

The 24th CIRP Conference of Life Cycle Engineering

## Cycle-oriented Evaluation of Production Technologies: Extending the Model of the Production Cycle

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### Abstract

Permanently evaluating and adopting suitable production technologies due to the dynamic environment is a major challenge for producing companies. However, influencing factors that show cyclic behavior can be anticipated and are predictable to a certain extent. Thus, lifecycle models facilitate the forecast of predictable factors and assist in deriving recommendations for action timely. The developed cycle-oriented planning and evaluation approach provides a cycle stage specific technology requirements profile. The conceptual framework ascertains the suitability of established production technologies using fuzzy sets to meet the vagueness inherent in soft requirements. The presented extension of the production cycle model provides a holistic framework to identify deficits concerning properties of established production technologies proactively. This enables a continuous technology evaluation approach resulting in the timely identification of technological need for action.

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Peer-review under responsibility of the scientific committee of the 24th CIRP Conference on Life Cycle Engineering

*Keywords:* Technology planning; Manufacturing process; Production planning; Cycle management

### 1. Introduction and definitions

The suitability of production technologies to fulfill a specific production task is changing over time [1, 2] depending on internal and external influencing factors of the production environment [3]. To compete within such a dynamic environment, monitoring and anticipating those influences becomes an increasingly important element of developing competitive advantages (cf. [4, 5]). In this connection, applying production technologies which fulfill current and future requirements in the best manner offers high potential for cost reduction [6] and efficiency [7]. Consequently, it is of utmost importance to permanently analyze the appropriateness of the applied production technologies. Since the development of requirements resulting from the production environment is difficult to predict, this is a major challenge for producing companies (cf. [8, 9]).

Lifecycle models assist to anticipate and monitor influencing factors that show cyclic behavior, in the following defined as temporally and structurally recurring patterns comprising

defined phases [10]. The management of interdependencies of multiple cycles in terms of planning, modelling, organizing and monitoring is understood as cycle management [10]. The term “technology” denotes all emerging and established manufacturing processes [11] and techniques (including the manufacturing resource) that are required to produce a product. In this context, the combination of single technologies in order to manufacture a specific product is regarded as a technology chain [1, 12].

The objective of this novel approach is to identify a decline in the technology’s suitability proactively and to evaluate resulting opportunities earlier than the competition does. A proactive technology management approach is characterized by continuously assessing established production technologies as well as identifying, evaluating and acquiring alternatives and capabilities in advance of needs [5].

## 2. Cycle-oriented management of production technologies

Due to a wide range of developed models and methods (cf. [13]) considerable scientific achievements were gained evaluating production technologies at a single point in time and synchronizing technology planning activities to product development (cf. [14]). The literature documents fruitful approaches focusing on the optimization (e.g. [15]) and standardization (e.g. [7, 16]) of technology chains. In the sequel, the most relevant ones with regard to the continual assessment of production technologies are briefly discussed.

### 2.1. Relevant approaches for the continual evaluation of production technologies

A generic model to determine the monetary value of an established manufacturing technology is presented by Schuh et al. [17]. The objective of this approach is to ascertain the value-contribution of an applied or future technology to the manufacturing system.

Stauder et al. [18] developed a conceptual approach to assess the substitution risk of production systems regarding to changes in the product program. The method comprises four steps and includes suitability analysis of production systems based on previous defined scenarios.

From a strategic point of view, Reinhart & Schindler [1] and Reinhart et al. [19] presented a technology chain calendar. Based on a static multi-criteria evaluation approach (considering uncertainties of the evaluation results) the suitability of a technology chain is determined in early stages of the product development process. Greitemann et al. [13] extended this approach to a dynamic model comparing competing technology chains over the planning horizon.

In order to plan innovation activities for manufacturing, Friedrich [20] published a methodology encountering the three determined deficits in established technology planning approaches: transparency, efficiency and effectiveness. Therefore, the “footprint model” is presented (based on [12]) comprising a static requirements- and ability-profile for evaluating competing production technologies.

Directly addressing lifecycle models, Abernathy and Townsend [21] developed a descriptive model of process evolution over time. For each stage of the manufacturing process lifecycle (uncoordinated, segmental and systemic stage) important implications were derived qualitatively.

