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A systematic approach to situation-adequate mechatronic system development by ASD - Agile Systems Design

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Abstract

The process of product development is a problem-solving process characterized by the continuous handling of uncertainties by development teams. For this reason, companies in the field of mechatronic system development implement agile approaches in their development processes in order to deal adequately with these uncertainties, which, however, reach their limitations in individual areas due to different characteristics of physical products. In addition, the development processes contain problems that are of a complicated or simple nature and can therefore be sufficiently planned and solved by plan-driven procedures. For this reason, in the present contribution principles from the literature are derived that support developers in their activities in mechatronic system development. In addition, a model is presented that allows developers to assess the planning stability of individual process elements at different process levels and thereby implement a situation- and demand-oriented degree of agile process elements into the development process.

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Keywords: Agile Product Development, ASD – Agile Systems Design, Product Development Process

1. Motivation

Product development processes have always been characterized by uncertainties that make robust and long-term planning difficult [1]. Uncertainty is defined as the inability to predict future results and events based on a difference between the amount of information required and the amount of information actually available [2]. However, a flexible alignment of development teams enables an increased reactivity to unforeseen events [3]. With the aim of making development projects more flexible, companies are increasingly implementing agile approaches to counteract the lack of responsiveness of plan-driven development approaches. However, agile approaches usually originate in software development and reach their limits in various areas due to the challenges in the context of mechatronic systems. [4]

However, the strengths of flexible approaches are already known, particularly in solving complex problems characterized by unclear cause-and-effect relations between the elements involved. Since development processes do not exclusively deal with complex problems, the question arises whether a purely agile approach in the development process is appropriate with regard to the effectiveness and efficiency of development teams [5].

Regardless of whether developers develop according to an agile or plan-driven approach, their synthesis and analysis activities mean that they are decisively responsible for the design of the product and thus for its later success [6]. Already in 1852 Ferdinand Redtenbacher stated that the engineer did not only combine science and craftsmanship, but rather took on the role of the creative inventor [7]. In a dynamic development context, this leads to the challenge of supporting developers in choosing an appropriate approach (agile, hybrid or sequential) to be able to ensure inventing in an uncertain environment. This support should take place in a flexible, situation- and demand-oriented manner in order to meet the respective requirements

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resulting from the complexity of the respective situation. A systematic that supports development teams through a complexity-compliant process design in carrying out their activities is presented in this article. The area of application of the approach is mechatronic system development. It picks up aspects from the field of agile software development, plan-driven hardware development and empirical product development experience from over 20 years and derives principles for flexible-structured mechatronic system development.

2. Background and State of the Art

2.1. Agile Approaches for Product Development

Agile approaches have their origin in software development and are based on the agile manifesto. [8] Approaches such as Scrum [9,10] or Design Thinking [11] have emerged along these lines, which serve to operationalize the principles defined in the agile manifesto. Under the assumption that agile approaches increase the responsiveness of development teams to changes in the development context [12], companies from the field of physical product development are increasingly implementing these approaches in their processes [13]. However, a number of challenges arise, not least due to the physical properties of mechatronic systems [4].

These challenges arise, among other things, from the fact that the approaches used here were created for the context of software development and do not take into account the requirements from the field of mechatronic system development [14]. A number of agile or hybrid approaches (a combination of agile and Stage-Gate [15]) are being developed in current research projects to support mechatronic system development [16,17]. On closer analysis, however, these approaches are in turn only an adaptation of existing approaches from software development and only partially meet the requirements of mechatronic system development [14].

2.2. Innovation - the Basis of Economic Success

According to SCHUMPETER, innovations form the basis of entrepreneurial success and are distinguished from inventions by their economic significance [18]. For an invention to be successful on the market, it must satisfy a demand situation and be introduced to the market through suitable marketing activities [19]. In particular, the identification of potential future customer and user needs that are to be satisfied by the later product is not a trivial undertaking [20]. Already in 1987 COOPER defined the *clear identification of customer requirements at the beginning of a development project* to be the most important factor with regard to the financial performance of the later product [21]. For this reason, a high level of customer integration in the product development processes is a decisive success factor for identifying a relevant demand situation on the market [22].

