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A systematic for realizing agile principles in the process of mechatronic systems development through individual selection of suitable process models, methods and practices

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Abstract

Agile elements support development processes of manufacturing companies by enabling increased customer integration and improved responsiveness to unforeseen changes in the development environment. However, existing agile approaches do not fully meet the additional demands that mechatronics systems development requires of these approaches, for example because of existing organizational structures not considered in the agile approaches. This results in challenges which can lead to considerable deficiencies in the product (e.g. with regard to safety requirements) or the approaches are rejected again. For this reason, this paper analyses a variety of agile and conventional methodologies, process models, frameworks, methods and practices regarding their suitability for the targeted integration of agility into the development processes of manufacturing companies considering different criteria and requirements. A broad literature research was carried out and the development modules (methodologies, process models, frameworks, methods and practices) identified were examined with regard to their suitability for support at both strategic and operational level. The modules were evaluated, among other things, at the strategic level with regard to their suitability for the realization of existing basic principles of agile development of mechatronic systems and at the operational level with regard to the optimization of existing agility-influencing factors. Based on this, a systematic was developed, which supports developers in the selection of agile and conventional development modules according to the objectives, relevant fields of action and specific factors influencing the agile capabilities of organizational units. The developed systematic enables a situation- and demand-based implementation of agility plus increased probability of a sustainable introduction of agility.

Keywords: Agile Product Development; ASD – Agile Systems Design; Tailoring Agile; Product Development Processes; Organizational Agility

1. Introduction and Literature Background

1.1. Agility in Product Development

Since the publication of the *Agile Manifesto* in 2001 [1], agility has become a keyword in the software development as agile processes are characterized by a higher degree of flexibility, reaction time and transparency [2,3]. Over the last years agile development has gained attention in the development of mechatronic products (= products which contain elements from the domains mechanics, electrics/electronics and IT) [3]. The conditions in the mechatronic industry are changing, e.g. the available development time decreases, whereas the range of functions and independency of elements within a system increases, and uncertain and continuously changing requirements become more present [4]. Agile development is therefore considered as a way to handle the increasing degree of complexity, ambiguity, uncertainty and volatility in the industry [4]. However, it must be considered, that the development of physical products differs fundamentally from the software development and new challenges arise from implementing agility in the physical development [4–7].

Based on ROPOHL's *Systems Theory* [8], product development can be understood as an iterative interaction of three

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systems: system of objectives, system of objects and operation system. The resulting system triple of product engineering describes the interaction between these systems. The operation system includes all resources, that are required to develop a product based on objectives and requirements. It synthesizes the system of objectives, i.e. based on its the state of knowledge objectives are defined, refined and redefined. The system of objectives includes all objectives to a product, their relation and justification and related requirements. The analysis of the system of objectives leads to the solution space, which is a mental model established by the operation system. It includes all approvable solutions to fulfill the current state of the system of objectives. Based on that, the operation system synthesizes the system of objects, which includes all artefacts that result during and after a development project e.g. final products, documents, prototypes. The analysis of the system of objects as part of validation activities leads to an enlargement of the state of knowledge, with which the operation system is again able to concretize the system of objectives. [9]

In the context of the system triple of product engineering, "Agility […] is the ability of an operation system to continuously check and question the validity of a project plan with regard to the planning stability of the elements in the system triple and, in the case of an unplanned information constellation, to implement a situation- and demand-oriented adaption of the sequence of synthesis and analysis activities, whereby the customer-, user-, and provider-benefits are increased in targeted manner" [5].