To visualize the changing suitability of a technology over time, Swamidass [2] applied Technology Characteristics Curves. The objective of the proposed method is to capture modernization opportunities as they arise during the process lifecycle. Therefore, estimated data for cost, quality and flexibility are considered defining the technology’s suitability.

Hayes and Wheelwright [22] presented the conceptual framework of the “product-process matrix”. The authors noted that the manufacturing processes have to be in line with the corresponding challenges of each product lifecycle stage.

Exploring the potential of the product lifecycle as a strategic planning framework, Magnan et al. [23] conducted empirical

analysis of the most appropriate manufacturing practices within each lifecycle stage.

Considering multiple products that demonstrate different lifecycles, Ferro and Aguilar-Saven [24] presented comparative tables and recommendations supporting the decision making which manufacturing process to implement.

### 2.2. Shortcomings and the need for further research

The review reveals three future areas of activities that are justified in the following: (1) focusing on the model of the production cycle, (2) applying a cycle-stage specific (dynamic) requirement profile, (3) enable to use value ranges for evaluating the technology’s suitability.

(1) In industrial practice, the product lifecycle from marketing perspective does not by default equal that of the duration of the production cycle of e.g. single components [9]. Aurich and Barbian [25, 26] separated the market lifecycle and production period of a product. The authors introduced the model of the production cycle (also regarded as production period) as the duration between the start of production and the end of production. Cooperating with one of the leading manufacturer of commercial vehicles, Schönmann et al. [9] quantitatively and qualitatively derived four phases of the production cycle (cf. section 3.2) to evaluate technologies.

(2) Although ascertaining the current and future suitability of a technology has major impact on replacement decisions, only a few approaches consider including established production technologies. A cycle-stage specific requirements profile for evaluating production technologies over time is not existent to the knowledge of the authors. Consequently, the timely derivation of technological need for action (e.g. declining suitability of the applied technology) has not sufficiently been addressed.

(3) As stated in section 1 the development of requirements resulting from the production environment is hardly predictable, in particular with regard to the addressed mid- and long-term planning of this approach. With that in mind, an evaluation framework needs to include and consider both types of requirements and abilities: exact values (e.g. size) and value ranges (e.g. costs) due to vagueness and uncertainty.

### 2.3. Objectives and benefits of the novel approach

The main objective of this novel approach is to extend the model of the production cycle into a framework for evaluating production technologies proactively. This framework serves as a solid foundation for deriving technological needs systematically. Based on the cycle-stage specific technology’s requirements profile, the properties (or abilities) of the applied technology must be reflected. Deviation from the requirements profile shows technological need for action. Using the cyclical pattern of the production cycle of a product or component allows to anticipate the future progression and to proactively derive required actions.

Since there are many uncertainties related to both, the evaluation of technologies as well as the classification of cycle

stages due to variability of circumstances and the use of expert knowledge, fuzzy sets are taken into account. The theory of fuzzy sets represents a well-established approach for modelling vagueness (not to be confused with probability) by taking into account imprecision in a mathematical sense [27].

**3. Principles of the developed framework**

The following section briefly introduces some of the essential methods and models for developing the novel framework. Furthermore, the evaluation criteria for determining the technology’s suitability are presented.

*3.1. Fuzzy sets*

Fuzzy sets were introduced in 1965 by Lotfi Zadeh [28] as a generalization of classical, crisp sets commonly used in mathematics. In classical set theory, objects can either belong or not belong to a set. Fuzzy sets however allow partial membership, which enables expressing vagueness in a mathematical framework. This partial membership is defined by the membership function of the fuzzy set, e.g. a trapezoidal or triangular function. Logical operators have been defined on fuzzy sets, and are applied in many disciplines under the name of fuzzy logic (see e.g. [29] for a deeper insight).

*3.2. Phases of the production cycle*

The model of the production cycle (cf. [9]) comprises three distinct stages (Series start-up, Series production, End of series production [30]) comprising four single phases (based on [25, 26]), namely Pioneer production (product ramp-up and growth), High volume series production, Low volume series production and decline as well as Removal (fig. 1).

manufacturing process perspective, depending on the cause and degree of adaptations, several ramp-ups can be distinguished: process ramp-ups (manufacturing ramp-up), product ramp-ups (pilot production), and series ramp-ups (new product and new process) [31]. First-mentioned may also occur during the series production phase of a product, module or component (cf. fig 1). For example, the replacement of a machine is regarded as a manufacturing ramp-up while introducing a new product into an existing manufacturing process requires a product ramp-up (cf. [32, 33]).

