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TOWARDS AN EARLY CONSIDERATION OF RAMP-UP PHASE IN THE PRODUCT DEVELOPMENT OF COMPLEX PRODUCTS

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1. Introduction

Shorter product life cycles, increasing market competition and high development costs have driven firms to cut their development times and accelerate the introduction of new products into the market. The production ramp-up phase is increasingly becoming a critical point in the product life cycle. The ability to launch a product into the market under cost, time and quality-pressure is important to the success of companies. Deviations from the target can lead to significant economic consequences. An international study in the automotive industry ascertained that only 40% of all investigated production ramp-ups were economically and technically successful [Schuh 2005]. The use of new technologies and implementation of innovative approaches entails the risk that it may lead to unexpected problems in the development and manufacturing process. It is essential that potential ramp-up risks are identified and managed, especially for products with long development time, high complexity and high initial uncertainty.

The aim is to develop a methodology for the early identification and minimization of ramp-up risks to manage an efficient transfer of development results into production, assess the risk level and support decision-making in the development phase of the product. At the beginning of the paper a short overview of the terminology of risk assessment, uncertainty and production ramp-up in the context of development is given. The methodical approach for assessment of ramp-up risks is then presented.

2. Background

An efficient product transfer from development to production fails due to the long development times and high initial uncertainty of complex products. The risks that can arise due to unforeseen events must be identified during development. Despite the numerous ways of securing development within the pre-series, not all risks can be covered. This section focuses on the basic ideas in the fields of risk assessment, uncertainty and production ramp-up.

2.1 Risk assessment methods

The following section gives a brief overview of the most common methods for the identification, evaluation and classification of risks. First, however, the term risk is defined. For this paper, Lührig's definition of risk is used: "Risk is the result of a negative deviation from the expected value size. It is not known whether and in what amount the deviation occurs. But what can be specified is the subjective or objective probability of the occurrence (probability) of this event and/ or the amount of deviation (impact)" [Lührig 2006]. There are different perspectives on the general definition of risk, which depend on the circumstances and goals of the risk analysis. This paper follows the asymmetric effect-related risk assessment, also known in the literature as 'risk in the narrow sense'.

The literature contains various methods; only two of the most established methods will be presented [Pahl 2007]. The Failure Modes and Effects Analysis (FMEA) is a method that systematically analyses the components and their failure mode characteristics to assess risk and reliability of the product. The starting point is the decomposition of the product into subsystems. The essential feature of the method is the identification and evaluation of all possible causes of an error to determine the effect they have at the component level. It is a widely used method but requires detailed system or component design. Additionally, it does not capture component interactions explicitly and relies on expert knowledge.

The Fault Tree Analysis (FTA) is a method that captures event paths from failure root causes to top-level consequences. This approach is applied during product development to ensure safety and improve the reliability of products/systems. FTA enables the user to identify all critical paths that could lead to a negative event, such as system failure. However, FTA also relies greatly on expert input. The interactions and system dynamics are not adequately captured to support design decisions in early development phases.

2.2 Classification of uncertainty and strategies to handle uncertainty in the field of product development

The development of complex products is characterized by high initial uncertainty. This leads to increased difficulties in planning and executing development projects. Uncertainty is a term that is discussed in a number of different fields of literature. From a product development perspective, uncertainty is either internal (endogenous) or external (exogenous) [De Weck 2007]. Internal uncertainty can be divided into the product and corporate contexts. New products have an element of novelty, which implies an element of technical risk. These technical uncertainties are usually resolved during the development process. Components that are already in use in other products could be affected by uncertainty if the components are placed in a new context with new interactions between the components. Failure to consider the interactions between components and other systems leads to change propagation and unexpected failures. In the corporate context, uncertainty affects the product and process planning and resource allocation in the design process (Figure 1).

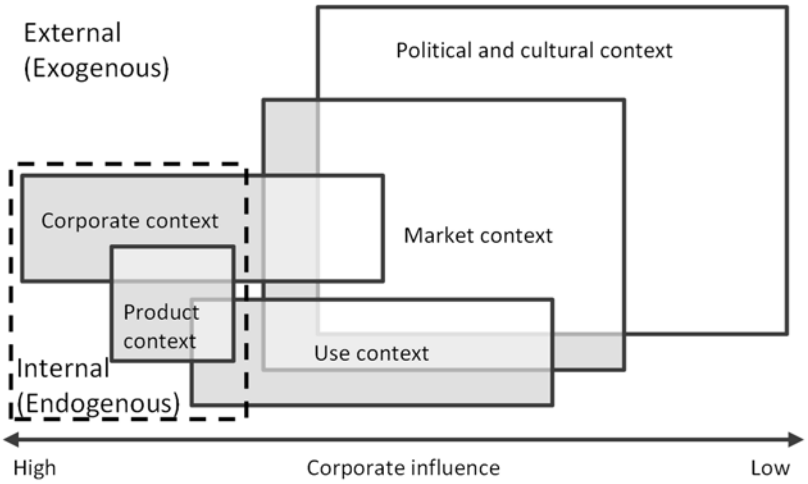


Figure 1. Corporate influence on sources of uncertainty, based on [De Weck 2007]

