A Strategic Evaluation Approach for Defining the Maturity of Manufacturing Technologies

G. Reinhart, S. Schindler

Abstract**—**Due to dynamic evolution, the ability of a manufacturing technology to produce a special product is changing. Therefore, it is essential to monitor the established techniques and processes to detect whether a company's production will fit future circumstances. Concerning the manufacturing technology planning process, companies must decide when to change to a new technology for maintaining and increasing competitive advantages. In this context, the maturity assessment of the focused technologies is crucial. This article presents an approach for defining the maturity of a manufacturing technology from a strategic point of view. The concept is based on the approach of technology readiness level (TRL) according to NASA (National Aeronautics and Space Administration), but also includes dynamic changes. Therefore, the model takes into account the concept of the technology life cycle. Furthermore, it enables a company to estimate the ideal date for implementation of a new manufacturing technology.

Keywords**—**Maturity Assessment, Manufacturing Technology Planning, Technology Life Cycle, Technology Readiness Level.

I. INTRODUCTION

MANUFACTURING companies are facing many dynamic changing and influencing factors, such as market demand or product life cycles [1]. In order to compete, they must permanently apply the most efficient and effective techniques and processes [2]. However, there exists a dynamic range of available technologies because of the evolutionary development through which manufacturing processes pass [3]. During this dynamic change, the competitive potential or the maturity of a technology varies as well as the number of users who are ready for implementation [4]. This evolution can be described as a kind of technology life cycle [5].

For these reasons, manufacturers need to detect whether the technologies used in their production will fit future requirements, such as quantity fluctuations within the product life cycles or increasingly strict environmental regulations [3]. Other potential external technologies may exist which accomplish production requirements in a closer to optimal way.

"Optimal" in this context refers to fulfilling cost-effective and strategic objectives. According to Porter, technology leadership is one particular method for companies acting in high-wage countries to maintain competitiveness [6]. Sourcing new manufacturing technologies enables manufacturers to hold and increase their competitive advantages. At the same time, new processes determine the company's options by constraining future product and production costs, for example [7]. However, organizational and technological risks thereby also increase [8]. In order to minimize these risks, only technologies which offer a certain measure of maturity (technology readiness level) should be used in the production environment [9]. In this context, "maturity" refers to the stage of development of a manufacturing technique or process.

This article presents a strategic evaluation approach for defining the maturity of manufacturing technologies by using defined stages. The model is based on the technology life cycle according to Ford & Ryan [4] and considers selected technology readiness levels (TRL) according to NASA [10]. After introducing these concepts, the approach for defining the maturity of manufacturing technologies is presented. The article concludes with a rough summary and conjecture on future research work.

II. STRATEGIC TECHNOLOGY PLANNING

Regarding the planning process for manufacturing technologies, the planning horizon can be divided roughly into short- and long-terms (Fig. 1). The operational technology planning takes place in the short-term. Herein, the planning data consist of precise information, such as defined unit quantities or detailed geometry dimensions.

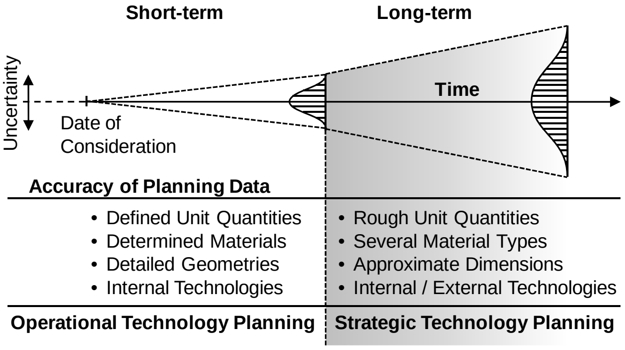

Fig. 1 Planning Horizon of Operational and Strategic Technology Planning (based on [11])

In contrast, strategic technology planning focuses on the In the context of operational technology planning, only internal technologies are considered for application. long-term horizon. Compared to the operational planning, the

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uncertainty in the strategic planning process increases while the accuracy of the planning data declines. In contrast to operational technology planning, the strategic aspect includes the possibility of considering internal as well as external manufacturing processes and techniques for future production.

