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Dealing with development risk and complexity in planning situations within product engineering processes

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Abstract

Every product development process is unique and individual. Nevertheless, patterns of recurring and similar elements exist in different processes which experience specific characteristics depending on the type of project. In addition to the different objectives that form the basis of a product development process, projects differ primarily in their share of new development and their degree of complexity. In order to deal appropriately with the resulting uncertainty, implementing agile approaches in processes of mechatronic system development is becoming more popular with the aim of making the development project more flexible. However, it must be borne in mind that not every development process requires an agile approach. Although plan-driven approaches have a poor ability to react to changes, they provide clear structure that leads to a common understanding of the process and a clear definition of objectives. Since a development project does not only contain problems that are well-suited for an agile or a sequential approach it is important to adapt the process to the underlying situation and requirements. In sufficiently plannable situations a purely agile approach would entail the loss of structure. On the other hand, a purely sequential approach for highly uncertain problems means that the process has to be adapted frequently in order to react appropriately to changes and newly acquired knowledge. The approach of ASD – Agile Systems design helps developers to implement suitable development procedures at different process levels depending on the degree of planning stability. In this context, this contribution presents a methodology that examines the influence of new development and complexity on different elements and supports developers in process planning by combining flexible and structuring elements to avoid multiple replanning.

Keywords: Agile Product Development; Mechatronic System Development; Prodcut Development Process; ASD – Agile Systems Design

1. Introduction

Product development projects are carried out within a project-specific context consisting of different objectives and constraints. As a result, there is no product development process that is valid for several projects. [1] Nevertheless, patterns of recurring and similar elements, such as phases and activities, exist in different processes across different industries [2]. In addition to different objectives, projects primarily differ in their share of new development of the product to be developed and the degree of complexity. As the proportion of new developments increases there is higher technical risk and uncertainty since the required knowledge to ensure that the product can fulfil its function must first be generated or organized in form of experts. [3] Developers have always had to deal with uncertainty [4]. It is defined as the difference between the amount of information required to perform a task and the amount of information already available. [5] In order to respond appropriately to the uncertainty resulting from the share of new development and the degree of complexity, the implementation of agile approaches as Scrum or Design Thinking in processes of mechatronic system development is becoming increasingly popular with the aim of making the process more flexible and ensuring the ability to react to unforeseen events. [2,6] Agile approaches are well suited if, due to changed boundary conditions or new findings, adjustments or a replanning of the project plan frequently have to be made. [2,7] However, despite their success in software development they quickly reach their limits in mechatronic system development due to the physical shape of the product. [6] As the product development process can be seen as a problem solving process traditional plan-driven approaches seek to optimize this process [8,9]. They are used in

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physical product development for decades and offer a clear structure leading to a common understanding of the process and a clear definition of objectives [10]. For this reason, objectives, requirements, framework conditions, etc. must be defined beforehand [11]. These characteristics mean that plan-driven approaches are well suited for environments that are stable and subject to low change, but they lack the ability to adapt. [12]

However, a development process consists of several problems requiring different approaches (agile or plan-driven) due to their degree of complexity and share of new development of the product to be developed. Furthermore, these factors are related to the product and process complexity [13]. Therefore, it is important to adapt the process to the needs and requirements of the underlying situation. [2] Developers currently lack an approach that supports them in planning engineering generations [14] depending on the share of new development of subsystems and the degree of complexity of the underlying problem. In this paper a method is presented which uses the new development share and the degree of complexity as input factors in order to analyze their influence on the different elements of the project plan. This creates awareness of the plannability of the process so that planning is only carried out as far in advance as the state of knowledge permits. Hereby the robustness of the project plan is increased on overall process level and the number and extent of necessary changes in process and product are reduced.

2. Literature Background

2.1. Dealing with uncertainty and complexity

Product development can be abstractly described by the system triple of product engineering. It includes the system of objectives, the system of objects and the operation system. [15] The *Advanced System Triple Approach* [16] complete the development process by including analysis and synthesis activities. The operation system continuously transfers the system of objectives into the system of objects. In the course of the process, the system of objectives is continuously expanded and concretized by the operation system taking up objects of the system of objects and deriving new objectives through analysis and synthesis activities. Due to the iteration of analysis and synthesis activities uncertainty can be mitigated. [16]

In the understanding of product development as a socio-technical system, complexity depends on the system-specific context [17] GERALDI ET AL. [18] describe complexity using the five factors *socio-politics, pace, dynamic, uncertainty and structural complexity*. Furthermore, the term *VUCA - Volatility, Uncertainty, Complexity, Ambiguity* is becoming increasingly popular to describe system circumstances against the background of complexity [17,19]. As various degrees of complexity require different procedures, SNOWDEN AND BOONE introduced the *Cynefin framework*. With its help the operative context of a system can be determined and appropriate procedures from a management point of view can be derived. Simple and complicated contexts are characterized by stability and a clear cause and effect relationship. Based on facts right answers can be determined although a complicated context often requires expert knowledge. Complex and chaotic contexts on the other hand include problems that are great subject to change. Therefore, this kind of context is characterized by unpredictability and instability. There is no apparent cause and effect relationship. [7] Since BREITSCHUH ET AL. assume that several domains of the *Cynefin framework* exist in parallel in product development projects, the framework is extended by combining the operational context with complexity as a system property, in order to detect the transition from one context to another. [20] Therefore, the factors defined by GERALDI ET AL. [18] and *VUCA* are summarized into four complexity factors: *Pace, Availability of Knowledge and Transparency, Structural Complexity* and *Lack of Definition and Agreement,* which are defined as impact factors in domain transition [20]. As preserving complex states of social systems requires energy BREITSCHUH ET AL. include *entropy* as a further measure. [20] Entropy is to be understood as a measure of the lack of knowledge in order to conclude from the macroscopic state of a system the microscopic state of all its elements [21]. The combination of complexity as a system property, the operative context and entropy results in the definition of the Entropy Compass (see Fig. 1). It serves as a means to describe and analyze the present project situation including the influencing factors on the probability of domain transitions. In addition, it represents a classification scheme for procedures to cope with the degree of entropy, which is defined by the complexity dimensions and reflects the planning stability of the respective development situation. [2,20]