1.2. Plan-driven Approaches in Product Development

Plan-driven approaches are common in the development of physical products [10]. All plan-driven approaches are characterized by extensive upfront planning to reduce chaos and achieve a higher degree of stability, predictability and assurance in the development of products. [11,12]. A well-known process model in plan-driven development is the systematic approach by PAHL AND BEITZ [13], which led to a fundamental understanding of engineering design processes by proposing a structured sequential model of four phases: *task clarification*, *conceptual design*, *embodiment design* and *detail design*. Each phase is defined by a sequence of activities, which must be executed before deciding on the start of the subsequent phase. [13] Another plan-driven model is the *Stage-Gate Model* by COOPER [14]. It is a "conceptual and operational map for moving new product projects from idea to launch and beyond". It prescribes a series of development stages, each consisting of cross-functional and parallel activities, followed by gates with go/kill decisions. [14] A further plan-driven model is the *V-model* of the guideline VDI 2206 [15]. It supports a cross-domain development and divides the development process into three parts: system design, domain-specific design and system integration. In addition to that continuous validation and verification assure the properties of the product. [15] Plan-driven approaches may be too rigid in order to handle a rapidly changing environment as extensive upfront planning means a loss in flexibility. [11,12]

1.3. Agile Approaches in Development

Several agile approaches have been developed over the years and introduced primarily in the software development industry. [16,17] A well-known and widely used agile framework is *Scrum* [18,19]. It describes product development as an iterative cyclic process with validation continuously executed during the development process. That allows a continuous integration of requirements along the development process and thus proper adaption to changing conditions. [20,21] Since agile methods and practices are originally designed for small teams and do not give recommendation on scaling agile, several frameworks, such as the *Scaled Agile Framework* (SAFe), *Large-scale Scrum* (LeSS) or *Disciplined Agile Delivery* (DAD), have been developed to enable an adoption of agile to larger settings [22]. Agile development is gaining ground in the mechatronic industry due to its potential benefits when dealing with continuously changing and uncertain requirements [3,6,7,23]. Benefits anticipated in the implementation of agile approaches include better communication within teams, a higher degree of flexibility and a higher degree of transparency [3]. However, it must be pointed to the fact, that the implementation of agile development approaches in the mechatronic system development is limited due to fundamental differences between the development of physical products and the software development, where agile has its roots [4,7,24].

1.4. Hybrid Approaches in Development

Hybrid approaches possess the structure of plan-driven approaches and the flexibility of agile approaches and are therefore considered as a way to implement agile in the development of physical products [25]. A well-known hybrid process model is the *Agile-Stage-Gate model* developed by COOPER [25]. It combines the traditional *Stage-Gate model* with different agile practices, such as time-boxed sprints, retrospective and daily stand-up meeting, and includes additional adjustments for the development of physical products, e.g. the definition of a ′done sprint′. [26] Another hybrid model is the model of the guideline VDI 2221, which describes a "methodology for developing and designing technical systems and products" [27]. The revised version of VDI 2221 is less rigid than the previous version and integrates the concept of so-called iteration-loops. It is based on the iPeM – integrated Product engineering Model, which is another hybrid process model [28]. It is "a generic process model and includes the relevant elements and structures to derive agile product development processes." It considers the "interaction between activities, requirements, results and methods" and is based on the system triple. [28]

1.5. Implementing Individual Agile Development Modules

Previous research worked on different approaches to tailor development processes. For example, DIEBOLD [29] reviewed agile practices and developed an approaches for the identification of suitable agile practices at mainly team and project level of software companies based on various criteria and goals. KLEIN [30] focused on development processes in machinery and plant engineering. He investigated agile practices and developed a methodology for an application-specific integration of agile techniques into the activities of a mechatronic development process. REISS [31], on the other hand, focused on the recommendation of methods of product development and knowledge and innovation management for a specific situation.

The approach of *ASD – Agile Systems Design* according to ALBERS [24] is a development approach for mechatronic systems, which combines agile development and the fundamental understanding of the *model of PGE – Product Generation Engineering* [32]. Based on observation of successful projects in the area of mechatronic system development, nine principles were derived supporting developers in the mechatronic system development process by serving as a guideline for the alignment of activities, and identification, development and adoption of practices [33]. They are operationalized by appropriate methods, whereby their weighting is individual for each use case. Thus, the method setup is also individual, with which agility is introduced into a specific use case. [24,34] DIEBOLD differs in terms of agility between technical agility, which comprises agile methods and practices, and cultural agility, which is reflected in agile principles [35]. Referring to DIEBOLD sustainable agile transition requires a symbiosis of both [35]. ALBERS ET AL. developed a method to identify the individual situation, which included, besides the determination of the fields of context of product development and fields of action [36,37], the derivation of the set of agile principles relevant for an individual situation, and the determination of additional agile factors influencing the agile capability. Thus a requirements profile for an individual process solution is created [34].

