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DESCRIPTIVE ATTRIBUTES OF ANALYSIS USE CASES IN THE DATA-DRIVEN VALIDATION OF ELEMENTS IN THE SYSTEM OF OBJECTIVES

Wagenmann, Steffen (1,2);
Weidinger, Felicia (1);
Schöck, Moritz (2);
Albers, Albert (2);
Bursac, Nikola (3)

1: TRUMPF Machine Tools SE+Co.KG;
2: IPEK, Karlsruher Institute of Technology;
3: Technical University of Hamburg

ABSTRACT

Usage data of reference systems can be analyzed in the development process for the validation of system elements. The process model for data-driven validation of elements in the system of objectives aids developers in performing such data analyses. The conducted studies show that the basis for an efficient analysis process is a common understanding of the system and the goal of the analysis. Therefore, a template was derived over the course of case studies describing the elements in the system of objectives. The template covers the three descriptive dimensions general information, technical system and data. It allows a comprehensive description of analysis use cases. On average it takes 11 minutes for developers to aggregate all necessary information and consequently fill out the template. An A/B-Test confirmed the comprehensibility and applicability of the template even for developers of different domain knowledge. Through its contribution to a sustainable knowledge management the template provides an added value for the developers for conducting analysis.

Keywords: Big data, Complexity, New product development, Data-driven development

Contact:
Wagenmann, Steffen
TRUMPF Machine Tools SE+Co.KG
Germany
steffen.wagenmann@trumpf.com

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1 INTRODUCTION

With the increase of digitalization in all areas of a company, the way in which products are developed is changing. The use of machine data for decision-making in the product development process is still in its infancy, but it holds great potential for developers to gain a better understanding of the actual use of the mechatronic systems to be developed (Albers et al. 2018). Currently, the data of reference system elements is rarely used in the development process (Bogner et al. 2016). One reason is the high amount of time required to perform data analyses. According to Wagenmann et al., the average time required to perform a data analysis for validation in development is 3 weeks. In this context, two thirds of the total workload is accounted for the basic and interdisciplinary work (Wagenmann et al. 2022a). Many developers currently have little knowledge in data science. Therefore, there is a great deal of uncertainty regarding the information needed to perform the analysis. Furthermore, in mechatronic system development, the interdisciplinary combination of domain knowledge is essential to master the complexity (Heimicke et al. 2019). To compile this domain knowledge efficiently and to document it comprehensibly, a systematization of the information acquisition is necessary. As a result, data analysis processes in development become more attractive. In addition, a uniform understanding of the elements in the system of objectives is important to make the interdisciplinary collaboration in mechatronic system development target oriented. This paper presents an approach for the systematic collection and documentation of the information necessary to perform data analyses in interdisciplinary product development processes for mechatronic systems.

2 STATE OF RESEARCH

2.1 The system triplet of product engineering

The system triple of product engineering describes product development processes as a continuous interaction of three systems, which are illustrated in the following Figure 1.

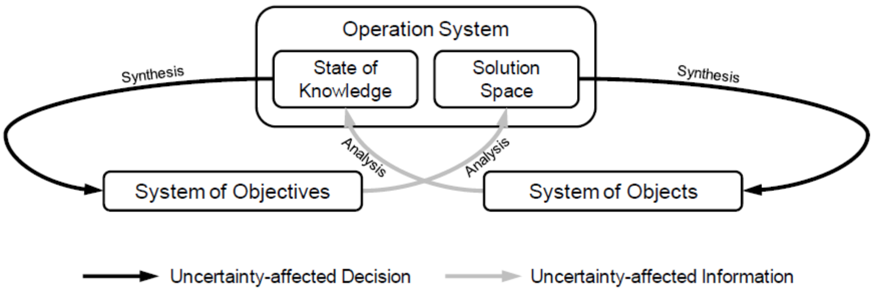

Figure 1. System triple of product engineering describing the continuous mitigation of uncertainty by information gaining and decision making (Albers et al. 2011)

The operation system contains all methods, processes, and activities as well as the resources required for the realization of a product development. The system of objects contains all documents, artifacts and intangible objects that are created during the development process. The system of objectives describes the desired end state of the product. Elements in the system of objectives are all requirements, the planned properties of the product as well as their dependencies, restrictions, and boundary conditions. The continuous validation of the elaborated products according to the system of objectives is a fundamental activity in the product development process. Only after a successful validation the achievement of the goal can be considered certain (Albers 2010).