The satisfaction of customer needs through the later product as well as the assurance of the product quality and product value felt by the customer must be ensured continuously in the product development process [23]. An incremental development of products is suitable for this purpose. Accordingly, prototypes that already realize certain functionalities are generated and iteratively extended early in the product development process in order to continuously validate them from the customer and user point of view. This is to ensure the satisfaction of the respective requirements by the later product. [24]

For this purpose, the product profile is an element which supports the modelling of customer, user and provider benefits on the one hand and the representation of these views in validation activities on the other. It represents a model of a bundle of benefits "which makes the targeted provider, customer and user benefits accessible for validation and explicitly defines the solution space for the design of a product generation" and thus contributes to targeted validation [19].

2.3. Modelling of Product Development Processes

Product development describes the translation of requirements into technical and commercial solutions or services. Each product development process is unique, but all processes have similar and recurring elements. [25] Based on this understanding, various process models with different purposes were generated to support product developers in transforming requirements into solutions [26].

Under the understanding that a need arises from an unsatisfactory current situation, the product development process can be understood as a problem-solving process [27]. This unwanted starting point is transformed into a desired target state (the solution), whereby the path (process) between these two states is unclear [28]. This transformation can be identified in the product creation process at different process levels (see Fig. 1). For example, fundamental thought and behavior procedures can be identified as cycles of short synthesis and analysis sequences at the micro-process level, summarized in terms of content and described as operational working steps or activities, which in turn can be integrated into larger working sections (Phases) [29]. These phases are structured at the overall project level by milestones that require different, previously defined product maturity levels. [30]

From the understanding of product development as a socio-technical system, the process of product development can be represented as the continuous transformation of a system of objectives into a system of objects through an operation system (based on [31]). The latter is made up of activities, methods and processes as well as developers and all other resources necessary for the development of the product. The system of objectives contains all objectives, their justification and interaction as well as boundary conditions to a solution, but not the solution itself. On the basis of the system of objectives, a solution space is created that represents a mental representation of all solutions that fulfil the system of objectives. Based on this, the development team (as part of the operation system) synthesizes various objects (prototypes, the final product) in the product development process, which are combined in the