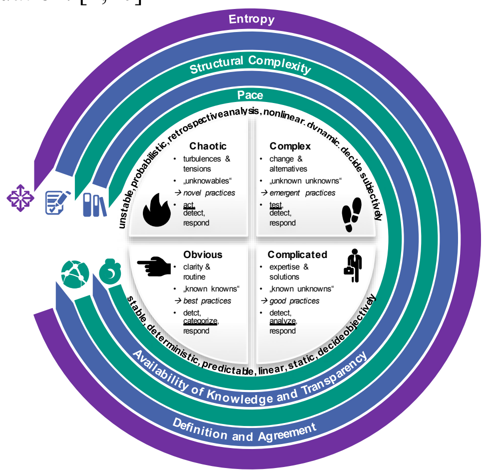

Fig. 1. The Entropy Compass according to BREITSCHUH ET AL. [20]

The operative context has great impact on the planning stability of a project. While plan-driven approaches such as VDI 2221 [22] are well suited for complicated contexts, agile approaches have proven themselves in complex contexts. For an appropriate handling of context transitions it is necessary to recognize the nature of the problem. This requires the consideration of the operative context and the system properties. [2]

2.2. Agile vs. plan-driven approaches

In development projects, a basic distinction is made between agile and plan-driven procedures. Depending on the type of problem, the two approaches are suitable for different purposes. Plan-driven models such as VDI 2206 [23], Stage-Gate [10] or Waterfall [24] are characterized by a high degree of detailing. Requirements for the product and its features have to be specified in advance. [11] The overall goal is to standardize the development process in order to maximize its functionality and reduce changes of requirements [25]. The transparent structure on which the plan-driven approaches are based leads to a common understanding of the process and a clear definition of objectives [10]. From the traditional point of view of project management, a project is determined by three factors: cost, time and scope, more known as *The Project Management Triangle*. With plan-driven approaches, the scope and product requirements are usually defined at the beginning of the project. Costs and time adapt flexibly in each case. [26] However, not all product requirements can be completely identified in at the beginning of a project. Changes lead to time-consuming and costly revisions. [27] The later the changes occur in the process, the more effort is involved, since all partial solutions downstream of the change must also be adapted [28]. Moreover, the customer is not a constant part of the development process but only when required [12]. The discovery of changing needs may therefore be delayed [29]. Nevertheless, plan-driven approaches are suitable for larger projects that take place in a stable context and which are characterized by minor changes, as well as products whose design is extensive and the increments to be developed take more time. The management of such projects is based on a series of documented plans and is focused towards the customer on adhering to the contractual conditions. [12]

When in 2001 the Agile Manifesto was published by a group of practitioners from the IT industry the application of agile approaches to project management has become more and more important. [30] Agile development itself can be traced back to methods such as Scrum and Extreme Programming. The individual methods contain different approaches, each of which has its own advantages and can be combined with each other. The primary goal of agile approaches is the rapid creation of added value and a short response time to changes. [12] Products are developed incrementally in iterations by self-organizing teams to meet the requirements of a dynamic environment. In contrast to traditional approaches, the customer is strongly integrated into the development process in order to consider his needs and feedback in the further development. [31] In contrast to plan-driven approaches duration and costs of each sprint are defined in advance but the scope can be adjusted. [26] Its results are continuously evaluated, validated and adapted to reduce the risk of developing a product that does not meet the customers' requirements. [26] In order to save development time, no time-consuming documentation is required. However, this property is to the disadvantage of agile methods. Since no detailed product documentation is provided, it is difficult for new developers to familiarize themselves. [32] Due to the increasing share of electrics, electronics and information technology mechatronic products become highly complex [33]. The growing uncertainty and dynamics various industries are facing emphasize the importance of agile methods in mechatronic system development as well as an optimal level of organizational agility [6,34]. In doing so, a number of challenges have to be mastered that arise with the use of agile methods in the development of physical products. [6] To counteract this, hybrid approaches combine agile and plan-driven methods to exploit the strengths of both. The goal is to find an optimal balance between flexibility and process stability. The boundary conditions of the respective process must be considered in order to derive the main characteristics of plan-driven or agile approaches accordingly. [27] An example of this is provided by the approach of ASD – Agile Systems Design [2]. Assuming that within product development processes problems with different complexity levels co-exist [2], the approach of ASD – Agile Systems Design "supports the developer during the innovation process as a holistic, structuring approach for the agile development of mechatronic systems, the associated product strategy, validation systems and production systems, consisting of principles, methods and processes of PGE – Product Generation Engineering." [35] It is based on nine principles that support development teams in developing mechatronic systems. The principles serve the company- and context-specific design and application of suitable development practices. These provide guidelines for aligning action with them. The model of ASD – Agile Systems Design is used to select suitable development procedures on different process levels depending on the planning stability of the

