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A. Weckenmann and G. Akkasoglu

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Maturity Determination and Information Visualization of New Forming Processes considering Uncertain Indicator Values

A. Weckenmann, G. Akkasoglu

*Chair Quality Management and Manufacturing Metrology,
Naegelsbachstrasse 25, 91052 Erlangen, Germany
E-mail: akkasoglu@qfm.uni-erlangen.de*

Abstract. Operative or strategic decision-making during the development of novel objects is complicated and mostly based on fuzzy assumptions or uncertain information. Consideration of information uncertainty would enhance the reliability of any evaluation of the current development status of new objects. Decisions could be made with a higher safety. The development status equates to the maturity and is to be assessed by previously elicited indicators in relation to phase-dependent requirements. Within this paper, a reference-model based maturity method considering uncertain indicators is introduced for enabling the determination and assurance of the development status in a quantitative and systematic way. The method is applied within the development of a novel metal forming process namely the Sheet-Bulk Metal Forming, which aims to unite the advantages of sheet metal and bulk metal forming. Additionally techniques for visualizing the determined maturity value are proposed to support subsequent decision processes in the context of maturity assurance or improvement.

Keywords: Maturity method, Sheet-bulk metal forming, Fuzzy Logic, Information visualization.

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INTRODUCTION

Increasing competitive pressure and customer demands are met by today's companies through development of innovative products and processes. The design and analysis of novel development objects like products or processes are complex due to low previous knowledge and distinct creative phases. Operational decisions within the design process are mostly based on uncertain and fuzzy information about the development status. Especially in the early stages of development the number of recognizable and thus exactly quantifiable features is low (Figure 1, left). Paradoxically, in these early stages the number of influenceable features is to be classified as high. Towards the end of development the number of recognizable features raises, but the number of influenceable parameters decreases together with the change effort. That relates to the increasing modification effort according to the rule-of-ten, which indicates that the (financial) effort for changes is increasing tenfold with each development stage (Figure 1, right).

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FIGURE 1. Paradox in development processes [1] (left) and Rule-of-Ten (right)

A reliable determination of the development status is hindered by the high information uncertainty concerning the assessment of indicators during the early phases of development (Figure 2, left). The information uncertainty is influenced by the complexity of the development, the level of knowledge and the recognizable features of the system to be developed. In early design phases there exists a low level of knowledge and the number of recognizable and thus quantitatively assessable characteristics of the development object is small [1]. It can be assumed that towards the typical “design freeze”, wherein important features of the development object are bindingly defined, the information uncertainty decreases continuously until it stagnates within the conceptual level of development. After the “design freeze” the number of recognizable features raises further in the test phase and the information uncertainty about the system to be developed decreases.

Due to the information uncertainty about the development status, in the early stages of development it is very likely that false or ineffective decisions are made or necessary changes are initiated too late. This can lead to a delayed release of serial production and a reduced efficiency due to increased resource consumption or low quality of the development object at the start of serial production (Figure 2, right). To support the preventive decision-making and problem solving processes within early development, a method for the evaluation and assurance of maturity has been designed.

FIGURE 2. Assumed curve progression of information uncertainty while development (left) and the effect of preventive changes in early development phases (dashed lines) (right)

The adaption of fuzzy logic takes into account the information uncertainty in the assessment of maturity relevant indicators and the development status is determined more reliably. The indicators are elicited based on a reference model of the development and manufacturing process. The additional application of visualization techniques for presenting the determined maturity provides adequate information for subsequently initiated problem-solving processes.

MATURITY METHOD CONSIDERING UNCERTAIN INPUT PARAMETERS

The maturity method in consideration of uncertain indicators aims to increase the transparency of the development status by providing a reliable and quantitative basis for operative or strategic decisions in the early stages of development of an innovative product or process. Thus, development objectives can be met in a more efficient way with the same or reduced development time. The term of maturity in the context of this paper is defined as

the assessed development status of an object (product or process) at a specific time t_i by characteristic indicators in relation to phase-dependent requirements on them.