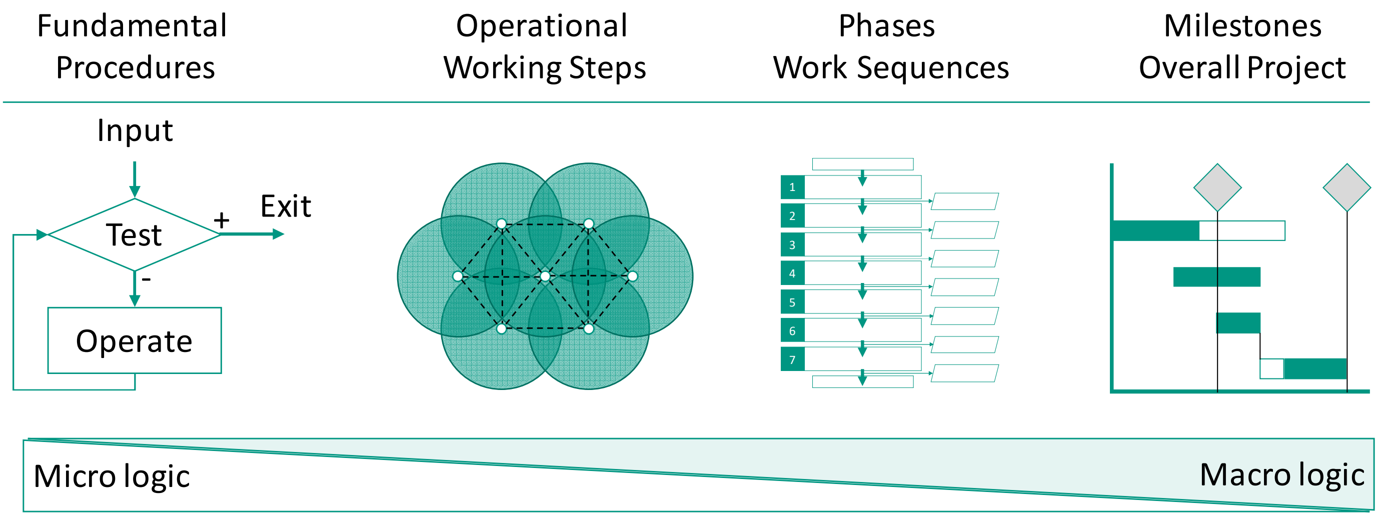

Fig. 1. Degrees of breakdown of the product development process based on [30]

system of objects. An alignment of the system of objects with the system of objectives leads to an expansion of the knowledge base and thus to the ability to continuously concretize the system of objectives. [6]

2.4. Complexity in Development

Complexity as a system property is essentially outlined by two perspectives: On the one hand based on five factors [32] and on the other hand as a general term of *VUCA - Volatility*, *Uncertainty*, *Complexity*, *Ambiguity* [33]. The two perspectives on complexity as a system property can be combined into four complexity factors: *Structural Complexity*, *Lack of Knowledge and Transparency*, *Lack of Definition and Agreement* and general *Pace* [34]. Complexity as an operational context, on the other hand, is defined according to the *Cynefin* framework by the framework conditions under which product development activities are carried out [5]. A complex operational context is therefore characterized by frequent and rapid changes, emergence and general instability. In contrast, complicated operative contexts are stable, but require extraordinary expertise in problem solving. The context has a massive impact on the stability of forecasts and plans: In complex contexts, plans often have to be adapted in order to react, for example, to changed boundary conditions or new findings [34].

However, in complex contexts, plans can be built on a long-term, stable basis. For complicated contexts, elaborate, plan-driven approaches such as VDI 2221 therefore exist [35]. On the other hand, there are proven iterative-incremental approaches for dealing with complex contexts such as Scrum. The open question is therefore how to deal with transitions between these contexts within parts of a project - i.e. how to switch flexibly between agile and traditional development approaches. The first step is to determine the nature of the problem to be solved (complicated or complex). This requires both the operational context and the system characteristics to be taken into account. The entropy compass (see Fig. 2.) provides the combination of these two perspectives [34]. Complexity is defined here as a state of socio-technical systems.

In addition, entropy is introduced on the basis of the understanding from thermodynamics as a measure of the lack of knowledge in order to deduce from the macroscopic state of a system the microscopic state of all its elements [36]. In other words, increasing entropy and reduced planning stability go hand in hand [37].