External uncertainty can only be partly influenced by the company. External uncertainty arises from the market place in which the product is operating and the political and cultural context. During development, there is often a high uncertainty about operational conditions of the product, which could lead to maintenance and service problems. Market prediction of customers and competitors is also characterized by high uncertainty. Innovations from competitors can change the market and customer behavior rapidly. External uncertainties in the political context are characterized by changing regulations, such as emissions.

How could uncertainty be implemented in the risk assessment? The qualitative values have to be transformed into quantitative values, especially for consideration in early design phases. For an effective consideration of the uncertainties in product development, Jetter presents several approaches [Jetter 2005]. The aim of the “front-loading” strategy is early identification and resolution of possible problems during the product development process. Hence, the extent of uncertainty is reduced in early stages. Through the transfer of knowledge from project to project, similarities between new and previously developed projects can be recognized as early as possible so that solutions can be adopted. Uncertainty can be significantly reduced by collecting sufficient and accurate information. This is problematic in turbulent environments, e.g. development. The problem of information dynamics can be overcome by reducing time to market. The shortening of time reduces the probability that customer requirements and available technologies change dramatically.

Another strategy is to increase flexibility by maintaining the scope of action as long as possible. Within the scope of development, there should be more than one product concept developed in parallel; concept selection and design freeze should take place relatively late. Flexibility is also determined by the architecture of the product. While a change in integrated product architecture is a costly operation, modular structures enable a flexible response to future changes in conditions through replacement of individual modules.

2.3 Interface between development and production – ramp-up phase and influencing factors from a product perspective

The growing importance of the research field “product ramp-up” as a critical interface between development and production process can be explained, as already mentioned, by the shortening of product life cycles and development times, the increasing product complexity and variety, and the decreasing vertical integration. Many approaches in the literature are driven by industry-specific problems in the automotive and semiconductor industries [von Wangenheim 1998], [Terwiesch 2001]. The ramp-up phase marks the start of the transition between the completed product development and the series production. The transfer from development to production takes place in stages. Changes and disturbances in the product and in the process are usually resolved within the pre-series and pilot production with the help of numerous prototypes. The end of this phase represents the achievement of the previously defined output quantity and quality of the product and then proceeds into series production [Terwiesch 2001]. The generic production ramp-up phases in the automotive industry are presented in Figure 2.

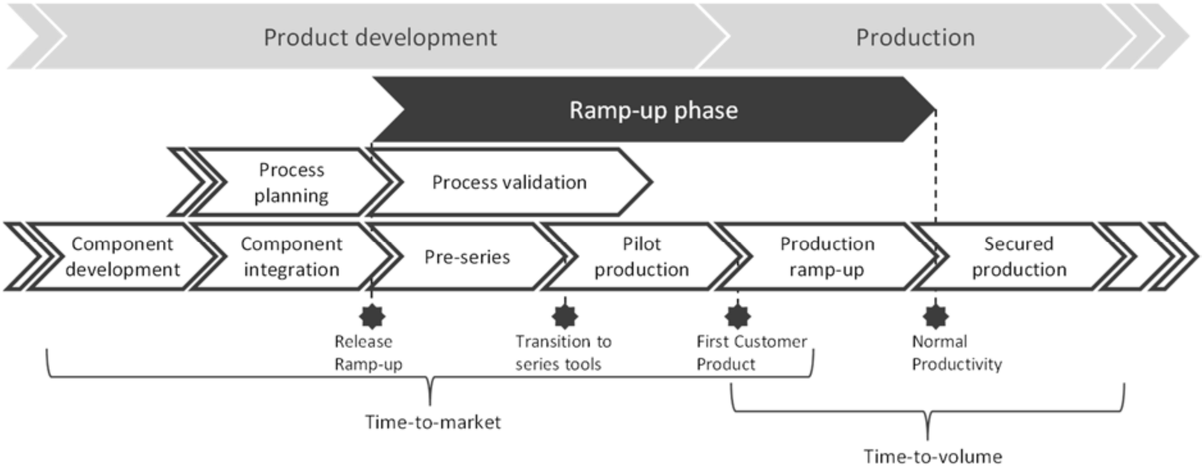


Figure 2. Overview of the ramp-up phase, based on [von Wangenheim 1998]

The ramp-up phase is a dynamic phase with many changes and mistakes that significantly affect the following processes in the company. The complexity arises from the initial integration of the various design objects (such as technologies, processes, products, supply chain) and disciplines (product development, production, logistics, purchasing) [Schuh 2005].