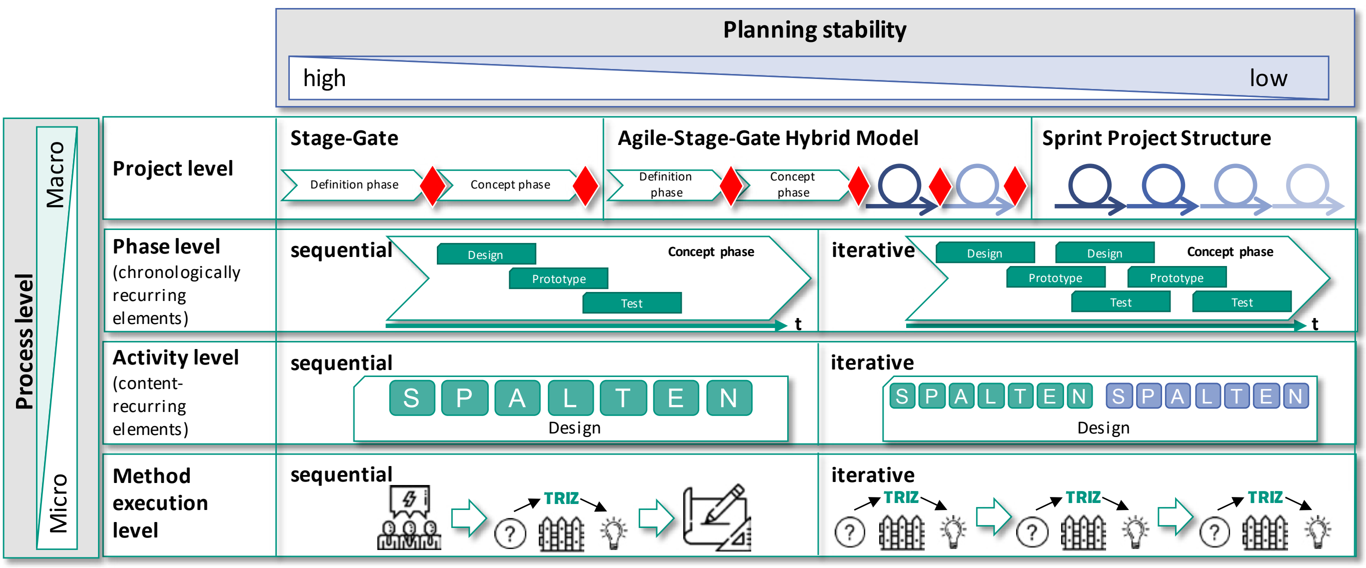

Fig. 2. Model of process design with ASD – Agile Systems Design. [2]

given development context (see Fig. 2). At the respective process level, a distinction can be made between sequential and iterative procedures. For this purpose, the planning stability of the development context is determined using the Entropy Compass. The development procedure for solving the problem is selected flexibly. Thus, developers can implement a situation- and demand-oriented degree of agile elements into the development process. If the development context is subject to a high degree of planning stability, a sequential approach is used. If the planning stability is rather low tasks are handled iteratively. [2,36]

2.3. The Model of PGE - Product Generation Engineering

PGE – Product Generation Engineering is the operationalization of the sixth principle of the ASD “Each Product is Developed on the Basis of References” [2]. The model comprises the development of technical products which are characterized by the adaptation of subsystems as well as by the new development of subsystems. The development of a product generation is always based on a reference system, which includes reference elements. Reference elements can be both predecessor and competitor products whose structure and subsystems have been adopted or used as a starting point for variations. [37] This understanding allows the reuse of already existing subsystems by distinguishing three types of variations: carryover variation (CV), embodiment variation (EV) or principle variation (PV). While CV refers to the adoption of existing solutions, EV (adaptation of the design while retaining the solution principle) and PV (realization of a function while using a new solution principle) are combined as the share of new development. [38] Depending on the type of variation, different patterns can be identified in projects. [39] The model facilitates planning, classification and description and thus the management of a product development task. The development of a product generation G_i is structured by engineering generations $E_{i,j}$. They describe the status of the intended customer, user and supplier benefits of the product generation G_i. Like product generations, engineering generations are based on at least one reference element, such as the previous development generation $E_{i,j-1}$, and can be described by the same types of variations of technical subsystems. The development process of engineering generations is structured by the phases: *Define* $E_{i,j}$, *Realize* $E_{i,j}$, *Validate* $E_{i,j}$. In the beginning, the system of objectives for the engineering generation $E_{i,j}$ is defined. The system of objectives is then transferred into the system of objects. Finally the engineering generation $E_{i,j}$ is validated whereby the technical implementation is evaluated against the defined objectives. The number and timing of engineering generations depends on the characteristics of the product generation G_i like the share of new developments and the origin of reference elements. [40]