2.2 Model of PGE - product generation engineering

The model of the PGE - product generation engineering states that the development of new product generations is always based on one reference system. The reference system for the development of a new product generation is a system whose elements originate from already existing or already planned socio-technical systems and their associated documentation. These elements are the basis and starting point for the development of the new product generation. Reference system elements can be already existing products such as direct predecessor generations, competitor products, products from other industries or

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systems from pre-development projects (Albers et al. 2019). Furthermore, the usage data of reference system elements can be used as instrument for validating requirements in the product development process. The development of a new product generation takes place by the purposeful combination of carryover variation, attribute variation, and principle variation of subsystems of the reference system. Figure 2 shows an example of a punching machine with parts of the underlying reference system.

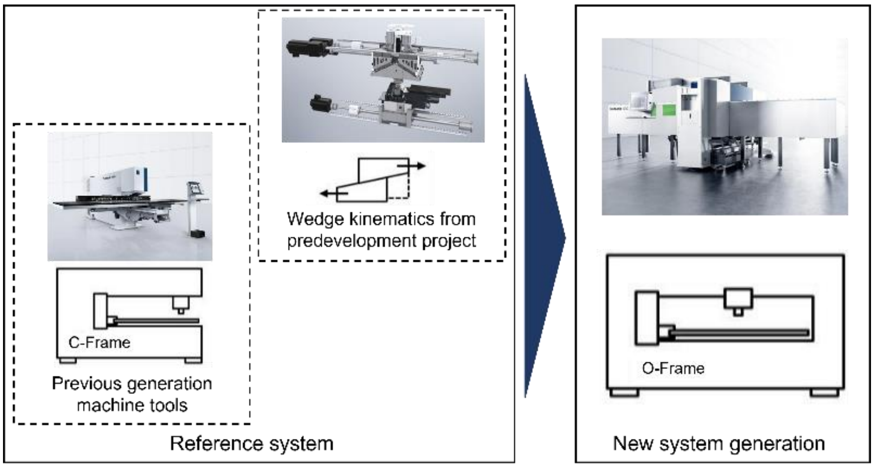

Figure 2. Punching machine with parts of the underlying reference system (Bursac et al. 2021)

The change from C-frame to O-frame represents a principle variation, the adoption of the wedge principle from the predevelopment project represents a carryover variation. The higher the proportion of design and solution principles adopted by the reference system for the new generation, the better the development risk can be assessed and minimized. (Albers et al. 2017)

2.3 Data-driven requirements management

In the development of mechatronic systems, requirements can be divided into functional and non-functional requirements. Functional requirements describe the functional scope of a new product or development generation. Non-functional requirements consist of quality requirements and general conditions. Requirements management is used for the transparent documentation in the development process. It enables systematic reuse as well as iterative and interdisciplinary further development of all requirements (Bursac et al. 2021). In data-driven requirements management, requirements are defined and validated based on the analysis and interpretation of data. In mechatronic system development, a large amount of data is generated as a result of digitalization (Bharadwaj und Noble 2017). However, simply collecting and storing data does not bring any benefits. Instead, the data must be processed and analysed with the help of new technologies such as data mining in order to generate knowledge (Bissantz und Hagedorn 2009). Thus, in the future, decisions will no longer be made based on intuition and empirical values but based on the knowledge generated during data analysis. This strengthens the informative value of decisions and minimizes the risk of misjudgements (Anderson 2015). Furthermore, customer-orientated requirements can be derived from the results of the data analysis to improve product development processes and increase the competitiveness of the company (Menon et al. 2005). To be data-driven, an organization must provide the right culture and processes. Currently, the biggest obstacle to the use of data analytics in organizations is the lack of understanding of how the results of the analysis can be used to improve the business (LaValle et al. 2011). In addition, insufficient knowledge of the data generated by mechatronic systems and its quality lead to a loss of acceptance of the analysis results derived from the data. Therefore, internal processes need to be improved and new, more efficient processes for using data in organizations need to be implemented (Wagenmann et al. 2022b).