The maturity method identifies the current development status by evaluation of selected indicators with the help of a fuzzy logic approach. Thus information uncertainties within early development stages can be considered. Figure 3 shows the principle of the maturity method by illustrating the total maturity in dependence of the specified dates of maturity determination t_i (e. g. milestones or quality gates). The graph of the set-maturity results from requirements specified for each development phase. The final value of the set-maturity represents the target level of maturity, which is to be achieved towards the end of the project for fulfilling its general objectives. For the maturity progression a continuous graph is assumed, which can have both positive and negative gradients. With the discrete-time determination of maturity, quality management (QM) methods are to be derived and applied taking into account the PDCA cycle for assurance and control of the development status. Thus the maturity progress can be influenced positively and the target-maturity can be achieved within a shorter development time.

Maturity relevant indicators for the phase-dependent assessment of the maturity are elicited on the basis of a reference model of the development process and the system to be developed (Figure 4). The definition of reference models is non-ambiguous in the literature [2]. Within this manuscript a reference model is defined according to [3]:

A reference model is an abstract process or system model with elementary operations or components for a defined target, which has a status of recommendations for the reuse and its validity is defined by its perceived adequacy to subject-specific purposes.

The design of a reference model for the development process encompasses comprehending, structuring and modeling of elementary planned activities with the help of an adequate and standardized language (e. g. UML, IDEF, EPC). The reference model of the system to be developed encompasses elementary components in relation to the planned final status of the system and is also to be modeled with an adequate and standardized language (e. g. SysML). Parameters and the values of the

components are also to be integrated in the reference system model. This permits also including specific requirements on the final system status within the reference model.

FIGURE 3. Principle of the maturity method

With the help of the reference model of the development process progress indicators can be defined, which are evaluating the advancement of selected process steps, e. g. “Approach of the purchase order”. The reference model of the system to be developed permits the definition of status indicators, which are assessing the development status of selected system components. For this purpose, firstly the output parameters of the components to be monitored and their input parameters are to be collected within a cause-and-effect matrix. Subsequently known and assumed relationships between the input and output parameters are gathered in the matrix.

The selected indicators are to be characterized and assigned to specific maturity levels within the Maturity Level Matrix. The aim of the Maturity Level Matrix is to support the maturity assessment on the one hand and the maturity assurance on the other. With integrated methods and tools of QM to each maturity level, a systematic management of the development status in the case of deviations from the set-values is provided.

FIGURE 4. Design of the maturity method

The design of the Fuzzy System comprises the uncertainties and fuzzy assumptions within the maturity determination by parameterizing its variables like “number of

linguistic terms per indicator”, “type and support of the membership function” or “defuzzification method”. Possible sources of uncertainty can be imperfect or incomplete knowledge (limited view on a system because of its complexity / model-based development), acquisition errors (quantitative errors in measures), lexical vagueness and linguistic inexactitude (subjective appraisal) as well as stochasticity [6]. For the design of the inference matrix of the fuzzy system the preliminary prepared cause-and-effect matrix can be applied.

Having determined the development status an adequate provision of the created data and information by visualization can support decision or problem solving processes. Unsorted and extensive data is to be organized and structured task-specific. Possible interrelations between the assessed development status, indicators, assuring measures and the reference model are to be placed in the foreground to simplify decision-making. Relevant maturity data is to be presented by an applicable visualization technique after the preprocessing of data. With perceiving and interpretation of the viewer, cognitive thinking processes result in decision-making for problem solving. On the basis of the decision, measures for gaining new data can be initiated or links between data can be added or changed [7].

The maturity method will be applied within the framework of the transregional collaborative research centre 73 (www.tr-73.de), which develops a novel metal forming process namely the Sheet-Bulk Metal Forming. Before the application of the method, characteristics of the novel metal forming process are presented in the following chapter.