Time delays in the development and introduction of high-tech products has a strong negative impact on gross profits. Especially in complex series products, the transition phase has special requirements for the design of the interface between development and production. Extensive knowledge is required due to the large number of systems, components and parts in which different technologies can be used. There is a highly significant correlation between the duration of the ramp-up and the complexity of new technologies, the extent of system change and the project scope. Decreasing depth of development requires additional coordination with external organizational units and generates organizational complexity [von Wangenheim 1998].

An essential cause of this is the number of design changes of the product during the development and ramp-up phase. A successful transfer into series production is affected by the novelty or innovativeness of the product and its quality (maturity). The probability of a delay during the ramp-up phase increases with the degree of innovation of the product and process technologies. Qualitative studies warn that the achievement of the target parameters (time, cost and quality) requires an efficient network across the entire value chain, including the degree of new products in the company, the integration of suppliers into the development process and the flexibility of manufacturing processes [Schuh 2005], [von Wangenheim 1998]. Terwiesch identified three main ways to reduce ramp-up time. First, a gradual transfer of pilot series to series production significantly increases the performance. Second, clear responsibility and a cross-functional organization promote a better transition between development and production. Thirdly the introduction of product platforms leads to more effective use of previously collected experience on new products [Terwiesch 2001]. An overview of the factors and their dependencies on efficient ramp-up, from the product development perspective, is summarized in the following figure.

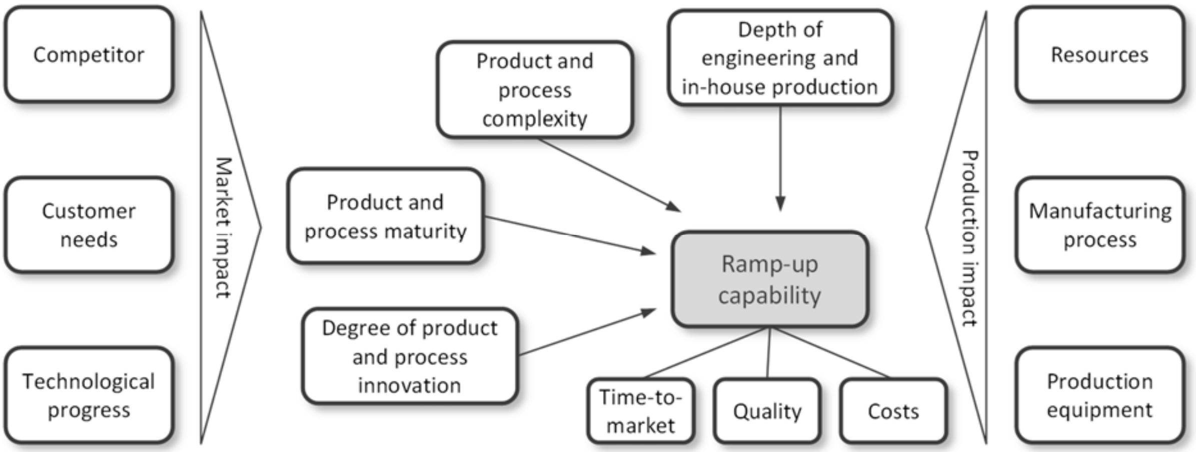


Figure 3. Influencing factors of the ramp-up capability

2.4 Aims of a new method

The majority of risk analysis methods developed focus on securing product design and its requirements. Especially in long development times, estimation of the variability and uncertainty at an early stage of the development is still poor. It must always be correlated with deviations from the target in the development process. Hedging practices will help to minimize impacts and potential risks. Uncertainties need to be considered when performing a risk assessment of individual factors before the ramp-up phase. At the beginning of development, the scope of action is larger and the costs of changes lower.

Deviations and delays occur mostly in conjunction with production. A pre- and pilot series with a large number of prototypes is not practicable for complex products with high unit cost. This leads to numerous design changes during the development and ramp-up phase. Production ramp-up methods are focused on the problems of the industry and their products. The focus is the preparation for production in terms of organization, manufacturing equipment, logistics, etc. [Elstner 2011].

