolouris G., "DESYMA: assessing flexibility for the lifecycle of manufacturing systems", *International Journal of Production Research*, Vol. 45, No. 7, 2007a, pp 1683-1694

Browne J., Dubois D., Rathmill K., Sethi S.P., Stecke K.E., "Classification of flexible manufacturing systems", *The FMS Magazine*, Vol. 2, No. 2, 1984, pp 114-117

Chryssolouris G., "Flexibility and its measurement", Annals of the CIRP, Vol. 45, No. 2, 1996, pp 581-587

Chryssolouris G., "Manufacturing systems: theory and practice", 2nd Edition, Springer-Verlag, New York, 2006

Cox T., "Towards the measurement of manufacturing flexibility", *Production & Inventory Management Journal*, Vol. 20, No. 1, 1989, pp 68-89

De Toni A., Tonchia S., "Manufacturing flexibility: a literature review", *International Journal of Production Research*, Vol. 36, No. 6, 1996, pp 1587-1617

Georgoulias K., Papakostas N., Mourtzis D., Chryssolouris G., "Flexibility evaluation: a toolbox approach", *International Journal of Computer Integrated Manufacturing*, Vol. 22, No. 5, 2009, pp 428-442

Meyer C., "Betriebswirtschaftliche Kennzahlen und Kennzahlen-Systeme" 3rd Edition, Verl. Wiss. & Praxis, Sternenfels, 2006

Newman W.R., Hanna M., Maffei M.J., "Dealing with the uncertainties of manufacturing: flexibility, buffers and integration", *International Journal of Operations and Production Management*, Vol. 13, No. 1, 1993, pp 19-34

Reinhart G., Krebs P., Rimpau C, Czechowski D., "Flexibilitätsbewertung in der Praxis: Einsatz einer Methode zur lebenszyklusorientierten Bewertung von Flexibilität in der Produktion", *wt Werkstattstechnik online,* Vol. 97, No. 4, 2007, pp 211-217

Rogalski S., Ovtcharova J., "Flexibilitätsbewertungen von Produktionssystemen: ecoFLEX – eine branchenübergreifende Methodik", *Zeitschrift für wirtschaftlichen Fabrikbetrieb*, Vol. 104, No. 1-2, 2009, pp 64-70

Rühl J., "Monetäre Flexibilitäts- und Risikobewertung: Stochastische Simulation von Produktionssystemen während der Produktentwicklungsphase", Shaker Verlag, Aachen, 2010

Schuh G., Gulden A., Wemhöner N., Kampker A., "Bewertung der Flexibilität von Produktionssystemen: Kennzahlen zur Bewertung der Stückzahl-, Varianten- und Produktänderungsflexibilität auf Linienebene", *wt Werkstattstechnik online*, Vol. 94, No. 6, 2004, pp 299-304

Schuh G., Wemhöner N., Friedrich C., "Lifecycle oriented evaluation of automotive body shop flexibility", In: Zaeh M.F. et al (eds), CARV 2005. Utz, Munich, 2005

Seidel H., Garrel J. von, "Flexibilität in der Produktion kleiner und mittelständischer Unternehmen", *wt-Werkstattstechnik online*, Vol. 101, No. 4, 2011, pp 278-279

Sethi A.K., Sethi S.P., "Flexibility in manufacturing: a survey", *Journal of Flexible Manufacturing Systems*, Vol. 2, No. 4, 1990, pp 289-328

Suarez F.F., Cusumano M.A., Fine C.H. "Flexibility and performance: a literature critique and strategic framework", Sloan School WP# 3298-91-BPS, MIT, 1991

Zäh M.F., Sudhoff W., Rosenberger H., "Bewertung mobiler Produktionsszenarien mit Hilfe des Realoptionenansatzes", *Zeitschrift für wirtschaftlichen Fabrikbetrieb,* Vol. 98, No. 2, 2003, pp 646-651

Zäh M.F., Bredow M., Möller N., Müssig B., "Methoden zur Bewertung von Flexibilität in der Produktion", *Industrie Management*, Vol. 22, No. 4, 2006, pp 29-32