DEVELOPMENT OF THE SHEET-BULK METAL FORMING

The steady increase of global competitive pressure and customer requirements for design, functionality and efficiency of products can be faced effectively with the design of new manufacturing processes. Uniting different manufacturing methods can increase the product spectrum and the process robustness by reducing the process chain. The latter also leads to an enhanced efficiency of the manufacturing process with reduced through-put time. Especially the metal forming processes have a wide dissemination in global industry and are characterized by high resource efficiency particularly through high material utilization. Thus the extension of existing process limits of metal forming processes is of particular interest. The development of the novel Sheet-Bulk Metal Forming (SBMF) aims for uniting the advantages of sheet and bulk metal forming processes in terms of flexibility and possibilities. By combining the different metal forming processes the limitations of each one can be exceeded and the workpiece complexity can be increased. Customer requirements considering quality, cost and time of formed workpiece can be met more efficiently. The SBFM is defined as

the plastic changing of the shape of a plain semi-finished product not changing the specimens integrity. During the forming process both two- and three-axial strain- and stress-conditions as well as changes in shape occur simultaneously or shortly after each other. [8]

The task of the new metal forming processes is manufacturing geometrically complex functional components out of sheet metal with an initial thickness of up to 3

mm in order to achieve the objectives shown in Table I. The development of the new forming process has challenging properties, which have to be faced to be successful. The design process of the SBMF is characterized by simultaneous engineering and transregional collaborative work. Furthermore the development of the SBMF possesses the characteristics presented in Table 1.

TABLE 1. Objectives and characteristics of the SBMF process.

Sheet-Bulk Metal Forming	
Objectives	Characteristics
Functional extension of sheet metal parts	Identification of cause-and-effect relationships
Increase in workpiece complexity	Investigations about the variances of products produced
Expansion of the design options	Phases of simulation and experimentation
Improvement of economic efficiency	Iterations between simulations and experiments
Shortening of process chains	Design of tools (hard materials)
Increase of process robustness and reliability	Extensive generation of knowledge

These challenges and the high degree of cross-linking of work during the development complicate decision-making due to the low transparency of the overall development status. Exemplary it is difficult to decide, when the new forming process is mature enough to ensure the quality of the manufactured products reliably so that the start of production can be released.

APPLIANCE OF THE MATURITY METHOD IN THE DEVELOPMENT OF SBMF

Reference Model

The reference model for the development of new metal forming processes has been designed and consequently validated within the development for the SBMF. For representing the development activities the Unified Modeling Language UML and its Activity Diagram in Version 2.4 [9] has been applied. The distinctive phases of simulation and experiments have been considered as well as the typical iterations of optimization within the development while modeling the reference process model. For clarity the main phases of the reference model of the development process of new metal forming processes and the expected results in each phase are shown in Figure 5 [10].

The reference model of the manufacturing process to be developed has been modeled with the Block Definition Diagram of the Systems Modeling Language SysML in Version 1.2 [11] and enfoldes the input material, semi-finishing manufacturing process, semi-finished part, combined manufacturing process and the work piece.

FIGURE 5. Main phases of the reference model for the development process of new metal forming processes

Figure 6 illustrates the principle of the reference model for the aimed manufacturing process combining deep drawing and swaging. The process steps and the target variables, which are significant for determining the development status, are enlisted in the figure as well as considered influencing parameters. The input material and the semi-finishing process are not included in the figure for reasons of clarity.

FIGURE 6. Reference model of the combined manufacturing processes deep drawing and swaging

Maturity Indicators and the Maturity Level Matrix

Maturity relevant indicators considering the progress of the SBMF are deduced with the help of the reference process model for new metal forming processes (Figure

5). For facilitate the maturity determination, the indicators are summarized in a Maturity Level Matrix, wherein the values of the characteristics of each progress indicator are assigned to specific maturity levels. The Maturity Level Matrix additionally supports the maturity assurance with integrated recommendations for methods, which can be applied for increasing the maturity after having determined the deviations of the indicators from their set-values. Following progress indicators and their characteristics have been deduced for the development of the SBMF:

- *Definition of Objectives (Quality and manufacturing objectives):* Current state analysis, SMART definition of objectives, communication of objectives
- *Simulation model:* Model verification, model validation, uncertainty analysis
- *Investigation of tool concepts:* Concept definition, virtual/experimental investigations, range of investigations
- *Process analysis:* Process robustness, comparison to the state of the art, process evaluation
- *Product quality:* Product design, possible product spectrum
- *Supplier Management:* Assessment and selection, contract specifications
- *Information handling:* System view, content view

The assessment of the maturity with the progress indicators is carried out by evaluating their characteristics. For a principle illustration of the Maturity Level Matrix the indicator “Process Analysis” in consideration of its characteristics is shown in Table 2.