Due to the strong influence of the ramp-up phase on the success of the product, it should be considered in the early stages of development. Therefore, the aim must be to provide a basis for decisions during development of the product. The risk identification and assessment of new products must be practicable with given initial uncertainties. In the following section, a methodical approach is presented that provides an assessment of influencing factors from development to ramp-up phase.

3. Proposal of a methodological approach to assess the influencing factors on ramp-up phase

This section develops a methodology that is able to describe and evaluate the influencing factors and their effects on the start of production. Statements about the ramp-up capability of the developed product will help to facilitate the development within a targeted risk communication and serve as the basis for efficient decision-making processes [Elstner 2011].

The framework for the general procedure is presented in Figure 4. The procedure is divided into five steps and should be linked to the development process and its milestones. This means that an assessment must be repeated at regular intervals to identify potential deviations and enable process-accompanying monitoring.

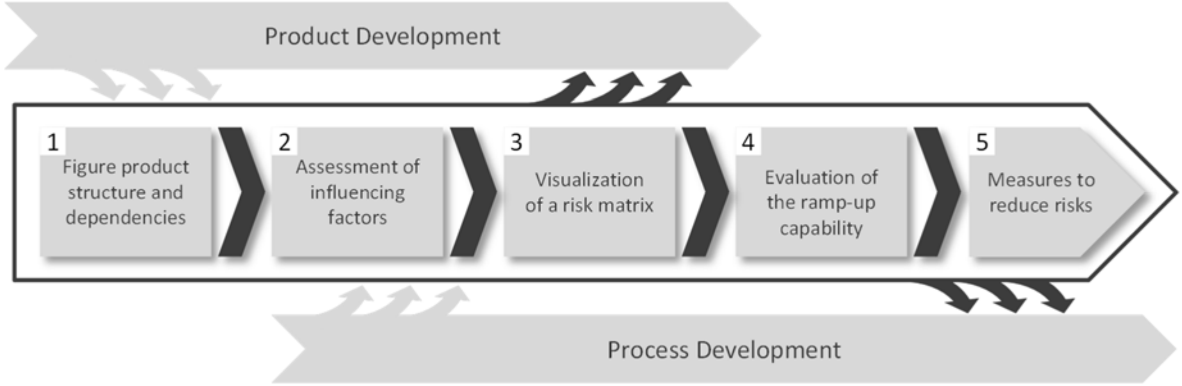


Figure 4. General procedure of the approach

The first step is the investigation of the existing product structure and the planned new product structure. The comparison should help to establish a link between degree of novelty and complexity of the product. The structure then feeds into the second step to evaluate the previously identified influencing factors. The third step is a visualization of the estimated values in a risk matrix. As in the first two steps, the visualization is carried out at component level. An aggregation of the individual components and their individual risks are then performed in the fourth step. The predictable indicator of the ramp-up capability helps to illustrate development within the project and to provide measures to cover components during the ramp-up phase. These measures for the identified risks are provided in the last step, including product structuring measures at a very early stage of development.

3.1 Figure product structure and dependencies

The components developed within the concept phase of the product can be shown at a very early stage of development. Concrete conclusions about the performance of the product can only be partially made. In the first step, the existing product structure and the new product structure should be mapped, based on patterning methods such as modularity and platform strategies. Using an easy visualization method of the components in the product with low time and effort is helpful, particularly in an early design phase with high uncertainty. Therefore, the existing representation methods developed at the Institute of Product Development and Mechanical Engineering for the modularization of product families will be used [Krause 2011]. The individual components of the product family are shown in the Module Interface Graph (MIG) in Figure 5. With the help of a MIG, the components and their interfaces can be mapped in their approximate positions.

In addition, the graph is an efficient tool for mapping relationships and flows, such as information or electrical flow through the product.

A direct comparison with the existing structure enables a simple estimation of the degree of novelty of the components and their dependencies within the assembly. More information on aspects such as production and development of the individual components must be determined separately. For example, colour labelling of foreign-made or engineered components in the MIG could be possible and useful. The simplified product example in Figure 5 illustrates the differentiation between products. The casing (C) has a new shape, necessitating a change in the manufacturing tools; the battery (AP) of the previous product is split into two separately batteries (AP1 and AP2) with additional interfaces. The investigation of the new product gives an initial impression of the upcoming changes in the manufacturing process, supplier components, product complexity and integrated technologies.