Fig. 3 shows the visualization of the development risk using the first generation of the dual mass flywheel as an example. The framework allows to assess the risk associated with the development of a product. The share of new development and the level in the system structure are one of the influencing factors for the development risk. The higher the share of new developed subsystems is the greater is the respective development risk mostly due to technical reasons. [41]

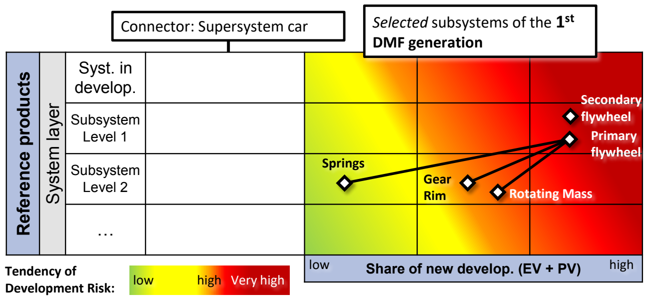

Fig. 3. Visualization of development risk according to ALBERS ET AL. [41]

3. Aim of Research

The increasing dynamics with which companies in mechatronics system development are confronted is leading to an increasing integration of agile approaches into the product development process. In contrast to traditional approaches, there is an awareness of uncertainty and changing information bases. A more detailed view on the development process of product generations is possible by structuring it into engineering generations. Development teams currently lack a method that supports them in planning engineering generations depending on the development risk of the respecting subsystem and the degree of complexity of the development situation. Therefore, a method is presented in this contribution based on the ASD – Agile Systems Design as it assumes that development teams face problems with a varying degree of complexity in a project. Since the selection of an agile or plan-driven approach is dependent on the degree of planning stability, the method should include mechanisms which allow developers to estimate the operational context. Furthermore, the number of required engineering generations of a product generation or the respective subsystems is correlated with the share of new development. In addition, the necessary depth of technical detail of the engineering generations being developed influences the planning of iterations with regard to their length and the activities and competences required in each case. [42] In addition to the assessment of planning stability, the technical risk must therefore also be estimated. In order to support development teams in planning engineering generations in a project-specific, situation- and demand-oriented way, the following questions have to be answered:

1. Which elements are part of a development process and which are relevant for its planning?
2. What influence do the risk portfolio of PGE – Product Generation Engineering and the entropy compass have on the classification of elements and thus on the plannability of processes?
3. How can these correlations be used to plan product development processes in accordance with their share of new development and planning stability?

The questions are answered based on a literature research as well as experiences in product development. Based on the results of the first two questions, a methodology is developed to support development teams in process design of engineering generations based on the technical risk and the degree of complexity. Recommendations for action with regard to project planning are derived from the third question.

4. Results

4.1. Recurring, similar elements in product development processes

Recurring, similar elements, such as phases or generic activities, are continuously subject to analysis and synthesis activities during the product development process. In order to identify those elements literature in the context of *The Advanced System Triple* [16] is analyzed. The elements from literature were distinguished into those that specify the project, such as objectives, requirements and framework conditions, and those that are relevant to the design of the project plan. The literature analyses led to 27 elements shown in Table 1. Elements which are marked bold are relevant for the planning of the development process.

Table 1. Recurring elements in product development processes

Element	Source	Element	Source
Objective	[16]	Customer	[35]
Function	[35]	**Phase**	[2]
Test	[43]	**Deliverable**	[10]
Team	[1]	Document/Information	[1]
Costs	[1]	**Infrastructure**	[1]
Reference system element	[44]	State of knowledge	[16]
Attribute	[35]	Boundary condition	[35]
Requirement	[44]	Stakeholder	[35]
Shape/Implementation	[45]	**Milestone**	[10]
Decision	[10]	**Activity**	[2]
Product Profile	[35]	**Vision**	-
Method	[46]	Completed project documentation	[41]
Tool	[47]	Solution space	[16]
Engineering generation	[14]		

The elements do not refer exclusively to the overall project, but equally to different subsystems and engineering generations. By designing the development process, activities are modelled in a chronological sequence in the project plan. It provides time and content orientation in the development project. As the development process of mechatronic systems is usually modelled as a Stage-Gate process, the project plan includes phases, activities, milestones and its deliverables as traditional Stage-Gate elements as well as teams, costs and infrastructure which are assigned to activities. The vision reflects the final product. Usually, the actual course of the project deviates from the project plan due to unforeseen events [47]. The resulting delta between the project plan and the actual course of the project can be used retrospectively to evaluate planning stability. The Entropy Compass, on the other hand, allows only the estimation of planning stability in the beginning of a project [2]. In the course of the project, the project plan and its actual course must be adapted to each other. The resulting effort depends on the time and progress of the project. The earlier the adaptation is carried out the less effort is necessary as a result of new planning or rescheduling. If, on the other hand, the actual project progress is not explicitly checked until a later point in time, the adjustment effort increases. Besides planning stability uncertainty is considered as an important factor for the selection of a suitable approach. The higher the new development share of the project, the higher is the necessity to generate situation-specific knowledge and to define the technical system in order to validate the solution continuously. Consequently, the uncertainty of the development project also increases. The occurrence of uncertainty in process planning is summarized under the term *planning uncertainty*. As a project is determined by the factors cost, time and scope, concrete values must be assigned to them during project initiation. With regard to the identified elements, deliverables reflect the scope or the progress of the project, which must be available at a certain point in time. The factors are defined at the beginning of each project, by assigning a target value to them. The target value takes into account the project-specific context. The same applies to the other elements that are relevant to the project plan. Since there is an interaction between the factors, this must be taken into account. For example, if the duration of activities in a phase is reduced, the scope decreases which means that the deliverables cannot be achieved and/or costs increase. Due to the interrelations the possibilities to define the factors increase. The definition of deliverables is of particular importance as elements such as activities, infrastructure and test can be derived from it. The more knowledge and experience are available within the development team the more reliable is the definition of target values. The higher the reliability with which factors can be defined, the lower the planning uncertainty. For example, a high share of new development leads to a low availability of situation-specific knowledge. This must be generated by activities of validation during the project. Due to that it is not possible to assign reliable target values to the factors during the project initiation. In the course of the project their actual value is measured. The greater the deviation from target value and actual value, the lower the planning stability. The aim of process planning is to create planning stability by selecting a suitable development approach. A high degree of planning uncertainty therefore requires a robust approach to ensure planning stability.