In order to determine which external technologies are worth being considered for application within the company, a detailed evaluation is needed. Thereby, several evaluation criteria such as profitability or feasibility have to be considered. One main aspect is the evaluation of the technology's maturity. The answer to the question of whether a technology is sufficiently matured must first be answered. In this context, a method is needed for estimating and quantifying the maturity of a technology even though the information about the processes lacks precision.

III. MANUFACTURING TECHNOLOGY LIFE CYCLE

Analogous to the biological life cycle of plants and trees, manufacturing technologies also exhibit cyclical behavior what can be described by the concept of technology life cycles [4]. Along this life cycle, a technology exhibits very different characteristics, such as the accumulative exploitation of competitive potential, as shown in Fig. 2, or changing process stabilities as seen in [3]. Various models exist in the scientific literature to describe these different characteristics. Each considers very special attributes. Mathematical models of technology diffusion, for example, take into account the number of companies who use a special manufacturing technology. Other models include the possibility of reaching competitive advantages within several development stages [12].

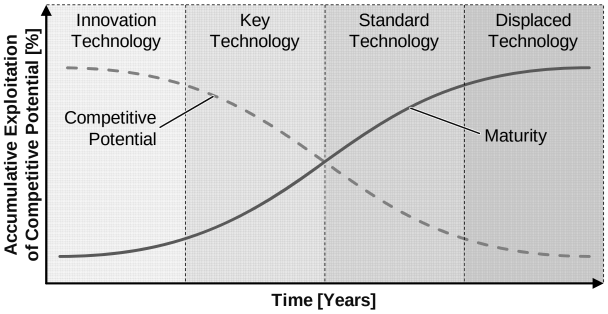

Fig. 2 Technology Life Cycle by means of Competitive Potential and Maturity (based on [3], [4])

One model which considers the strategic aspects of using a technology is the Ford & Ryan model [4]. According to Ford & Ryan, the possibility of achieving competitive advantages strongly depends on the maturity of a technology. The model classifies the life cycle of a technology into four different strategic roles.

Thereby, the accumulative exploitation of competitive potential on the one hand and the growth of maturity on the other hand are considered. Fig. 2 illustrates the technology life cycle model of Ford & Ryan. Herein, the competitive potential and the maturity of technology are plotted over time. Along the life cycle, the four different stages are passed through: innovation technology, key technology, standard technology and displaced technology. Depending on the current stage, a manufacturing technology exhibits different properties [3]. While standard technologies offer great productivity, displaced technologies have become obsolete and are no longer worth being used due to inefficiency. Through using and refining a manufacturing technology by one or several companies, the maturity increases while the competitive potential decreases. Competitive potential in this context means the possibility to gain advantages compared to other competitors, such as reduced processing times, decreased production costs or the development of new product features.

For defining the current stage of a manufacturing technology and assessing its maturity, Ford & Ryan provide some qualitative indicators, such as the time needed for further development or the duration of competitive advance [4]. Nevertheless, qualitative factors only offer a rough estimation for the maturity of a manufacturing technology. For example, the indicators presented by Ford & Ryan [4] are often identical for more than one stage. Thus, the indicator investment in technology development affects the innovation technology, standard technology and displaced technology states of the technology life cycle concept in the same way.

The limits of the four stages are also not particularly clear as there are no constraints concerning time or accumulative exploitation. Moreover, the ability for describing and analyzing the previous development is limited. Forecasting future behaviour for these reasons is nearly impossible [12]. In this context, the model has to be enlarged to include temporal development. The model is not able to define the maturity of a manufacturing technology.

IV. TECHNOLOGY READINESS LEVEL

In the early 1980s, the National Aeronautics and Space Administration (NASA) developed a model for defining the current maturity stage of application components ("technology readiness levels" (TRLs)) for aerospace and astronautic systems [10]. The main purpose of using technology readiness levels is to support a company in making decisions concerning the development and the application of technologies.

Along with enabling a maturity assessment for product technologies, the model allows a comparison of maturity between different types of technology. Depending on the maturity, each TRL is characterized by singular types of observed and reported principles, activities and concepts or prototypes. Thereby, classification is primarily based on questionnaire responses and expert interviews within the company at issue. The first definitions included only seven levels and this number was later expanded to nine.