2.4 Process model for the data-driven validation of the system of objectives

The overall goal of the process model according to Wagenmann et al. is to methodically empower developers in the data-driven validation of elements in the system of objectives by analysing usage data of the reference system elements and deriving appropriate development decisions in interdisciplinary teams. (Wagenmann et al. 2022b) The first module is used for the identification of initial analysis use cases in the system of objectives that should be validated using data. In the second

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module, the analysis use cases are defined. For this purpose, the elements of objectives are specifically described and prioritized. The description serves to generate a uniform understanding of the underlying questions and the goal before the analysis is carried out. Access to interdisciplinary expert knowledge is essential for a deeper knowledge base (Duderstadt 2007). The definition of analysis use cases is followed by the identification and selection of the necessary tools and data. The knowledge base from the definition of the analysis use cases serves as input for a well-founded data selection. In the following module of the process model the scope analysis takes place. Thereby, opportunities and risks of the selected tools and data are analysed and evaluated. Subsequently, the data analysis is carried out. The output of the analysis are specific data sets and initial analysis results. Based on these analysis results, a preliminary validation of the data is possible. In the last module of the process model, decisions are derived from the initial analysis results. For this purpose, the analysis results must be made accessible to all relevant parties. From the discussion of the analysis results, it can be determined regarding the initial hypotheses or questions that a more in-depth analysis of individual aspects is necessary or that inconsistencies in the analysis results occur. In this case, all modules are iteratively run through until a complete decision-making process is possible. (Muschik 2011) In addition, a sustainable knowledge management system is established. All findings and learnings must be documented in a comprehensible and accessible manner to enable efficiency improvements for future analyses. Furthermore, the knowledge gained from the analysis results can be used for the further development of the process model and the resulting decisions (Wagenmann et al. 2022b).

3 RESEARCH QUESTIONS AND METHODOLOGY

The usage data of reference system elements can be analysed to validate elements in the system of objectives and to derive data-based decisions in the development process. This results in the potential to optimally adapt a new product generation to the requirements arising on the market and to use the available resources in a targeted manner. The process model for data-driven validation of elements in the system of objectives aids developers in performing data analyses and deriving decisions on the product design. The goal of this work is to develop supportive tools for developers to describe analysis use cases and subsequently perform analyses for the data-driven validation of elements in the system of objectives. In doing so, the following research questions are answered:

1. Which descriptive attributes are required for the description of analysis use cases for the data-driven validation of elements in the system of objectives in product generation engineering?
2. How can a standardized tool for the description of analysis use cases for the data-driven validation of elements in the system of objectives be designed?
3. What are the benefits of the application of this tool for the description of analysis use cases for the data-driven validation of elements in the system of objectives within product generation development?

This work is structured according to the Design Research Methodology (DRM) (Blessing und Chakrabarti 2009). In the descriptive study I, research question 1 is answered with the help of an empirical analysis of the research environment and the exchange with domain experts to generate a deeper understanding of the important dimensions for describing analysis use cases. In the prescriptive study, research question 2 is answered by developing a template as a supportive tool for developers to describe analysis use cases in the data-driven validation of elements in the system of objectives. The validation cycles for the synthesis of the template are illustrated in Figure 3.

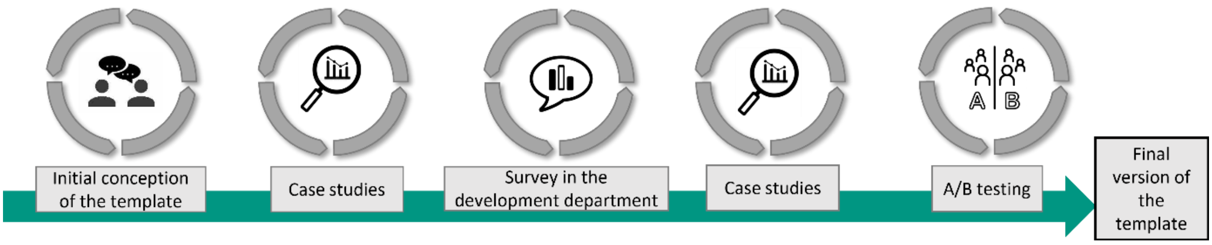

Figure 3. Validation cycles for the synthesis of the template for the description of elements in the system of objectives

The template was initially defined based on the previously identified dimensions. The initial template is further developed iteratively over the course of 28 case studies. Hereby, data analyses have been

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carried out based on real analysis use cases from the development department of a German machine tool manufacturer. The usage data for the analysis use cases originate from various data sources of machines for laser cutting, for bending as well as punching machines. In order to further increase the maturity level, a survey was conducted to ensure the completeness of the template and validate its understandability in the development department. In the descriptive study II, research question 3 is answered by validating the template in the research environment. The final validation is carried out by means of an A/B test in which participant from the development department, product management and sales evaluate the final template regarding its overall comprehensibility and applicability.