2. Research Design

In order to introduce agility in organizations with traditional plan-driven development processes, certain established aspects and structures must be kept [38] i.e. it is essential to combine both in the best possible way. Since each application case has individual demands on the methodical support and thus also on the combination of plan-driven and agile process elements, a procedure is needed to provide an appropriate combination of plan-driven and agile process elements. This paper aims to support organizational units in adopting agility in their development processes suitable for the individual application context through deliberate choice and combination of development modules by answering the following research questions:

- *Which development modules are suitable for the individual implementation of agility in mechatronic systems development processes?*
- *How can organizational units be supported in designing an individual combination of agile and plan-driven elements?*

In order to answer these questions, the research starts with a broad literature research for development modules in the area of product development and agile development, and subsequent investigations. A distinction was made between the following development modules: *methodologies*, *process models*, *frameworks*, *methods* and *practices*. Methods are prescriptive and have a process-like character. They are of operative nature and give a logical sequence of actions in order to find a solution for a task or problem. Process models display a sequence of actions and serve as a base for the usage of methods. They can be strategic (macrologic) or operative (micrologic). Methodologies contain several methods. They have more of a strategic character compared to methods. A Framework is a *body of order*, which displays a structure overview of the components. Compared to a process, frameworks do not have a sequence, rather they represent an artificial and arbitrarily order. Frameworks have more of a strategic character. Practices are defined as actions on an operative level in agile development. [39]

The research was conducted through databases such as Science Direct, SpringerLink and Emerald Insight, and was based on terms such as agile product development, agility, agile frameworks, agile methods, mechatronic systems development, product development processes. The thus collected methodological elements were then evaluated individually regarding their aptitude in the four fields defined by ALBERS ET AL., which are considered as crucial for situation and demand oriented implementation of agility [34]. Based on the thus created data a systematic was developed, that supports organizational units in the selection process of development modules suitable for the implementation context. Finally, the developed systematic was initially evaluated in the course of the restructuring of an annually recurring student innovation project. The development team of this project changes annually. The students (6-8 persons) learn different development methods during the year and apply them directly in the further development of an autonomous transport vehicle generation. The project is subject to a defined structure (different phases) within which the team can work in an agile way. The biggest challenge, which should be solved by the systematic developed in this contribution, is the transfer of built up process knowledge in combination with a pre-prioritized product backlog between two successive classes. The developed systematic was carried out with the product owner of the project, the coordinator and a lecturer and the developed methodology was implemented in a workshop. The team's work with the methodology was observed and the methodology was adjusted accordingly.

3. Results

3.1. Development modules for Agile Product Development

Various development modules consisting of methodologies, process models, frameworks, methods and practices were identified through a broad literature research, subsequently classified into strategic and operative development modules and refined by additionally decomposing methodologies, process models and frameworks, which have more of a strategic character, into their corresponding methods and practices on the operative level afterwards (referring to [39]). A complete list of 158 elements stemming from the product and agile development context was created. This list includes 10 process models and frameworks such as iPeM, Scrum and SAFe, and 148 methods and practices such as product profile, test-driven development, backlog and active stakeholder participation (see attached data in brief). The majority of agile methodological elements found are in the field of project management.

Based on the created list of development modules, a systematic aptitude evaluation was conducted in order to determine the suitability of each module for a specific application context., i.e. each development module was evaluated individually regarding: the nine ASD – principles [33], four fields of context of product development [36], thirty fields of action [37] and 228 factors which influence agile capabilities [34].