TRL 1	Basic principles observed and reported
TRL 2	Technology concept and / or application formulated
TRL 3	Analytical and experimental critical function and / or characteristic proof-of-concept
TRL 4	Component and / or breadboard validation in laboratory environment
TRL 5	Component and / or breadboard validation in relevant environment
TRL 6	System / subsystem model or prototype demonstration in a relevant environment (ground or space)
TRL 7	System prototype demonstration in a space environment
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)
TRL 9	Actual system flight proven through successful mission operations

Fig. 3 Technology Readiness Level according to the NASA [10]

Generally, the more developed a technology is, the higher is its readiness level (TRL). Beginning with formulated physical principles through validation prototypes, a technology passes through the nine levels from TRL 1 to TRL 9 up to a functional demonstration in successful mission operations. The nine technology readiness levels for component technologies being used in the aeronautics industry, according to NASA, are shown in Fig. 3.

The model of TRL shows some limitations when attempting to forecast the date at which a technology is ready for use. Defining the different TRLs depends on questionnaire outcomes and can therefore be very subjective [13]. Furthermore, the output consists of one single value, which complicates the evaluation and consideration of the historical development of a technology. This also constrains the observation of the development velocity, for example.

V. TECHNOLOGY MATURITY ASSESSMENT

One model that helps to simultaneously define the maturity of a manufacturing technology at different levels is the technology maturity assessment (TMA) according to Brousseau *et al.* [12]. Hereby, the approach of TRL was transferred to manufacturing processes and techniques. As shown in Fig. 4, Brousseau *et al.* reduced the TRLs from nine to seven. Thereby, the TMA model enlarges the principles of the TRL from NASA in focusing on micro as well as nano manufacturing processes and techniques. Furthermore, it takes into account all TRLs for maturity assessment.

The main objectives of the TMA model are to support the successful implementation of manufacturing technologies. Thereby, the model does not only suggest one single value for defining the maturity of a technology, but also offers an evaluation of the stage of development in every technology readiness level in a kind of maturity profile. Beginning at basic technology research activities, the development of a technology thus passes through several feasibility and demonstration stages.

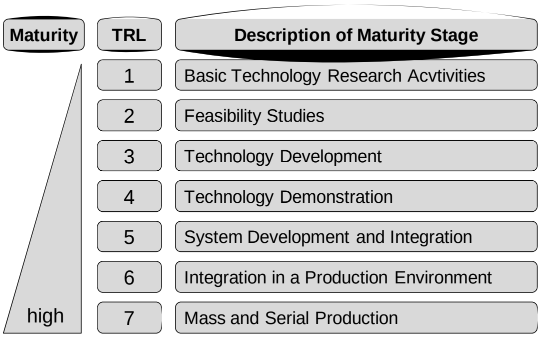

Fig. 4 TRLs of the Technology Maturity Assessment for Micro and Nano Manufacturing Processes (based on [13])

After the integration into real production resources and environments, the technology is finally used in a company’s mass and serial production. The perception of the TMA shows that the further development of a manufacturing technology does not only proceed in one stage, but rather in all seven levels at the end. Depending on research investments, the different stages mature in varying speeds.

Generally, the TMA model allows for the identification of the technology maturity that is not specific to a particular company, but rather is the result from several companies of one industry sector. For example, Fig. 5 shows the maturity profile of a micro manufacturing technology that is the result from interviews with both technology developers as well as users in the micro manufacturing industry.

As illustrated in Fig. 5, the research and development efforts of the seven TRLs are each quantified in percentages. In raising technology readiness levels, the research and development efforts tend to decrease. This is obvious because lower technology readiness levels are observed earlier than higher ones. Furthermore, the seven TRLs are ascending based on each other. For implementing technology demonstrators feasibility studies have to be examined before, for example.