4 DIMENSIONS AND CORRESPONDING ATTRIBUTES FOR DESCRIBING ANALYSIS USE CASES

The attributes for describing analysis use cases are observed and derived through accompanied analysis use cases. The analysis use cases originate from current development projects of a machine tool manufacturer and deal with the concrete use of these mechatronic systems by customers. The subject of the analysis use cases are validation activities of mechatronic systems with the help of machine usage data. The studies have shown that the basis for an efficient analysis process is a common understanding of the system and the goal of the analysis by all the players involved in the problem-solving team. Driven by the high complexity associated with mechatronic system development, misunderstandings can arise in interdisciplinary collaboration due to knowledge gaps. The same facts, based on the competencies and knowledge available to the developer, can be interpreted differently by different developers. As a result, for example, data-driven validation activities are performed in an uncoordinated manner, erroneous results are derived, and misguided decisions are made. By clearly describing elements in the system of objectives, knowledge and competence differences in problem-solving teams can be minimized. The description of the mechatronic system to be analyzed and the goals of the analysis task itself allow a common understanding to be created. Figure 4 shows the descriptive dimensions: *General information, technical system, and data*.

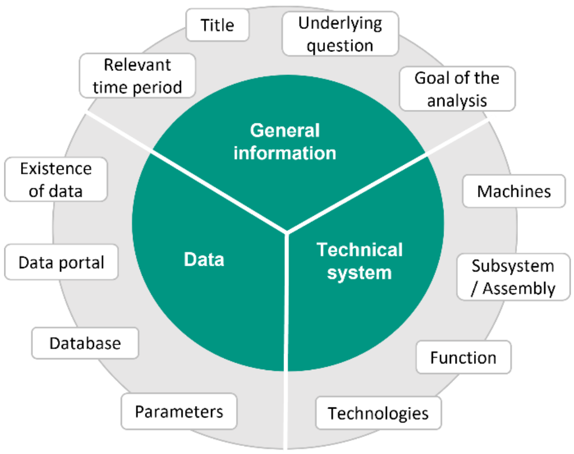

Figure 4. Dimensions and corresponding attributes for the description of analysis use cases

The dimensions are further subdivided into corresponding descriptive attributes. General information includes a title, the underlying question, the specific goal of the analysis, and the time to be considered for the analysis. In the application, this descriptive dimension serves developers as an orientation to the motives of the analysis task. Information on the technical system describes, for example, specific machine types, technologies, and functions. For functions in particular, a brief description of the function helps to create a uniform understanding of the system. Differences in the understanding of the operating principles of functions or the scope of functions can influence the subsequent analysis activities in the design of their objective. The case studies show that additional information on the functions is required in addition to the function description. Examples include test reports, interfaces to other system elements and change histories. In product development, this type of information can be bundled in requirements lists supporting this method of working (Bursac et al. 2021). Induced by the complexity of the systems under investigation, the analysis of use cases is carried out iteratively and

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continuously discussed with experts in order to uncover and eliminate errors incrementally. Consequently, the documentation of experts with specific knowledge of the systems under investigation is relevant for transparency and traceability. To be able to examine the analysis results as fully as possible, it becomes apparent that it makes sense for mechatronic system development to involve various experts with focuses in different disciplines in feedback loops. These feedback loops are necessary because the data quality in terms of consistency and completeness is often insufficient, or errors occur in the derivation of results due to an inconsistent understanding of the system.
Information about the data describes the origin, access, storage location, concrete designation and meaning, as well as the recommended approach for the previously described analysis goal. Access to customer machine usage data is still shared restrictively. As a consequence, developers who want to work with the machine usage data must have access to the data portal. These data portals then provide access to various databases which are managed by the responsible data owners. Tables on machine data in said databases often contain several hundred to thousands of parameter-value pairs. In terms of PGE, validation activities of current product generation can also be interesting for future product generations. The concrete documentation of analyzed parameters and values contributes to a sustainable data-driven validation process. After the analysis objective has been defined, the initial description of the planned procedure for the analysis and the iterative adaptation for documentation purposes have proven to be useful in a similar way. The procedure in the analysis is based on standardized statistical methods. In addition, two special cases can be identified: New parameter-value pairs must be calculated from existing parameter-value pairs and added as a column in data tables. Non-existent parameter-value pairs must be mapped by the logical combination of existing parameter-value pairs to delimit the analysis case under consideration from the population.