Each *methodology*, *process model* and *framework* were evaluated regarding the nine ASD – principles, four fields of context of product development and thirty fields of action. The *methods*, *practices* and *process models*, which have more of an operative character, were evaluated regarding the thirty fields of action and 228 agile factors. The evaluation was carried out using a numerical rating scale ranging from 1 (low aptitude) to 7 (high aptitude), and a binary evaluation, where ´Yes´ answers are assigned a value of 1 and ´No´ answers are assigned a value of 0, and was based on the following questions:

- To what extent is the methodological element able to realize the respective ASD – principle? - scaling from 1 to 7
- To what extent is the methodological element able to support the respective field of context of product development and the respective field of action? - scaling from 1 to 7
- Is the methodological element able to positively influence the respective agile factor? – Yes / No

The individual evaluations are based on knowledge gained from a broad literature research and were carried out by two researchers from the product development department. In case of discrepancy, the mean value of the ratings was calculated.

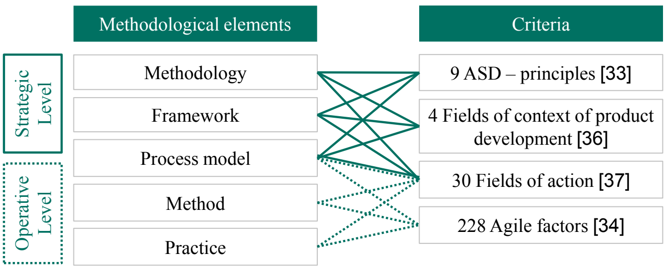

Fig. 1. Development modules and corresponding evaluation criteria

A total of 38.614 individual evaluations were made leading to a comprehensive overview and clearer understanding of the diverse opportunities to influence different aspects of product development in the agile context through implementation of appropriate methodological elements.

Since each individual development modules is able to influence a fixed set of context fields, fields of action, agile factors and principles positively, implementing one development module may not be sufficient for an application context. Thus, a combination of elements is recommendable to implement agility in product development processes. The generated evaluation tables serve as base for the further procedure.

3.2. Methodology for designing an individual process solution

The described systematic [34] as starting point to develop individual agile process solutions generates an individual method profile for each application context. It derives objectives and requirements for the individual implementation of development modules and process solutions by providing an individual weighting of the ASD – principles, selection of fields of context of product development, prioritization of fields of action and selection of relevant factors. To realize the individual method profiles [34] and based on the accomplished aptitude evaluation of the individual development modules in 3.1, a methodology for designing an individual process solution was developed consisting of two major steps: the determination of suitable methodologies, process models and frameworks for the strategic level, and the determination of suitable process models, methods and practices for the individual application context at operative level. The suitability of a methodology, process model or framework is defined by $u_{i,ASD}$ and $u_{i,LV2}$:

$u_{i,ASD}$ represents the suitability of a methodology, process model or framework i regarding the application-specific constellation of ASD – principles and is calculated as follows:

$$u_{i,ASD} = \frac{(\sum_{l=1}^{9} g_l x_{il} - 1)}{6}$$

where $g_l \in [0,1]$ is the weighting factor of the ASD – principle l derived by the systematic approach of ALBERS ET AL. [34], and $x_{il} \in \{1, \dots, 7\}$ is the aptitude value of the methodology, process model or framework i regarding the ASD – principle l (determined in 3.1). $u_{i,LV2}$ represents the suitability value of a methodology, process model or framework i regarding the individual set of fields of action:

$$u_{i,LV2} = \frac{(\sum_{h \in L} x_{ih} - n_L)}{6 n_L}$$

where $x_{ih} \in \{1, \dots, 7\}$is the aptitude value of the methodology, process model or framework i regarding the field of action h (determined in 3.1), L is the set of fields of action selected for the individual application context and n_L equals $|L|$.