TABLE 2. Maturity Levels of the indicator “Process analysis”

Indicator	Maturity Level			
	0% - 15%	15% - 50%	50% - 85%	85% - 100%
Process analysis	Cause-and-effect relationships are neither assumed nor documented in some way	Cause-and-effect relationships are documented within a cause-and-effect matrix	Cause-and-effect relationships are evaluated statistically in virtual experiments with the help of DoE	Cause-and-effect relationships are evaluated statistically in experiments with the help of DoE and parameterized for a robust process
	Development of manufacturing process is done w/o comparison to currently available processes	Development of manufacturing process is done with qualitative evaluation in comparison to currently available processes	Development of manufacturing process is done with qualitative evaluation of technical and economic aspects in comparison to currently available processes	Development of manufacturing process is done with quantitative and operative evaluation of technical and economic aspects in comparison to currently available processes
	The developed process evaluation not evaluated	Process evaluation is done qualitatively on the basis of non-documented indicators	Process evaluation is done by determining the process capability	Process is evaluated with the determined process capability and the evaluation of the process integration degree in comparison to set-objectives

With the help of the reference model for the manufacturing process (Figure 6) the status indicators for determining the maturity are represented by the target variables:

- Dimensional Accuracy
- Surface Quality

- Shape Accuracy
- Efficiency

Their evaluation will be done with the parameterization of operative indicators, which are represented by input, tool and process parameters. The correlations of the operative parameter with the target variables are firstly gathered in a cause-and-effect matrix, wherein following evaluations scheme has been adopted:

- Strong negative correlation: -2
- Negative correlation: -1
- No correlation: 0
- Positive correlation: +1
- Strong positive correlation: +2

The gained cause-and-effect matrix provides the assumed and within the development of the SBMF confirmed influences on the target variables. Exemplary the “Dimensional accuracy” correlates negatively with the “Deep drawing speed” (-1), because a high deep drawing speed leads to an insufficient dimensional quality of the product manufactured. The cause-and-effect matrix also facilitates the acquisition of complex and analytically difficult to describe relationships like the influence of the lubrication on the target parameters.

Design of Fuzzy System for maturity determination

On the basis of the Maturity Level Matrix and the cause-and-effect matrix two fuzzy systems with its linguistic variables, linguistic terms, membership functions and inference matrices for assessing the maturity with the progress indicators and the status indicators have been designed with the use of the software fuzzyTECH 5.71d. For each progress indicator and its characteristic as well as for the status indicators and their operative parameters linguistic variables have been constructed. Their linguistic terms have been implemented primarily with trapezoidal and triangle membership functions. Figure 7 shows the standardized parameterization of the membership functions for the input and the output variables of each fuzzy system for the progress and status indicators. The input aggregation is carried out by a GAMMA-Operator, which is suitable for modeling the human decision processes [12]. The GAMMA-operator is parameterized to $\gamma = 0.3$, what leads to a compensatory character of the transfer characteristic [12]. For the output aggregation the Max-operator is selected. The Center of Area (CoA) method is used for the defuzzification step to gain the “best compromising value” of the fuzzy output variable [12].