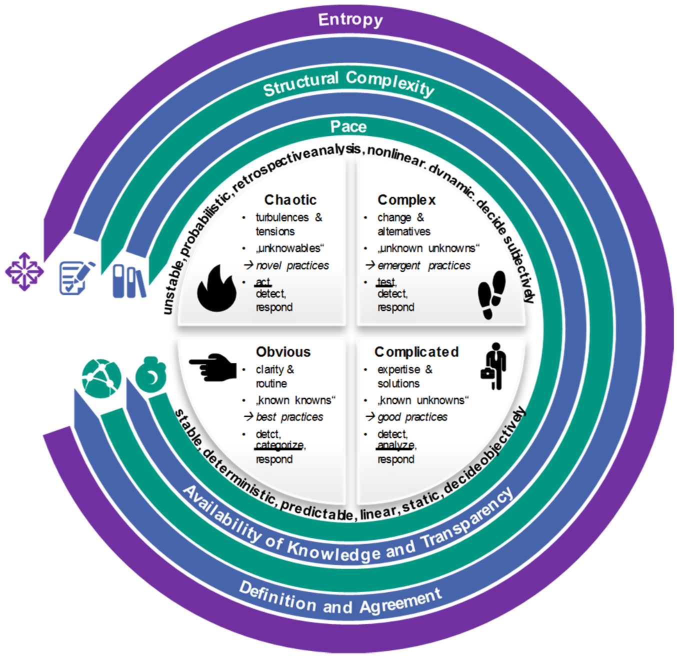

Fig. 2. The entropy compass according to [34]

2.5. The Model of PGE - Product Generation Engineering

Classical design methodologies distinguish development projects using the categories new design, adaptation design and variant design [38]. Such methodologies, however, do not adequately reflect real product development projects, as a new design without any references *on a white sheet of paper* is practically impossible to find [39]. A further possibility of categorization into incremental, architectural, modular and radical innovations has the disadvantage that only a retrospective classification of development projects is possible [40].

The model of the PGE - Product Generation Engineering represents the features necessary for the description of development projects and thus enables a demand-oriented support of the developer through the targeted use of methods and processes in everyday development. In the model of the PGE, product development is always based on a reference system. This is made up of reference elements which can originate either from partial solutions of the own company of predecessor generations, related series or variants, but also from products of other companies or from research. These are transferred into the next product generation through the activities of carryover variation as well as new development of their subsystems (embodiment and principle variation). A corresponding reference system must be defined depending on the target or approved new development share. [41]

3. Research Design

Companies are increasingly implementing agile approaches in their development processes in order to ensure high responsiveness to changes in a development context dominated by uncertainties. Since existing agile approaches have their origin in software development, they quickly reach their limits due to the different constellation of the context in mechatronic system development. In addition, there are still a large number of problems that are complicated or simple to solve according to the classification system described. Accordingly, an approach that supports flexible development in a project-specific, situation- and demand-oriented manner should include mechanisms that, on the one hand, enable the classification of the respective development situation with regard to its planning stability and, on the other hand, provide practices that meet the requirements and demands of mechatronic system development. To this end, the present paper first derives principles from the literature that set out a system of objectives for such practices. A model is then generated that allows development teams to assess their respective problem situation in terms of entropy and thus planning stability. In combination with the respective requirements of different technical subsystems, they are thus in a position to design the procedure in development by means of the appropriate degree of agility. To achieve this goal, the following research questions will be answered:

- How is the system of objectives designed for an approach that supports developers in dealing with different degrees of complexity in mechatronic system development according to the situation and needs?
- How can developers be supported in choosing a procedure appropriate to the situation, depending on the context-specific planning stability?

By initially answering the research questions in this article, a conceptual approach is developed, based on experience in product development and relevant literature in the field of product development. This will be continuously expanded and validated in future works.

4. Results

4.1. The Basic Principles

From observations of real development projects [19] and on the basis of the literature, nine basic principles were initially identified that support development teams in the development of mechatronic systems. These serve as guidelines to align activities with them and to identify, develop and adapt practices that support developers in the product development process. The principles do not lead to a standard recipe from a defined combination of certain practices, which makes it possible to develop successful products, but serve the company- and context-specific design and application of suitable development practices [42].

4.1.1. The Developer is the Center of Product Development

Through his creative work, the developer is responsible for the development of successful products [7,42]. For the best possible support of the developer in carrying out his activities, processes and methods must be adapted to his creativity, competences, needs and cognitive abilities. In addition, the selection of methods must also be based on these criteria. In the process of product creation, the developer interacts directly with his context [44] and contributes to a continuous and goal-oriented gain of knowledge, which in turn allows to identify relevant goals for a product and to synthesize them on the basis of the objects suitable for achieving these goals.