To assess the degree of complexity and thereby planning stability the Entropy Compass Tool is used. It allows project participants to estimate different characteristics of relevant project factors which results in an overall degree of complexity and thereby in the planning stability of the development situation. [36] As the degree of complexity and thus the planning stability influences the identified elements with regard to their plannability the Entropy Compass is divided into an upper and a lower half. While high planning stability generally results in good plannability of elements, the opposite occurs if the system to be developed is associated with low planning stability. Plannability is a characteristic of the specific system triple and a measure of robustness to what extent a planned project progress applies. The values of the elements change depending on whether the total entropy of the present development situation is classified in the upper or lower half. The following three values can occur: *well plannable, poorly plannable* or *no influence*. The upper half is characterized by a high degree of complexity and thus reduced planning stability. The opposite is true for the lower half. An excerpt of the results of the impact analysis for the factor complexity are shown in Fig. 4. It is limited to the elements that are relevant for process planning.

Elements	Degree of complexity of development context	
	chaotic / complex	obvious / complicated
Activities	poorly plannable	well plannable
Phase	no influence	no influence
Costs	poorly plannable	well plannable
Vision	poorly plannable	well plannable
Milestone	no influence	no influence
Test	poorly plannable	well plannable
Deliverables	no influence	no influence
Team	poorly plannable	well plannable
Infrastructure	poorly plannable	well plannable

Fig. 4. Extract of the impact analysis for the degree of complexity

The elements *phase, milestone* and *deliverable* are not influenced by the degree of complexity since they are part of the project level phase in ASD and refer to the overall system. In this contribution the planning on this level is considered to be similar to a Stage-Gate as mechatronic system development products are developed using this type of process which means that these elements are fixed.

To estimate the technical risk of subsystems which is linked to the planning uncertainty the framework of ALBERS ET AL. [41] is simplified by dividing it into 6 clusters (see Fig. 5). The subsystems are classified into one of the clusters depending on their new development share and the system level. The tendency of the development risk is expressed by the color scheme and is largely identical within a cluster.

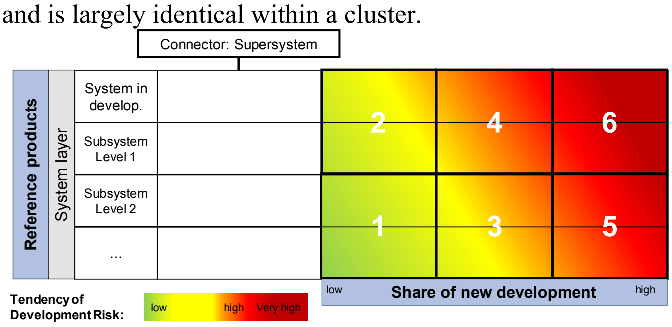

Fig. 5. Simplified framework for assessing the development risk

The subsystems specify the elements of planning depending on the development risk. For this reason, four values were defined in advance, which the variables can assume: *patterns known, patterns partially known, patterns not known* and *no influence*. Here, patterns in the process are meant. If, for example, a subsystem from the previous generation is integrated into the new generation via carryover variation, patterns of product development activities are known due to the high level of conformity of the system of objects. The elements which are part of the product development process do not occur independently of each other but have a mutual influence. For the impact analysis, this means that an element assumes the value *patterns known* if dependent elements have already been defined. If, for example, the element *test* has the value *patterns known*, then the *objectives* and *requirements* for the system to be tested, as well as its *functions*, are already known. Elements get the value patterns *partially known* if the dependent elements are partially defined, but the probability of changes due to new information is high. Accordingly, the value *patterns not known* is assigned to elements which cannot be defined at the beginning of the project because the definition of dependent elements is missing. It is only possible to discover the patterns of these elements in the course of the development process. If the elements are independent of the classification in clusters, they get the value *no influence.* An extract of the impact analysis is given in Fig. 6.