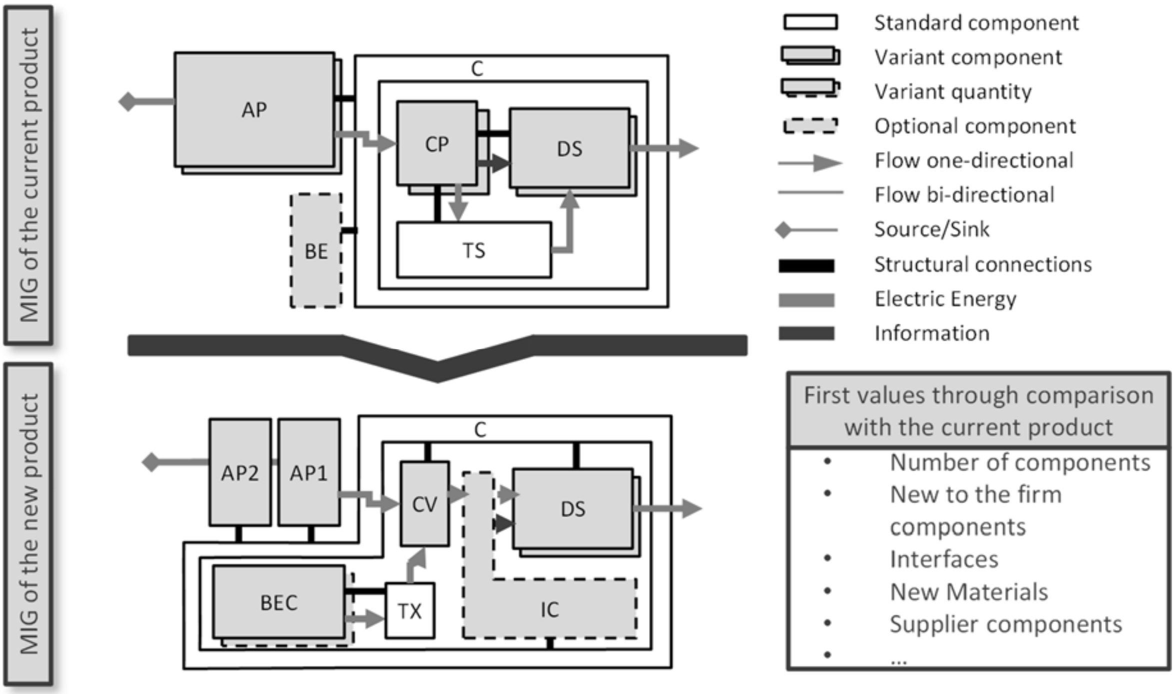


Figure 5. Comparison of product structure with help of the module interface graph (MIG)

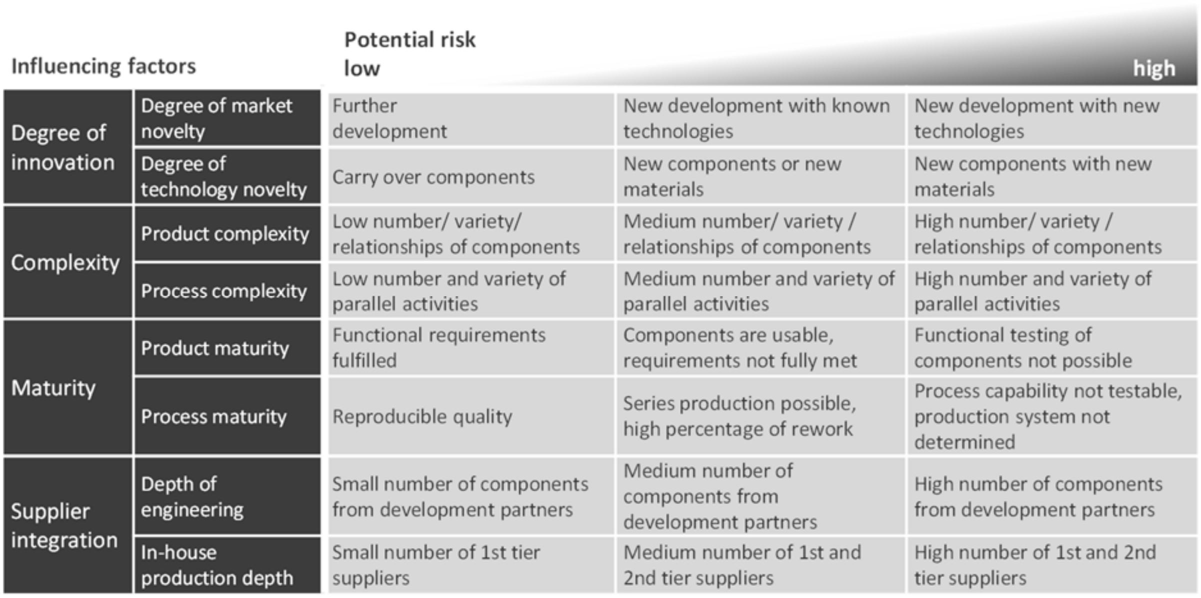
3.2 Assessment of influencing factors

In the next step, the individual areas are assessed for influencing factors, based on the product structure (Figure 3). The degree of innovation can be divided into market novelty and degree of technology novelty. A new development with new technologies can be classified as critical for ramp-up. There is a lack of experience in the manufacturing and integration of new materials and the performance of new components. If there are similar competitor products in the market, experience in the use of the product can be obtained. If this is not the case, particularly in advance of production, additional measures are necessary to secure the ramp-up phase.