5 TEMPLATE FOR DESCRIBING ANALYSIS USE CASES

The approach for describing analysis use cases will be further developed based on the described attributes and synthesized into a template as tool for describing analysis use cases. With the overall goal of empowering developers in the data-driven validation of elements in the system of objectives, the requirement for an efficient design of the template arises. The handling must be intuitive, and the developer must be able to gather the required information in the shortest possible time to minimize the effort required for the application. The template available to the developers is shown in Figure 5.

Description of analysis use cases		
Creation of template: Robert Smith, 27.11.2021		
Last change of template: Jane Meyer, 07.08.2022		
General informationen	Analysis title	Used stamping power on stamping machines
	Questions to be answered by the	How often is the maximum stamping power used for sheet metal manufacturing?
	Purpose of the analysis	Potential redesign stamping tools
	Relevant time period	Last 5 years
Technical system	Machine(s)	Stamping machines
	Relevant function / subsystem / assembly / technical system	Round and square stamping dies
	Explanation of the function / classification of the assembly	Stamping dies of different forms penetrate the sheet metal in order to manufacture parts. The stamping power varies for different application factors such as material or sheet thickness.
	Link for further information about the technical system	https://login.jira.com/Devproject/Stampingmachine/Analysis
	Contact person for expertise on the technical system	John Steward
Data	Existence of data for analysis ?	yes
	Data portal	Company Analytics Database 1
	Contact person for the data portal used	Link to list of corresponding Data Portal Service
	Database and table used	Database1: Stamping tool technology table STTT
	Data owner of the database used	Link to list of corresponding Data Owners
	optional: tool for data export	N.A.
	Data fields and parameters on which the analysis is based	qrt_stamping.102 / message.stamping_power.186
	Procedure for this analysis	message.stamping_power.186 > 0 and message.stampingtool = exists
	Notes on data analysis	N.A.
Prior knowledge	Have similar use cases already been processed?	no
Other	-	

Figure 5. Template for the description of analysis use cases based on the dimensions

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The previously identified attributes for the description are represented in the template as components of the superordinate description dimensions general information, technical system, and data. The goal of the analysis can be derived from the title and the description analysis use case via the formulation of the initial questions. The period under consideration is the basis for the subsequent identification and selection of necessary data.

The next section of the template describes all required information about the technical system. In its structure, the template guides the user to successively concretize the relevant aspects for the description of the technical system in sub-steps regarding the initial questions or hypotheses. A better understanding of its benefits or its function is created. Depending on the complexity and the question, it may be helpful to include a technical drawing or the image of a CAD model of the reference system in the template to increase the understanding of the technical system and the purpose of the analysis. Furthermore, all attributes that make use of other knowledge databases are linked directly in the template. For example, the technical system description dimension contains a link to the requirements list associated with the object under investigation. Developers can thus directly view all information available on the system and subsequently store the template in the correct location for all other developers. A condition for the creation of a common system and analysis goal understanding is the absence of redundancy of the template in the sense of a document stored centrally for all. Thus, file storage in locations with restricted access is not expedient.