Elements	Value					
	Cluster of risk portfolio					
	1	2	3	4	5	6
Activities	patterns known	patterns known	patterns partially known	patterns partially known	patterns not known	patterns not known
Phase	no influence	no influence	no influence	no influence	no influence	no influence
Costs	patterns known	patterns known	patterns partially known	patterns partially known	patterns partially known	patterns partially known
Vision	patterns known	patterns known	patterns known	patterns known	patterns known	patterns known
Milestone	no influence	no influence	no influence	no influence	no influence	no influence
Test	patterns known	patterns known	patterns partially known	patterns partially known	patterns not known	pattern partially known
Deliverables	no influence	no influence	no influence	no influence	no influence	no influence
Team	patterns known	patterns known	patterns known	patterns partially known	patterns partially known	patterns partially known
Infrastructure	patterns known	patterns known	patterns partially known	patterns partially known	patterns not known	patterns not known

Fig. 6. Extract of the impact analysis for the development risk

In the next step, the identified elements, the tools for assessing the degree of complexity and the development risk as well as the impact analysis are combined into one method. In order to design the project plan, the *elements phases, activities, milestones, deliverables, infrastructure, costs, team, test* and *vision* are needed. For reasons of simplicity, the remaining elements are not explicitly taken into account. The method consists of three steps:

1. *Assessment of the degree of complexity of the context and assessment of the development risk of the subsystems to be developed:* The Entropy Compass Tool and the simplified risk framework are used in order to assess the degree of complexity and the development risk as input factors for the design of the project plan
2. *Classification of elements of planning:* Based on the resulting degree of complexity and the development risk the impact analysis is used to get information about the plannability (poorly plannable, well plannable, no influence) and the degree of definition (patterns known, patterns partially known, patterns not known, no influence) of the elements of planning.
3. Process design on phase level of subsystems: On the basis of the classification of the elements, the process of engineering generations can be designed according to situation and needs. The method is summarized in Fig. 7.

4.2. Exemplary Application of the Method

As the development risk of the system to be developed and the degree of complexity are both factors influencing the design of a project plan it is the first step to estimate them by using the Entropy Compass Tool and the simplified risk framework. Subsequently the impact analysis provides information about the plannability and the degree of definitions of the elements. The different value combinations resulting from development risk and degree of complexity require different handling in the planning of engineering generations. For this purpose, it is necessary to consider different process levels. The project as a whole is represented by the project level. Under the assumption that the planning resembles a Stage-Gate process on this level, milestones and the associated deliverables between the phases represent cross-departmental synchronization points [40]. Since the product generation consists of a number of subsystems [37], each of which has its own product development process the question of a suitable development procedure for the engineering generations of the individual subsystems at phase level arises. In principle, three different types of procedures can be applied: agile, sequential and hybrid. In order to demonstrate the application of the method, the development of a vehicle generation is studied. The focus is on the chassis and the powertrain as subsystems of the overall vehicle. As a first step the development risk and the operational context have to be assessed using the using the simplified risk framework and the Entropy Compass Tool. While the subsystem chassis is adapted as carryover variation from the predecessor generation the powertrain should be electrified in comparison to its predecessor which makes it a principle variation. By offering an electric vehicle in the product portfolio, the company is possibly striving to serve a new market segment. The high share of new development of the powertrain and the changing customer needs lead to the fact that the operative context can be described as complex. Furthermore, the powertrain can be assigned to cluster 6 due to its system level and its share of new development. Due to the operative context planning stability is low while the high share of new development leads to high planning uncertainty. Based on the resulting development risk and the degree of complexity the results of the impact analysis give information about the plannability and the degree of definitions of the elements of planning. Due to the described development context the majority of elements is characterized by the values *poorly plannable* and *patterns not known.* Based on the resulting classification of the elements the process of engineering generations can be designed on the phase level of subsystems. To take into account the high probability of changes due to the acquisition of new information in the course of the process, an incremental, iterative planning of the engineering generations $E_{i,j}^{Powertrain}$ is recommended. The *activities* should be planned as far in advance as the current state of knowledge permits since the probability of deviations from project plan and the actual course of the project is high. This can be attributed to the fact that case-specific knowledge is not sufficiently available in the beginning and must first be generated by validation activities. It is also recommended to plan the element *test* only as detailed as the information available allows. For example, it is possible to plan capacities at the start of planning, but to define test cases and test environment only when sufficient information and knowledge are available. By avoiding long-term detailed planning under high uncertainty, the adjustment effort is kept low. Furthermore, it is suggested to develop the engineering generations of the powertrain in several versions, the maturity level of which increases continuously. At the review points the version of the respective engineering generation must be fully validated. Due to the iterative process, knowledge gained from this can be integrated into a further version $E_{i,j,2}^{Powertrain}$ of $E_{i,j}^{Powertrain}$ .The basic activity *manage projects* is carried out in parallel with all other activities in a regularly recurring mode to support the product development process, to adapt the project plan if necessary and to reduce uncertainty. When looking at the development of the chassis, case-specific knowledge and experience in the development team is high, resulting in a lower degree of complexity and thus in a complicated context accompanied by high planning stability. In order to assess the development risk, it must be classified in the simplified risk portfolio. As the chassis is on the first system level and the share of new development is low, it is assigned to cluster 2. This results in low planning uncertainty. Furthermore, the *patterns* of the elements of planning are *known* and the elements are *well plannable.* At this point an iterative process design is not necessary. The high degree of knowledge and experience available in the team allow a more detailed planning which covers a larger time period. With regard to the engineering generation $E_{i,j}^{Chassis}$, whose system of objective is derived from the overall vehicle, this means that the probability of new findings leading to technical changes or changes in the project