Product complexity is derived from the number and variety of product components, and the number of relationships. The larger the dependencies between the components, the greater the change effort and propagation of errors during the ramp-up. For process complexity, the number, diversity and temporal parallelism of the activities are key influences on the criteria. Because of the large number of stakeholders and the strong interaction between individual activities, the risk of delay due to coordination of numerous interfaces is significantly higher.

Product maturity can be accounted for with the three dimensions of product, process and capacity. The components will be assigned according to their level reached and the concrete fulfillment of functional and technical requirements of one stage. During progress, the percentage of components that have reached a certain level at a certain time should be specified. The timing of this achievement is usually linked to quality gates. Early identification of deviations is an important factor in securing quality in the ramp-up phase. Lack of product maturity leads to unnecessary iterations in the development and represents an additional expenditure of time and money. Protection methods to reduce the negative effects of low maturity depend on the product characteristics.

To determine the depth of development and the necessary coordination between developers, the structure of the MIG can be used. Thus, the interfaces with external components and their approximate location can be determined in the product. Timely integration and consideration during the maturity assessment of suppliers is essential for transfer into series production. Other aspects are the availability of resources and the expertise of the supplier. This should be rated at the beginning of the development project and be used for selection. The following figure summarizes the factors and shows a rough differentiation of the potential risk factors in an early development phase. The initial estimation is only possible under uncertainty and in a qualitative framework. In the further course and a renewed assessment of the influencing factors, such as product maturity, a quantitative assessment can be performed using key performance indicators or test results.



Influencing factors		Potential risk low		high
Degree of innovation	Degree of market novelty	Further development	New development with known technologies	New development with new technologies
	Degree of technology novelty	Carry over components	New components or new materials	New components with new materials
Complexity	Product complexity	Low number/ variety/ relationships of components	Medium number/ variety / relationships of components	High number/ variety / relationships of components
	Process complexity	Low number and variety of parallel activities	Medium number and variety of parallel activities	High number and variety of parallel activities
Maturity	Product maturity	Functional requirements fulfilled	Components are usable, requirements not fully met	Functional testing of components not possible
	Process maturity	Reproducible quality	Series production possible, high percentage of rework	Process capability not testable, production system not determined
Supplier integration	Depth of engineering	Small number of components from development partners	Medium number of components from development partners	High number of components from development partners
	In-house production depth	Small number of 1st tier suppliers	Medium number of 1st and 2nd tier suppliers	High number of 1st and 2nd tier suppliers

Figure 6. Example of qualitative assessment of influencing factors and their potential risk

3.3 Visualization of a risk matrix

The assessment of factors in the very early stages of development is based on incomplete information. The evaluation approach must cope with the evolutionary character of the transition between development and production and must be in a position to deliver decision in the absence of information. In order to supplement missing information in the early stages, the approach must resort to empirical analysis or expert assessments; the performance of the product and the manufacturing processes can only be predicted. Only in the course of development is it possible to replace qualitative evaluation methods with quantitative ones. The choice of evaluation approach is significantly influenced by the stage of development and the prevailing uncertainty. This implies that a significantly greater dispersion of the evaluation results can be expected, for example, for an assessment in the concept stage, as opposed to an assessment during prototype production. Despite high uncertainty, the assessment is required to secure the highest possible response time. It is important that the assessment supports the decision maker in a transparent way, despite the uncertainty of the available information. The fuzzy set theory represents a possible mathematical way of accounting for uncertainties in the information [Tauhid 2007]. This approach will be integrated within the methodology of assessment for the ramp-up, to realize estimation during development and avoid problems occurring during initial production.

A portfolio approach is adopted to assess the factors described in Figure 7 and their potential risk. The advantage of this method is high flexibility: adjustments can be made for new influencing factors. The risk portfolio can be used for the risk assessment of the proposed factors. Therefore, the probabilities of risk events and their impact on the target criteria are plotted against each other. For the influencing factors, the probability of potential risk and its impact can be estimated and transferred using fuzzy logic on an integral scale. The assessment is based on the given product structure and its relationships. The crosses in the graph represent the possible deviation in the assessment of potential risk and its impact. The larger the cross, the more uncertain is the estimation.