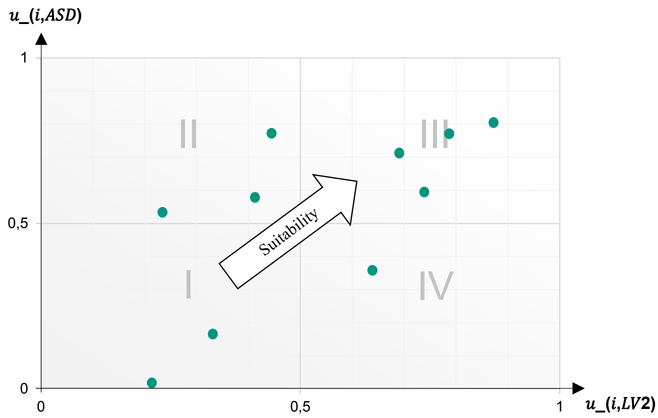

Fig. 2. Exemplary portfolio for methodological elements at strategic level

The goal is to determine the methodologies, process models and frameworks with the highest suitability values, i.e. after calculating $u_{i,ASD}$ and $u_{i,LV2}$ for each methodology, process model or framework i from 3.1., the methodologies, process models and frameworks with the highest value for both $u_{i,ASD}$ and $u_{i,LV2}$ are determined as best suited for the individual application context. Fig. 2 illustrates the corresponding portfolio for methodologies, process models and frameworks, where each point represents an individual methodology, process model or framework defined by $(u_{i,LV2} \mid u_{i,ASD})$. The best suited methodology, process models and frameworks are generally located in quadrant III as it is characterized by high values in $u_{i,LV2}$ and $u_{i,ASD}$, i.e. methodologies, process models and frameworks located in quadrant III are in general best suited for the individual application context as they are able to realise the individual set of ASD – principles to the best possible extent and at the same time to support the individual selected fields of context of product development and fields of action optimally. Hence, methodologies, process models and frameworks located in that quadrant are aimed at.

The determination of suitable methods, practices and process models on the operative level is based on the individual set of factors and fields of action relevant for the individual application context [34]:

The set of methods, practices and process models principally suitable for an individual application context is defined by the set of methods and practices able to positively influence the individual set of agile factors:

$$V := \{j | x_{jk} = 1\ ,\ k \epsilon B\}$$

where $x_{jk} \in \{0,1\}$ is the aptitude value of the method or practice j regarding the agile factor k (cf. 3.1) and B is the set of agile factors selected for the individual application context.

The suitability of a method, practice or process model j to support the individual set of fields of action is calculated as follows:

$$u_{j,h} = \sum_{h \in L} g_h x_{jh}$$

where $g_h \in [0,1]$ is the weighting factor of the field of action $h \in L$ derived by the systematic approach of ALBERS ET AL. [34] and $x_{ih} \in \{1, \ldots, 7\}$ is the aptitude value of the process model, method or practice j regarding the field of action $h \in L$ (cf. 3.1).

By calculating $u_{j,h}$ for all $j \in V$ and sorting the elements by size of $u_{j,h}$, an individually prioritized list of methods, process models and practices is created. The higher the value in $u_{j,h}$, the more suitable the element, i.e. methods, process models and practices $j \in V$ with a higher value in $u_{j,h}$ than others, are, in addition to the fact that they positively influence the individual set of agile factors, able to support the individual prioritized set of fields of action to the best possible extent.