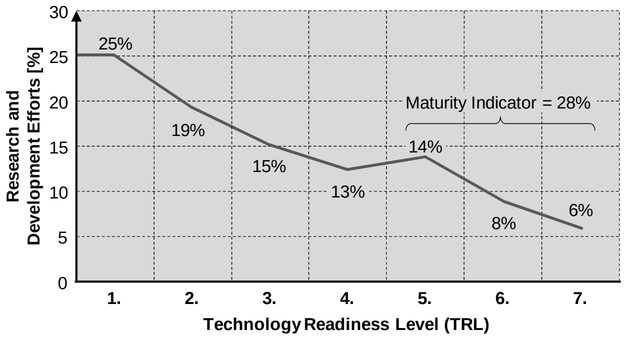

Fig. 5 Maturity Profile by Means of Research and Development Efforts of a Micro Manufacturing Technology (based on [13])

Next to the maturity profile, Brousseau *et al.* also present a special maturity indicator, a kind of measure for the suitability of a commercially exploitable technology [13]. Hereby, the maturity indicator results from the sum of the research and development efforts of the last three TRLs.

These three stages focus on the technology development and integration into a real production environment. The higher the maturity indicator, the more mature the technology is and the safer the operational integration of the process in the production system can be realized. Regarding the planning process of manufacturing technologies from a strategic point of view, the TMA model provides a useful basis. The maturity profile of the different technology readiness levels shows, in particular, development gaps for further development. The TMA does look at the different TRL explicitly, but does not consider the temporal development. However, .he maturity effort of the seven TRLs is changing. Hence, forecasting future behaviors for a technology is not possible. Furthermore, no influencing factors exist that allow the quantification of a single technology readiness level.

VI. STRATEGIC EVALUATION APPROACH

To unify the advantages of the models of Ford & Ryan [4] and Brousseau *et al.* [13], the two concepts must be combined. Furthermore, indicators and limits have to be identified and formulated in order to permit maturity definition, forecasting and quantification. Depending on the limits, the classification of the single technology readiness levels becomes deducible.

Loss rates and process costs are important indicators for the maturity of a manufacturing technology, for example. The loss rate of a manufacturing process is a kind of measure for reliability and stability [11]. The integration and the usage of a technology do not make sense before the loss rate has fallen below a defined minimum (e. g. 5 %) [9]. From this point of view, the loss rate is a factor which influences the maturity of a technology directly.

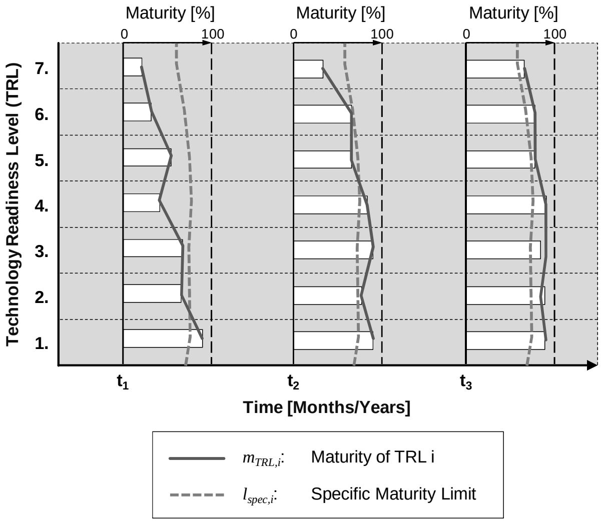

Fig. 6 Estimating the Maturity of a Manufacturing Technology and Forecasting the Time of Development

Next to directly influencing factors parameters also exist which affect the maturity indirectly. Process costs do not provide a conclusion regarding the technology's maturity, but the contemplation of the costs over time is indeed an indicator.

Depending on the velocity of decreasing cost changes due to economies of scale, for example, a maturity assessment becomes possible by estimating the research and development effort. In this way, conclusions concerning the technology's maturity also become feasible. The principle of estimating the development time to decide when a technology is sufficiently matured for applicability in the production system is pictured in Fig. 6. Herein, the maturity profile of the TMA model is plotted against time. Herein, the research and development efforts of Brousseau *et al.* [13] have been changed by the maturity.

In this approach, two different types of maturity exist, the maturity of the technology M_T and the maturity of each technology readiness level m_{TRL}, which is illustrated in Fig. 6. The picture shows the maturity development of the seven TRLs at several times (t_1-t_3 in Fig. 6). Both, the maturities of the different TRLs $m_{TRL,i}$ as well as the specific maturity limits $l_{spec,i}$ result from expert interviews. Thereby, special questions for each TRL concerning the product, required auxiliary materials and relevant process parameters are analyzed. The results of the questionnaires are linguistic statements which can be reproduced by Fuzzy Logic-based uncertainties [8]. Furthermore, the specific maturity limits $l_{spec,i}$ are also determined within the expert interviews.