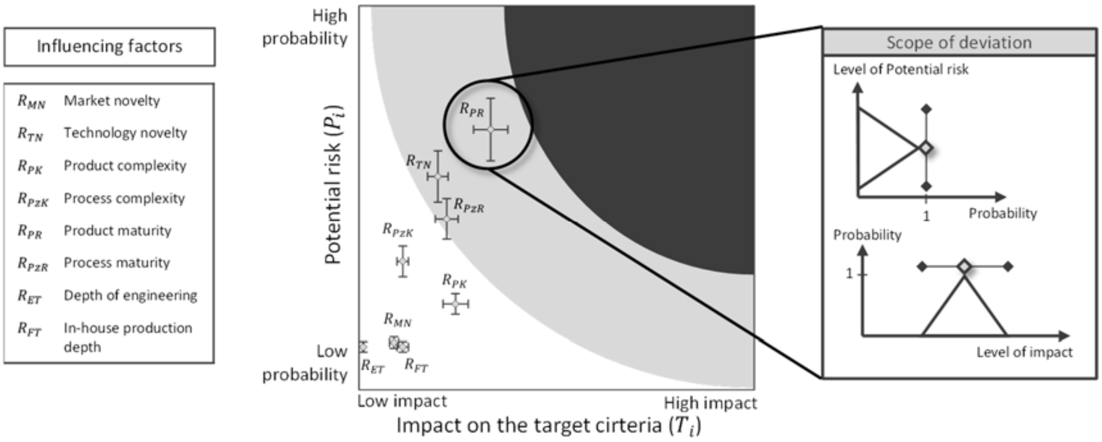


Figure 7. Example of risk matrix for visualization of the potential risk and their impact

3.4 Evaluation of the ramp-up capability

The individually assessed risk factors of the subsystems are summarized for the final evaluation of ramp-up capability. The significance of ramp-up capability is limited to a comparison of development stages and helps monitor the planned targets in terms of time, cost and quality. Long-term optimization and validation of critical components can help in the development of complex products. A detailed analysis of the subsystems can be carried out in the third step. For overall evaluation of the product, however, the sum of the maximum values has to be determined to analyse the performance of the product launch (Figure 8).

The potential risk and the impact will be divided and calculated separately to get a comparative value. For the calculation, the estimated range of deviation of each risk character will be summarized across the scale for potential risk and impact (Figure 8, top right). The application of the individual values is limited by a closed surface (curve) of the maximum values. One value for the potential risk and one for the impact can be calculated based on the area formed with the help of the center of gravity. The classic multiplication of potential risk value by impact can be performed to get an overall value.

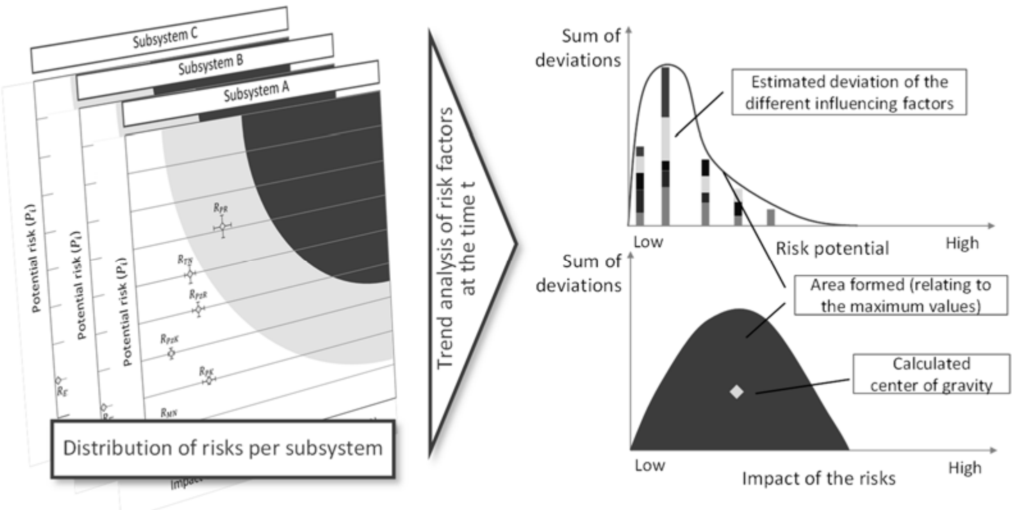


Figure 8. Consolidation of the individual risks for the ramp-up capability

The aggregation of individual factors across the entire product structure provides initial statements on the ramp-up capability. The risk potential and scope can be applied for the state of development at different times. As part of a trend analysis, the ramp-up capability can be expressed in terms of area calculations. The smaller the center of gravity of the area under the curve of the maximum values, the more likely is an efficient ramp-up of production. The aim should be to achieve the lowest possible center of gravity of the area to reduce the impact and probability of deviations. A detailed comparison and investigation of the maximum values must be analysed in advance. The calculation of area only provides a basis for the monitoring of the entire ramp-up capability at this point.