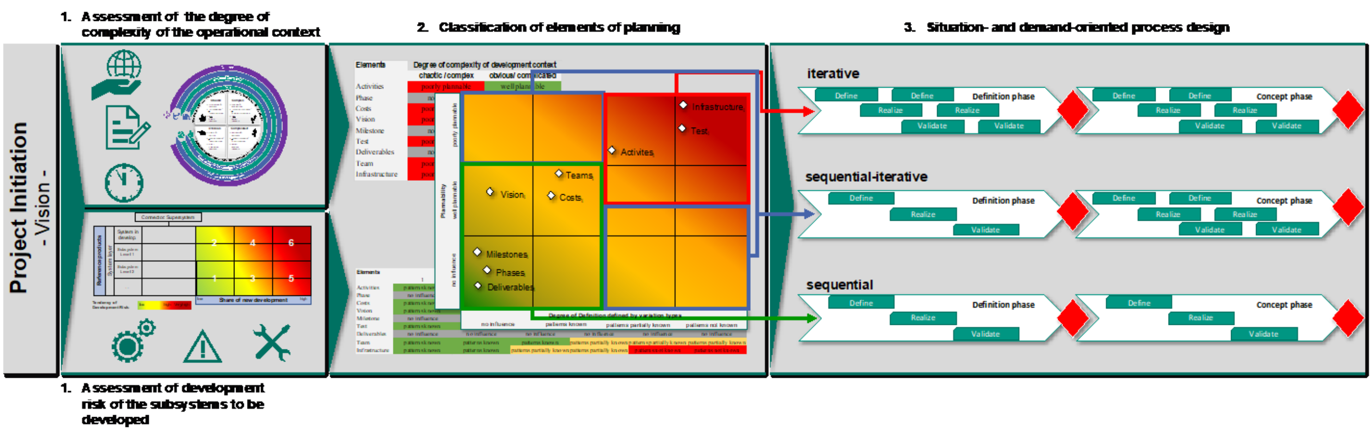

Fig. 7. Method for supporting the process design of engineering generations

plan is lower. An agile approach is not necessary at this point, as this would result in the loss of structure. Rather, a plan-driven, sequential approach should be chosen to stabilize the process. A hybrid approach that combines the advantages of agile and plan-driven methods is suitable for subsystems with a medium development risk. Depending on the degree of complexity of the context, the need for agile elements in the development process increases. Elements, whose *patterns* are *known* can be planned more detailed and in a longer term. Otherwise they should only be planned on the basis of the actual knowledge available and should be checked at regular intervals. Detailed planning of activities over a longer period of time should be avoided if their *patterns* are not *known*. If necessary, the existing results can be concretized in a further iteration cycle. The process of the engineering generations of the individual subsystems $E_{i,j}^t$ has to be completed at the milestone of the project level in order to integrate them into the overall vehicle, and to validate it. Findings from the validation of engineering generations E_i^t, and the overall system need to be transferred to the development of further engineering generations. The resulting process design based on the share of new developments and the degree of complexity is shown in Fig. 8.

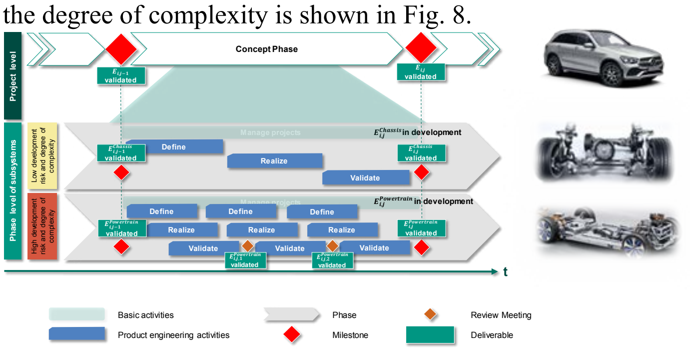

Fig. 8. Process design based on development risk and degree of complexity

4.3. Evaluation of results

In order to verify the results and assumptions of this contribution, they were formulated as statements and stored in a catalogue of questions. This was answered by representatives of different industries, who have experience in product development and project management. The survey was created with LimeSurvey and answered by n=23 participants from the automotive, drive technology, agricultural engineering and aerospace industries. Of the 23 participants, 21 have an engineering background. The participants could more or less strongly agree or disagree with the statements. At the beginning, the elements relevant for designing the project plan had to be evaluated with regard to their significance in the project plan (see Fig. 9). The two subsequent statements referred to the new development share and the degree of complexity in order to assess their influence on the choice of a suitable development procedure. Finally, statements were made on the results of this work in order to get a first impression of the perception of these findings in practice. The results are displayed in Fig. 10. For the evaluation, the mean value of the individual statements was calculated. The participants agree that all elements identified in this work that are used to draw up the project plan are relevant for its planning. The highest level of agreement is given to the classic Stage-Gate elements *deliverables, milestones* and *phases*.

In addition, there was the possibility to name further elements as part of the project plan. Here it was noted to explicitly distinguish *test* in *validation* and *verification*, since small changes, which are made in the course of the project, are partially only verified. In addition, risk management and the dependencies between the individual sub-projects and deliverables, as well as responsibilities, were mentioned as further components.