In Fig. 6 the maturity of the different technology readiness levels $m_{TRL,i}$ of one stage can be compared. Depending on the TRLs, two different limits exist, the total maturity limit and the specific maturity limit $l_{spec,i}$. Generally, a TRL can reach *100%* at the maximum, which is the total maturity limit. To be ready for implementation, a technology need not reach *100 %* of the total maturity. Nevertheless, technologies must mature up until a defined level to be suitable for implementation. This level is represented by the specific maturity limit $l_{spec,i}$, which descends from the company's strategy and the focused industrial sector. The specific maturity limit $l_{spec,i}$ must be determined for each TRL itself and thus can vary depending on the focused level. However, the application of a new manufacturing technology in the production environment only makes sense when the specific maturity limits $l_{spec,i}$ in all TRLs have been reached (grey and short dashed line in Fig. 6).

In contemplating the duration as well as the velocity of the maturity development in the different stages, the date for reaching the specific maturity limits $l_{spec,i}$, can be deduced. In this way, the optimal implementation of a technology can be determined with low risk. For evaluating the maturity of a technology M_T, the seven technology readiness levels $m_{TRL,i}$ must be considered. Thus, the maturity of the technology M_T results from the differences between the maturity of each technology readiness level $m_{TRL,i}$ and the total maturity limit according to the following equation:

$$M_T = \left(1 - \left[\sum_{i=1}^{7} \left(1 - m_{TRL,i}\right) \cdot q_i\right]\right) \cdot 100\ \% \qquad (1)$$

Thereby, seven quantifiers q_i are introduced, one for each TRL. Thus, a company is able to evaluate and quantify the different TRL regarding the point of interest. Normally, a technology user is not interested in basic research activities but requires high process stabilities. Thus, he would quantify the higher TRLs much more than the lower ones. The sum of the seven quantifiers q_i must be one. By definition, the maturity of a technology M_T is less than *100 %*, as long as the maturities of the seven technology readiness levels $m_{TRL,i}$ are lower than the total maturity limit. Hence, the maturity of a technology M_T can reach *100 %* at the maximum. An exemplary calculation of the maturity of a technology at a particular time is shown in Fig. 7.

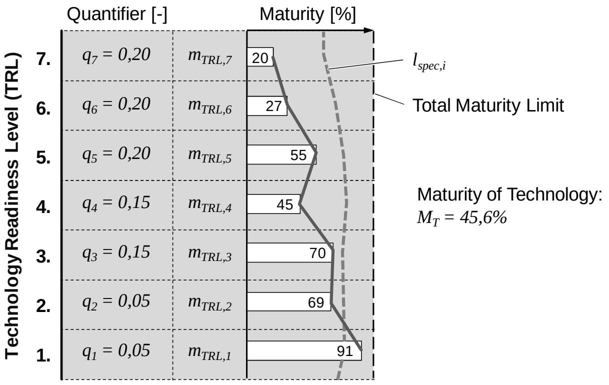

Fig. 7 Exemplary Calculation of the Maturity of a Manufacturing Technology at a Particular Time

VII. CONCLUSION

This article presents an approach for evaluating the maturity of a manufacturing technology by combining the concepts of TRL [10], TMA [13] and the technology life cycle according to Ford & Ryan [4]. Regarding the strategic technology planning process, it is essential to assess the maturity of the internal as well as external processes for a robust orientation of a company's future production strategy. Furthermore, a company needs to know when to install a new technology in the production environment. Therefore, the velocity and the duration of the maturation process have to be contemplated as well.

In the following research activities, the proposed approach must be validated by executing industrial case studies in the context of technology planning. Thereby, the qualitative data collected with the questionnaires can be confirmed by quantitative values. Moreover, the approach have to be enlarged by the integration of uncertainties. Therefore, the quantification and modeling of the uncertainties which underlie the evaluation of the technology's maturity have to be worked out. The maturity of technology does correlate with technical and organizational risks [10]. These risks represent uncertainties and can be described by probability distributions. In the same way, the linguistic statements from the questionnaires have to be described. Thereby, Fuzzy Logic-Integration is one possibility for quantification.

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