*3.3. Evaluation criteria of production technologies*

Over the past few decades, the literature documents manifold approaches and models for evaluating production technologies and manufacturing systems (cf. section 2). The most relevant ones are ordered by their applied measures in table 1.

Table 1. Overview of considered evaluation criteria.

Swamidass 1987 [2]	Kleindorfer & Partovi 1990 [34]	Koho 2010 [35]	Reinhart et al. 2009 [19] 2011 [36]	Friedrich 2014 [20]
Cost	Cost	Cost	Profitability	Cost
Flexibility	Flexibility	Volume Flexibility	Competitive Potential	Flexibility
Quality	Quality Dependability	Quality Time	Maturity Product Feasibility	Quality Product Feasibility
		Product Flexibility	Resource Efficiency	Ecology
		Reliability of lead/delivery time		Throughput Investment

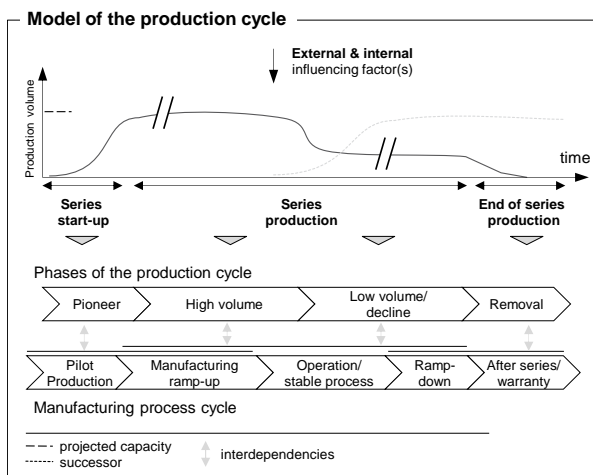


Fig. 1. Exemplarily modelled production cycle [9].

Obviously, the time intervals of the stages and phases may vary depending on company’s strategy and industry. From the

Based on this review, five evaluation criteria are selected according to their usage frequency: cost, quality, volume flexibility, sustainability and product feasibility. Additionally, the criteria *interconnectivity* due to the gain in importance of data transmission and exchange in production is considered. The economic aspects of a technology are taken into account regarding to manufacturing *cost* per unit (e.g. material cost, maintenance cost, setup cost) [17, 36]. *Quality* comprises criteria to evaluate the ability to match specifications like design, performance or reliability and to meet the expectations and requirements of customers [34, 35]. *Volume flexibility* describes both the range of volume that can be produced profitably and the ability to profitably change the production volume according to demand [35]. The *sustainability* include the ecological evaluation of a production technology in terms of energy and material efficiency [18]. Moreover, it is necessary to ensure that the technology is in accordance with current and future legal requirements. The *product feasibility* contains relevant data about the current product and future adaptations (as far as already known). Besides rough product

properties (e.g. geometry dimensions) also materials and functional surfaces are contemplated [36].

The objective of the evaluation process is to determine the technology’s cycle-stage specific suitability. Therefore, the six measures are aggregated to a single target value (fig. 2).

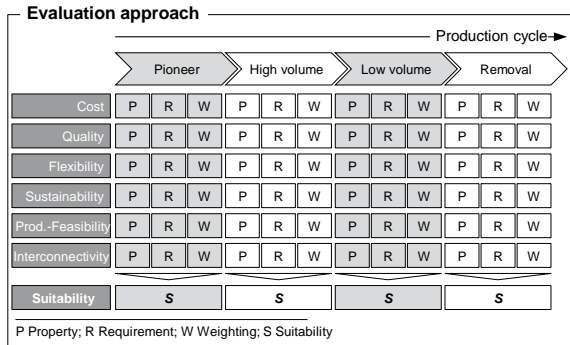


Fig. 2. Evaluation criteria.

4. Framework for cycle-oriented technology evaluation

Before the holistic framework for evaluating production technologies is presented, a basic overview of the underlying procedure model is considered necessary (fig. 3). Four single steps are separated, which are subsequently discussed.