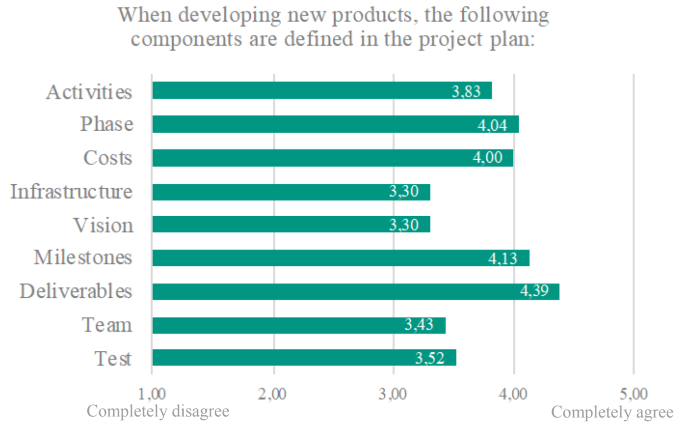

Fig. 9. Evaluation of the relevance of planning elements

The participants agree that the degree of complexity and the share of new development have a significant influence on the plannability of elements and on the detailed planning of the project plan. As far as the structure of the method is concerned, it can be concluded that it uses the right input factors in order to support developers in choosing an appropriate development approach. The positive correlation between the long-term character of the detailed planning and the probability of deviations from the actual course of the project and the project plan is approved. Similar support is given to the statement on the adjustment effort. Accordingly, the connection between adjustment effort and planning horizon can be confirmed in practice. What is striking about the evaluation is that the last two statements are a logical conclusion from the previous ones. Nevertheless, their agreement is lower. The reasons for this assessment cannot be determined on the basis of the survey described.

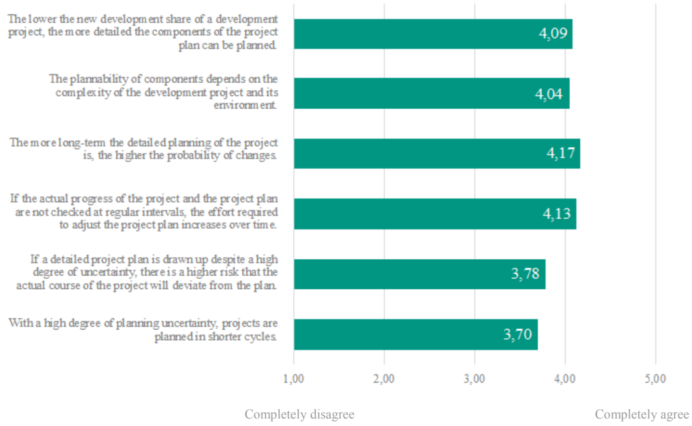

Fig. 10. Evaluation of assumptions and results

The causes for the decision of the participants would have to be examined further with the help of appropriate methods. With regard to the consistently positive evaluation, it can be concluded that the method takes up essential variables for the choice of a suitable development approach and draws correct conclusions from them. Nevertheless, the evaluation reveals trends, but is not representative due to a small sample size.

5. Discussion

In this contribution, a method was presented that supports teams in planning engineering generations according to situation and need. Besides varying degrees of complexity, the share of new developments of the product to be developed is considered as it influences planning uncertainty and the number of engineering generations. Recurring elements of development processes were identified from the literature to analyze the influence of new development share and degree of complexity by means of an impact analysis. The results of the subsequent evaluation can be regarded as positive as they confirm the relevance of such a method in practice. Nevertheless, the survey format could only show trends regarding the assumptions and conclusions of the method. Due to the relatively small sample size of n=23 and the limited number of sectors in which the respondents work, as well as a similar job description, this is not representative of the population as a whole. In particular, the reason for the lower approval of whether projects with uncertainties are planned in shorter cycles would be of interest for deriving recommendations for action. One possible reason for this could be the working environment of the participants, as the majority of those surveyed are active in the automotive industry, whose processes are generally similar to a Stage-Gate process. This could also explain the increased approval of the relevance of classic Stage-Gate elements for the planning of development processes. In order to be able to make more precise statements about this, the next step would be to conduct expert interviews. So far, no statements can be made about the application of the method in practice. Here the method would have to be validated as the subject of further research work in a real development context in order to be able to draw conclusions about its structure and the support provided.

6. Conclusion & Outlook

The development of a new product generation consists of a number of subsystems, which differ in their share of new development and the degree of complexity. Accordingly, there is no procedure that applies equally to all subsystems. Based on the state of the art in research, this work was able to demonstrate not only the degree of complexity but also the importance of the share of new developments in the choice of a suitable development procedure. Based on the fact that patterns of recurring, similar elements occur in product development processes, these, including existing relationships between them, were identified at the beginning. The developed method combines the technical risk, based on the share of new development as well as the degree of complexity, which is composed of the operational context in which the project takes place and the system properties. Based on the qualitative assessment of these factors, developers can estimate the technical risk and planning stability of the development situation, which influence the definition and plannability of the elements of a product development process. Subsequently, the influence of the share of new development and the degree of complexity on the elements was analyzed. The resulting characteristics support development teams in designing processes of engineering generations according to the respective situation and requirements.

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