FIGURE 7. Parameterizing of the input and output variables for the fuzzy systems of the progress and status indicators

The relationships between the input and output variables of the fuzzy systems for the indicators have been generated semi-automatic with the help of the software. The correlation of the assessed characteristics with the progress indicators is set to very high. On the basis of the compiled cause-and-effect matrix the correlations of the operative parameters and the status indicators are communicated to the software. The number of IF-THEN-rules for the rule block of the fuzzy system to be established increases with the number of defined linguistic terms per linguistic variable and the number of linguistic variables. For reducing the design effort of the fuzzy system dramatically and for enabling a comprehensive design of the fuzzy logic rules intermediate variables, which are classifying the available input variables of the fuzzy system, have been used [12].

The determination of the maturity is carried out with the generated fuzzy systems within the specific date t_6 . For determining the maturity the input variables are rated in a quantitative manner with values between 0 % and 100 %. An appropriate visualization of the current and set-values supports decision-making for improvements. A visualization concept for the determined maturity thus is introduced in the next chapter.

Visualization Concept for the Determined Maturity

In terms of providing information for an efficient data evaluation it is necessary to present the developed maturity data adequately. For this purpose different kinds of charts and visualization types are suitable, such as the course map for temporal relations or the bar graph for current states of certain features. Decisions on the basis of information can

be influenced by their preparation. Hence a visualization concept for the representation of the determined maturity values have been designed which has been implemented for reasons of efficiency in a cockpit system [13]. Figure 8 shows the designed cockpit visualization which takes account of the charts for the actually assessed progress and status indicators of the development for SBMF process with the table of their current and required set-values for the specific date t_6 . Also the charts for the overall maturity determined in previous phases are provided.

The bar graph for the specific date t_6 shows the determined values and set-values of each indicator in a sorted wise. For presenting the deviations of the indicators from their required values a sorted circle diagram is applied. The overall maturity of the up to now evaluated phases is on the one hand illustrated in a diagram with the current values on the x-axis and the set-values on the y-axis. The bisecting line represents the equality of the current and set-values. Below the bisectrix the current overall maturity value is lower as the required one. Above the line the current maturity is higher than the set-value. Additionally the so far assessed overall maturities and their required values are displayed in a time graph in relation to the specific dates t_i .

The so far assessment and visualization of the maturity indicators for the development of the SBMF process shows up the largest deviations of the requirements and where need of action exists. The indicator "Process Analysis" possesses the largest discrepancy of its required value. Measures for the assurance of this indicator can be deduced from the Maturity Level Matrix. Exemplary the increased appliance of Design of Experiments (DoE) under real conditions can support the identification of statistically significant cause-and-effect relationships. Furthermore the analyzed cause-and-effect relationships of the manufacturing process can facilitate increasing its process capability.

FIGURE 8. Parameterizing of the input and output variables for the fuzzy systems of the progress and status indicators

SUMMARY AND OUTLOOK

The introduced maturity method permits the quantitative determination of the current development status based on specific indicators taking into account their uncertainty during assessment, which is particularly high in early development phases. Thus necessary interventions into the development can be shown already in early development stages and decision can be made on the basis of reliable data.

Within this paper the design and principle of a maturity method considering uncertain input data by use of fuzzy logic has been presented. Additionally, the principle and use of an adequate visualization of generated data is proposed. The maturity method has been applied exemplarily within the development of the novel Sheet-Bulk Metal Forming (SBMF) process. The development process and the system model, which in conjunction represent the reference model of the SBF, are constructed to enable deducing maturity relevant progress and status indicators. Based on the introduced Maturity Level Matrix for the progress indicators and the proposed cause-and-effect matrix for the correlations between the operative parameter and the status indicators the fuzzy system for considering uncertainty in evaluation of the indicators has been designed. The actual development status of the SBF has been determined with that fuzzy system. Appropriate measures for assuring the maturity can be deduced from the Maturity Level Matrix. Generated maturity data has been presented efficiently with a cockpit-visualization in order to support decision-making.

For a user oriented provision of results and to increase operability of the maturity method within development projects, the method is to be integrated in a computer-based information system. This allows an aim-oriented application of the maturity method and increases its efficiency as well as usability. In addition a software application can implement further communication possibilities like instant messaging, because insufficient communication is often regarded as the main factor for unsuccessful development results [14].

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