3.5 Measures to reduce risk

The assessment can be used to make decisions on strategies to reduce identified risks. Depending on various factors, it provides different approaches for a decisive contribution to risk minimization. Generally, the smaller the changes to the previous product, the smaller the deviations in the transformation of development results into production.

Mitigation strategies for the identified risks depend on the influencing factors and the development phase. For example, a low level of maturity of the components can be improved by a greater use of prototypes, test scenarios and, in parallel, digital backup. Identified problems in innovation and the degree of complexity in the concept phase can be addressed with the help of product structuring measures, such as modularization or platform development. This supports the increasing share of the parts carried over and the standardization of interfaces to reduce potential risk drivers. For detailed recommendations, product structures of previous products can be used as a starting point. Figure 9 provides structuring measures for influencing factors.

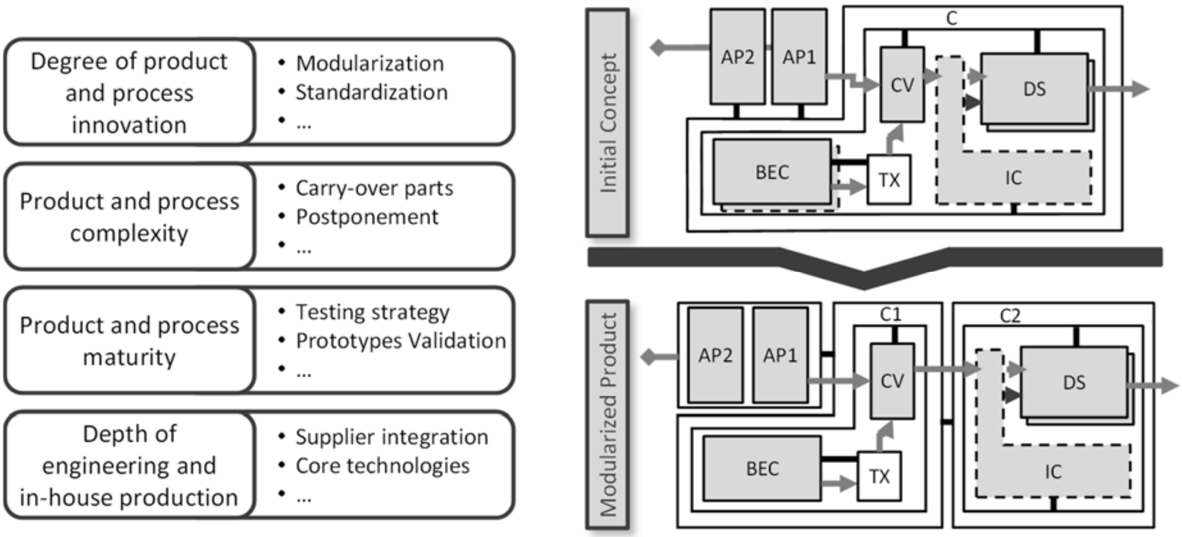


Figure 9. Example of mitigation strategies in the concept phase

A simplified example of restructuring the product complexity is presented on the right side of Figure 9. The starting point is to change the product structure with the help of, for example, modularization to improve the concept for ramp-up criteria. An increased degree of modularization allows, for example, separate testing of larger units. The modular concept supports the postponement strategy. To reduce the customization effort of the product, the customer-relevant attributes and variant components are summarized in an extra module (C2). A standardized module leads to scale effects and an increased learning curve.

4. Conclusion and further research

This paper highlights the need for early consideration of the ramp-up phase in the development of complex products. Empirical studies from other industries reaffirm the fact that the ramp-up phase is a critical part of the life cycle of innovative and complex products. The aim of this paper is to develop a methodology for the early identification and minimization of ramp-up risks. This must be done with the help of a risk assessment based on the influencing factors and their impact on the ramp-up criteria. The transparency generated helps to identify potential problems before production begins. The approach provides response strategies for any possible deviations from targets. The strategies form the input for the efficient transfer of development results into production. Further development of the approach requires validation by case study. In addition, further analysis is required of the interaction of risk factors, as well as mapping into a holistic assessment of the ramp-up capability of the product. Concrete recommendations for action must be substantiated with heuristics for different risk scenarios.

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