4.1.2. Each Product Development Process is Unique and Individual

In practice, there are no exactly the same product development projects, since each project is carried out within a project-specific context [25,45]. This means that no specific product development process exists that is valid for two or more different development projects. Nevertheless, recurring, similar elements, such as phases (recurring in time) or generic activities (recurring in content), exist in different processes across different industries, which are carried out in the process of product creation. However, since these are carried out in different projects on the basis of specific and differing systems of objectives, processes and methods must be adapted to the respective situation.

4.1.3. Agile, Situation- and Demand-Oriented Combination of Structuring and Flexible Elements

Structuring and standardizing elements help development teams orient themselves in complex situations characterized by instability and unpredictability. At the same time, a successful handling of complex situations requires a high degree of flexibility in order to adapt the procedure on the basis of gained knowledge or changed environmental conditions. By combining structuring and flexible process elements according to the situation and requirements, development teams can succeed in being responsive to changes and at the same time focus on defined development goals [15]. The continuous and iterative review and adaptation of the respective procedure is a decisive element in order to follow the most suitable procedure in the context of the respective development situation [46].

4.1.4. Each Process Element can be located in the System Triple and each Activity is based on the Fundamental Operators Analysis and Synthesis

Product development can be modelled as a recurring iteration cycle of analysis and synthesis activities [47], through which the operating system (developer, resources, knowledge, etc.) continuously concretizes the system of objectives and transforms it in detail and into objects of an object system. All process elements (e.g. goals, boundary conditions, methods, infrastructure, models, ...) can be clearly assigned to an element in the system triple [6]. The clear awareness of an appropriate allocation of different elements to the system triple supports development teams, for example, in identifying the currently required knowledge or the targeted construction of prototypes at a specific project point in time.

4.1.5. All Activities in Product Engineering are to be Understood as a Problem-Solving Process

The trigger for performing any activity of product creation is the deviation of an *ACTUAL* state from a *TARGET* state. *ACTUAL*, *TARGET* and the path from *ACTUAL* to *TARGET* may be partially or completely unknown [48]. The activities of product engineering serve to convert an activity-specific *ACTUAL* state into an activity-specific *TARGET* state using activity-specific operators. For this reason, every activity of product engineering can be modelled as a problem-solving process in order to support this systematic transfer of the *ACTUAL* state into the *TARGET* state [49]. This makes it possible to assign suitable development methods to different combinations of product development and problem-solving activities [50].

4.1.6. Each Product is Developed on the Basis of References

The development of products takes place in successive product generations, the development of which is structured in partially parallel development generations. Each development is based on a reference system, the elements of which are transferred to the next generation (G_n) by means of the systematic combination of the activities of carryover, embodiment and principle variation in relation to their subsystems [41,51]. This also applies to products of the first generation, which are developed based on existing solutions, e.g. on the market. [41]

The new development share of new product generations must be determined at the beginning of a development project according to the product strategy envisaged, whereby the use of the correct reference system elements has a decisive influence on competitive advantages.

4.1.7. A Product Profile, an Invention and a Business Model lead to a Product, which can be classified as an Innovation as far as it leads to a Diffusion on the market

The basis for the development of a successful product is the identification of the right demand situation in the future market [52]. The potential customer-, user- and provider-benefits are derived from this and are made accessible to development by means of the product profile. The product profile is satisfied by the conversion of ideas and concepts into an invention and introduced to the market through a suitable business model [19]. If the identified product profile is relevant to the market (validated), the invention has been successfully implemented and the business model for the product has been optimally designed, the potential of diffusion is increased [53]. As far as there is a diffusion on the market, the product can be classified as innovation retrospectively.