Applying this developed systematic to a specific application context results in an individual set of development modules best suited for the application context, consisting of process models, frameworks, methods and practices. The systematic and the database were implemented with various office solutions such as Excel and PPT, and then gradually applied to a student innovation project. Following the systematic approach by ALBERS ET AL. a requirements profile for an individual process solution for this student project was first derived [34]. The requirements profile included the context fields *personnel* and *project*, and six fields of action e.g. *design task*, *validation*, *knowledge and skills* and *competencies*. Moreover, a set consisting of 20 relevant agile factors was selected, which includes factors such as *development aligned to product profile*, *early and continuous validation*, *easy access to experienced user*, *acting in the interest of the customer*, *high problem solving competence*, leading to an individual weighting of ASD – principles with the first ($g_1 = 0{,}15$), eighth ($g_8 = 0{,}15$)and fourth ($g_4 = 0{,}14$) principle as the highest weighted ones for this application context. For the thus created requirements profile and based on the conducted aptitude evaluation of methodological elements in chapter 3.1, a set of development modules was derived following the developed systematic. As a result, a set of different strategic and operative elements best suited for the application context was created, which included iPeM, product profile, pull-validation, iteration, customer empathy map (Fig. 3). These strategic and operative elements were then implemented in the student project. A survey was conducted afterwards in order to gather feedback and input for further development. From the strategic point of view, the implementation of these elements has led to more transparency within the project, and problems such as knowledge transfer and chaos were reduced successfully. From an operational point of view, improvements regarding team organisation, communication and short-cycle planning could be achieved. However, some responses addressed the need for further development in the implementation as some tasks could be more intuitive and references between two tasks were missing.

4. Conclusion and Outlook

In this research a total of 158 agile and conventional methodologies, process models, frameworks, methods and practices, so-called development modules, were investigated. Each of them was evaluated regarding specific criteria crucial for a situation and demand-based implementation of agility in mechatronics systems development processes. The results of the

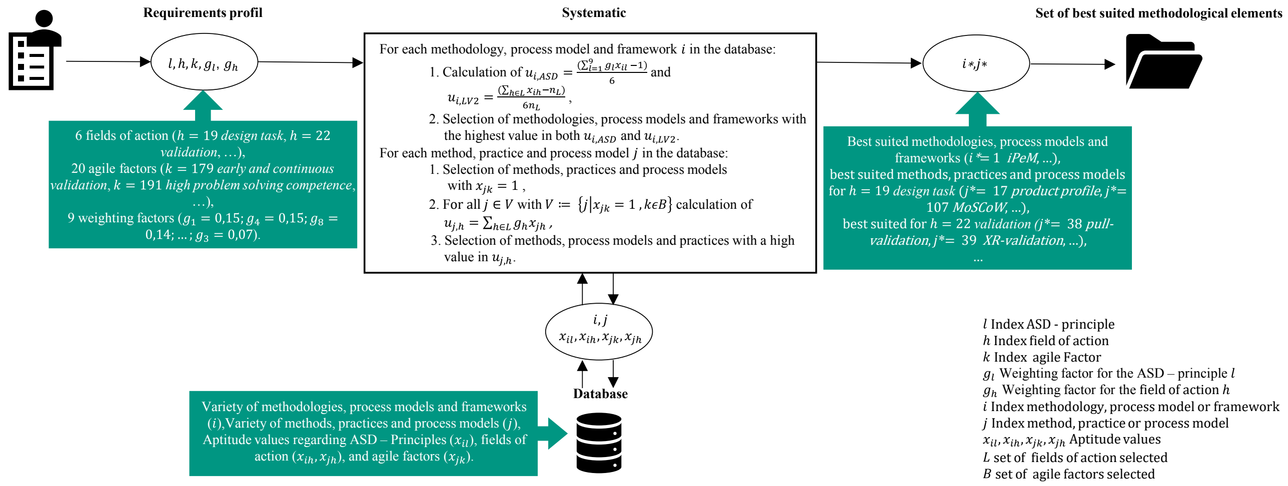

Fig. 3. Specific Results from using the systematic to restructure a student development project

evaluation have shown the broad range of potentials associated with the implementation of the development modules. Based on the thus collected data, a mathematical systematic was developed. It calculates a variety of so-called suitability values for the development modules considering individual context-related criteria. These values can help developers in the selection process of development modules suitable for the implementation context. The application of the developed systematic to the student innovation project and subsequent implementation of the suitable development modules has led to significant improvements at both the strategic and the operative level, the implementation, however, needs to be further developed towards a more user-friendly application. In future research this systematic will be implemented in further projects in order to evaluate the performance of the systematic in different use cases and to refine it accordingly as required.

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