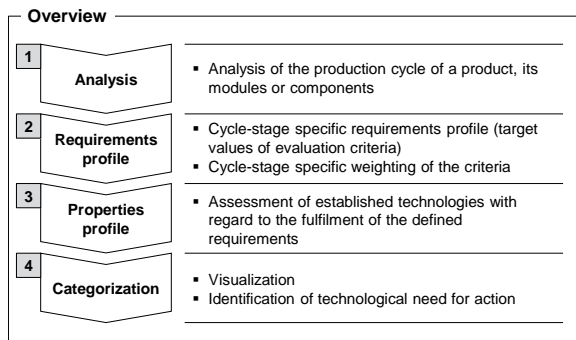


Fig. 3. Four single steps to the framework.

4.1. Analysis of the production cycle

In the first step, quantitative and qualitative data of the production volume of the product (respectively module or component) needs to be gathered. Further details of the data analysis are presented in [9]. Due to the fact, that the time-period of each of the four phases may vary considerably depending on industry and type of product, this must be done individually based on historical data or expert knowledge.

Since there are many uncertainties related to the classification of lifecycle stages due to imprecision or vagueness caused by variability of circumstances or verbal descriptors for attributes, fuzzy sets are taken into account.

4.2. Determining the cycle-oriented requirements profile

For each of the evaluation criteria, target values (or value ranges) have to be defined (further information is presented in [1], [12] and [20]). It is important to keep in mind whether those requirements vary over time. The “cost” usually is more important within the “high volume phase” compared to the “pioneer stage”, for example. This aspect is taken into account applying a cycle-stage specific requirements profile. Addressing specific industries, business objectives or competitive strategies, the evaluation criteria (or to be more specific the ability to fulfill them) can be weighted dependent on the cycle stage. To obtain the vector of relative weights of cost, quality, flexibility, sustainability, product feasibility and interconnectivity, the analytic hierarchy process (AHP) [37, 38] is applied within this approach.

4.3. Determining the properties profile

There are several approaches for determining the properties’ profile of production technologies considering uncertainties (e.g. [18, 36, 39]). In principle, four types of input parameter can be distinguished to evaluate the ability to fulfill single criteria. The technology’s evaluation is based on (1) historical values and experience, (2) comparative values of suppliers or subsidiaries, (3) studies or statements from experts comprising linguistic values and (4) probability distributions using different distribution types, mean values and variations.

The resulting property of each evaluation criteria is given as an exact value (e.g. mean), a values range or an arbitrary bounded function (e.g. probability distribution).

4.4. Categorization within the framework

As mentioned before, it is the objective of the framework to determine a cycle-stage specific suitability measure for production technologies. The six criteria (section 3.3) are thus merged to a single suitability measure. A common approach to match requirements with properties consists of generating a quotient of scalar values (e.g. [1, 20]). This approach, however being of practical benefit, has the downside that the resulting value is hardly interpretable for some criteria. Furthermore, the representation of the vague and uncertain properties as scalar values does not comply with the nature of the problem. Therefore, a novel approach is presented in the following.

The requirement profiles are separated into three fuzzy sets: “requirement exceeded”, “requirement fulfilled” and “requirement not fulfilled” with respective membership functions  $f_{ex}(x)$ ,  $f_f(x)$  and  $f_{nf}(x)$ . The membership functions have to fulfill the convex sum property  $f_{ex}(x) + f_f(x) + f_{nf}(x) = 1, \forall x$ . An example of different types of requirement profiles with fuzzy sets is shown in figure 4.

For each criterion, the property profile, represented by a function  $p(x)$  (see section 4.3), is matched to the requirement profile using an integral over the fuzzy sets and normalized with the integral over the properties profile, resulting in a fulfillment ratio  $RP_{ratio}$  for this specific criterion.

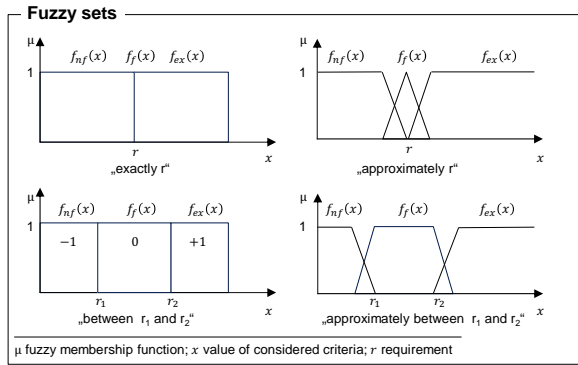


Fig. 4. Different requirement profiles and their fuzzy sets (based on [12]).