4.1.8. Early and Continuous Validation serves the Purpose of Continuous Comparison between the Problem and its Solution

Validation is regarded as a central activity in the product development process and represents a major challenge, especially for complex mechatronic systems. Therefore, it is important to understand validation as an ongoing activity during product development [54]. This is the only way to ensure that customer, user and provider benefits are achieved with the developed product. Validation by means of prototypes - virtual, physical, mixed virtual-physical - allows extensions to be made to the system of objectives, which, depending on the validation result, are defined as confirmation, definition, refinement and/or modification [24]. Therefore, the findings generated in this way determine the further course of action in the process. The later changes have to be made to the product in the development process, the greater the amount of resources - especially costs - that have to be used. Therefore, it is necessary to validate objects generated early in the process with regard to the fulfillment of customer, user and provider benefits in order to secure the further development direction and avoid undesired and unforeseen effects.

4.1.9. For a Situation- and Demand-Oriented Support in every Development Project, Methods and Processes must be Scalable

In the course of development projects, complex and non-complex development parts occur at variable times. This leads both to coherent states (i.e. the simultaneous presence of complex and non-complex states in different project parts) and to changes in the overall project state (identification of new requirements that require replanning). Such changes require an accompanying adaptation of thinking, methods and processes

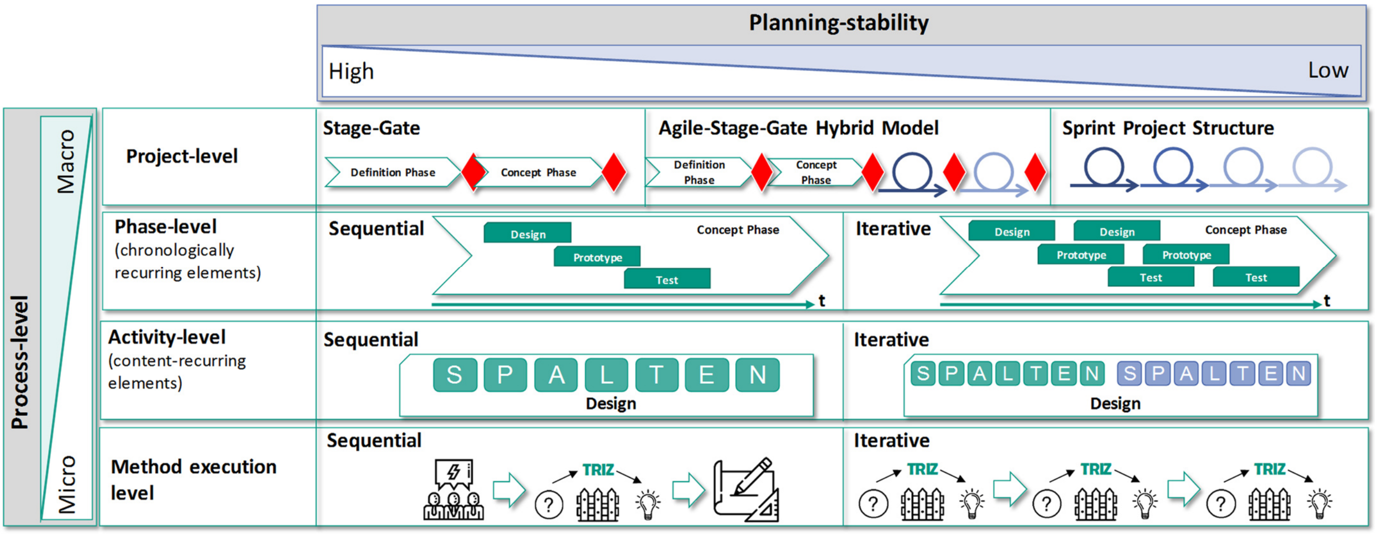

Fig. 3. Support in selecting the degree of flexibility depending on the situation and requirements

to support product development [55]. Furthermore, apart from their underlying context, projects vary in size, scope or strategic importance. In order to best support development teams in different development projects at all project levels described, development processes must be scaled with regard to the respective development context and the desired development goal in order to enable developers to act in a situation-adequate manner in the various development situations.

4.2. Agile Adaption of Flexible and Structuring Elements in ASD - Agile Systems Design

As the share of new developments in projects increases, so does the need to build up situational knowledge and to define the technical system in order to continuously check the suitability of the solution for the identified requirements. Accordingly, uncertainties in the development project increase with the increasing share of new development and thus also the entropy of the present situation, whereby the planning stability decreases. The awareness of possible new development parts in the technical system leads to the awareness that later changes are likely due to uncertainties, which leads to an increasing dynamic in the development context.

This aspect is used to generate a model based on selected principles (2, 3, 5, 6 and 9), which supports the developers in choosing the appropriate level of flexible and structuring process elements at different process levels (see Fig. 3.). At all process levels, a distinction can be made between sequential and iterative procedures. These are flexibly selected using the entropy compass depending on the planning stability available in the respective development context to solve the problem. This makes it possible to adapt the development process at different process levels.

If, for example, a company aims to penetrate a previously unknown market with a product that has to differentiate from its competitors through new unique selling propositions due to strong competitive pressure (possibly high new development shares), a hybrid approach is suitable at project level, for example. In this project, existing solutions in the market are first analyzed, then potentials are derived and these are incrementally converted into solutions. Due to the inability to predict the course of the project, detailed planning of the entire project is impossible. For this reason, the activities in the phases are initially planned as far in advance as the current state of knowledge permits and, if necessary, a further iteration cycle is carried out after implementation to concretize the results. When considering the activity level, there are activities that can be carried out on the basis of existing experience through a one-off problem-solving process (e.g. the specification of legal requirements in the context of the developed system and implementation through existing solutions, such as the position and color of the vehicle light). At the same time, there are activities that require iterations of problem-solving processes at the activity level (e.g. the technical specification of customer requirements for sporty driving behavior). These are continuously refined, implemented in technical systems and secured. Due to its universal applicability, the SPALTEN problem solving process [27] was chosen to support the activities.

There is the possibility of methodical support for the implementation of the activities. A sequence of different methods can also be carried out or certain methods can be repeated iteratively to concretize results. At all levels described, the Entropy Compass is suitable for supporting development teams in planning and adapting the process. The principles and the model are part of the ASD - Agile Systems Design for the development of mechatronic systems.

5. Discussion

The findings presented in the article have a conceptual character and require future expansion and validation. Nevertheless, an approach based on over 20 years of development experience [56] and literature has been condensed with the aim of supporting mechatronic system development. Thus, the approach goes beyond the pure adaptation of approaches from software development into the context of physical development.

Nevertheless, further elaboration of the approach requires a systematic approach. Thus, challenges were identified from the literature, but there is no concrete and quantitative assignment to the principles. In addition, future work must ensure the applicability of the approach. In addition, no supporting practices for the operationalization of the principles were assigned in this paper.

The area of application of the approach is mechatronic system development. Accordingly, it does not aim at reactive processes in the context of software development or highly regulated and heavy industries such as special-purpose mechanical engineering. As the approach is merely a framework and there is no methodological support for implementation, it is currently not possible to coordinate a project through the approach without expert support. This introductory concept will also be the subject of future work.

6. Conclusion and Outlook

Agile procedures for sufficiently plannable development projects are just as unsuitable for project implementation as a plan-driven procedure for the implementation of complex development projects. With the aim of supporting development teams in identifying the appropriate level of agility at different project levels, principles from observations from literature and real development projects were first identified that can serve to align the actions of development teams in the context of mechatronic system development. Based on this, a conceptual model was derived that brings suitable development procedures at different project levels in line with the degree of planning stability in the given development context. The entropy compass is used for this purpose. By applying the model, developers are flexibly supported in efficient and effective process design. The derived principles do not claim to be exhaustive and will be evaluated in further research work with regard to their relevance and comprehensibility. In addition, the applicability of the derived model is evaluated and continuously further developed. In future work, the principles will serve the targeted development of processes and methods.

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