The fuzzy membership function  $f_{ex}$  is implicated positively in the ratio, whereas  $f_{nf}$  has a negative effect, and  $f_f$  does not affect the ratio.

$$RP_{ratio} = \frac{\int_{-\infty}^{\infty} (f_{ex}(x) - f_{nf}(x)) \cdot p(x) dx}{\int_{-\infty}^{\infty} p(x) dx} \quad (1)$$

A  $RP_{ratio}$  of “1” relates to a property profile which is fully factored into the “requirements exceeded” fuzzy set, whereas a  $RP_{ratio}$  of minus “1” denotes a property profile fully contained in the “requirement not fulfilled” fuzzy set. A  $RP_{ratio}$  around “0” represents a criterion that is evenly fulfilled. After weighting the  $RP_{ratio}$  of each criterion with its specific weight  $W$  for the considered phase (c.f. section 3.3), the measure  $S$  for the suitability of the production technology is obtained. Again the suitability measure  $S$  can only take values between minus one (unsuited) and one (overfulfilled).

$$S = \frac{\sum_{i=1}^6 RP_{ratio,i} \cdot W_i}{\sum_{i=1}^6 W_i} \quad (2)$$

After evaluating the suitability measure for each phase of the production cycle, it is used to compare various machines over the planning horizon (cf. fig. 5). The figure is diagrammed with the production phases on the y-axis and the suitability measure on the x-axis. To account for the transition time between production phases, those are also described by fuzzy sets (here trapezoidal functions), which leads to smooth transitions and linearly interpolated suitability measures during the transition.

**5. Application example**

For illustration purposes, an example is provided comprising two production technologies (respectively manufacturing resources). Machine one (dashed line) is characterized by low production costs, but exhibits deficits in quality and flexibility, compared to machine two (solid line). The classification shows an overall better suitability for machine two, whereas machine one shows a small advantage in the second phase, where the costs per unit were set to be a very crucial factor.

This information facilitates deciding whether to replace established production technologies or not. Moreover, this information assists the allocation of production loads.

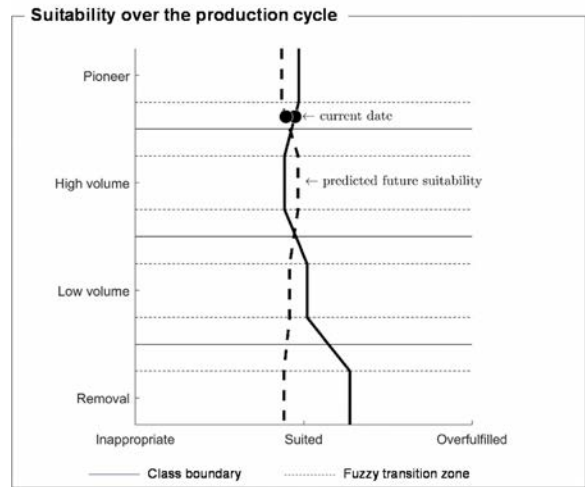


Fig. 5. Classification example of two machines in the framework.

**6. Conclusion and outlook**

Reviewing the literature regarding the management of production technologies, a holistic framework supporting the cycle-stage specific evaluation of a technology’s suitability within the production environment is not available. Based on established technology evaluation approaches, the model of the production cycle is extended, resulting in a holistic framework. The novel approach comprises four steps: (1) analysis of the production cycle, (2) definition of the requirements profile, (3) determination of derivations based on the properties profile and (4) categorization. The framework facilitates to focus further activities on critical elements. Since there are many uncertainties related to the classification of lifecycle stages e.g. caused by verbal descriptions for attributes, fuzzy sets were implemented supporting this task.

Based on this conceptual framework further research activities will initiate the industrial application and validation as well as refinements of each phase.

**Acknowledgements**

The German Research Foundation (DFG) funds this research and development project. We extend our sincere thanks to the DFG for the generous support of the work described in this paper, resulting from the subprojects A7 and T2 in the framework of the Collaborative Research Centre 768.

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