The understanding of the technical system and the question at hand forms the basis for the search for suitable data. Due to incomplete collection of data or poor data quality, the case can arise that no sufficient database exists for the initial question or hypothesis. Therefore, it must be specified for the description of the data landscape whether usable data exist for the analysis. The data location is specified successively in three steps in the template. In the first step, the data portal used is described. In the second step, the storage structure of the data stored there is comprehensibly described in the template in individual databases and spaces. In the third step, the concrete parameters required for answering the present questions are entered. Depending on the data portal used, it may be necessary to export the data to a local programming environment for processing and analysis. To describe the data landscape, contact persons must again be named for the data portal used and for the data used. Furthermore, the traceability of changes in the description of analysis use cases is important. The documentation of the time of the first recording and the last change with the corresponding responsible persons makes a significant contribution to this. With the change to a data-driven developing company, an increase of data analysis for validation purposes can be assumed. To make the process of data-driven validation of elements in the system of objectives as efficient as possible, it must be possible to use knowledge sustainably for future analysis. Efforts to perform data analyses can be optimized in this way. For example, code snippets and dashboard structures can be adopted or slightly adapted.

6 EVALUATION OF THE TEMPLATE FOR DESCRIBING ANALYSIS USE CASES

To evaluate the template at the individual level, the first study is to measure the time required to fill out the templates for all 28 use cases processed in the research environment. The results of this study are illustrated in Figure 6.

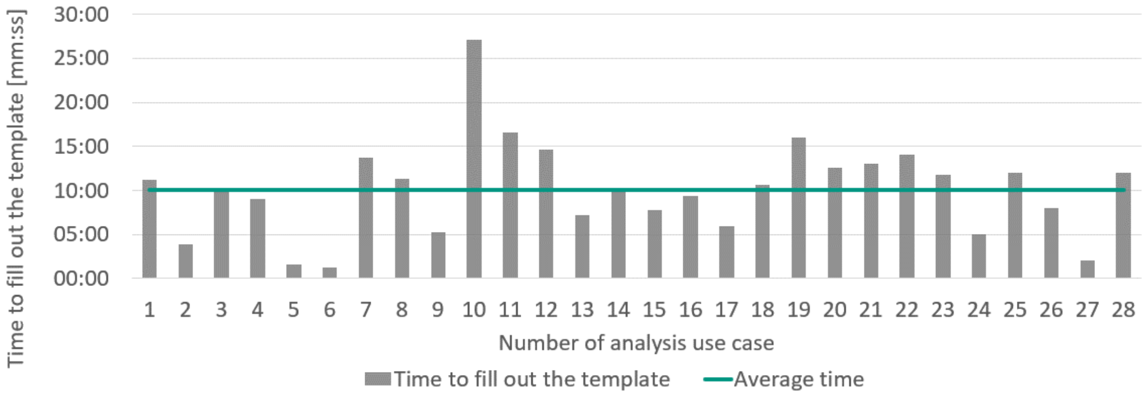

Figure 6. Time required to fill in the template for describing elements in the system of objectives

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The abscissa shows all analysis use cases that have been processed within the presented research. The ordinate shows the time required to complete the templates. The green dashed line indicates the average time required to fill out the templates across all 24 edited analysis use cases. The templates were filled out according to the order of the analysis use cases shown above from left to right, starting with use case number 1. In this study it is shown that an average time of 10 minutes is required to completely fill out the template. Learning curve theory states that there is a correlation between performance on a task and the time required to complete it. The more frequently a task is processed, the higher the efficiency and the lower the processing time required. Therefore, it was expected that the time a person needs to complete the template would steadily decrease over time (Henfling 1978). This assumption can be refuted with the time measurement carried out. Instead, the complexity of the use case, the accessibility to the required data and the existence of templates for thematically similar use cases have a direct influence on the time required to fill out the template. If analysis use cases have a low complexity, the description of the technical system is straightforward and clear parameters without any dependencies exist in the data. Thus, the information can be documented quickly. The more complex the technical system or the data structures are, the longer it takes to fill in the template. Furthermore, the availability of already completed templates for similar analysis use cases speeds up the completion of the template, since a certain amount of information is transferred directly from the already existing completed template. The basis for being able to use this advantage is a good and clear organizational structure in which similar analysis use cases and all associated documents can be found quickly and easily.

In the second study, filled out templates are evaluated in terms of comprehensibility and applicability in an AB testing. Thereby, 40 participants were asked to evaluate the filled-out templates qualitatively and quantitatively for three analysis use cases already processed in the research environment. For the survey, only persons who have not actively participated in any of the three use cases have been deliberately selected. As quantitative feedback, five theses were rated each on a scale of 1 (strongly agree) to 5 (strongly disagree). The quantitative results of the study are illustrated in Figure 7.

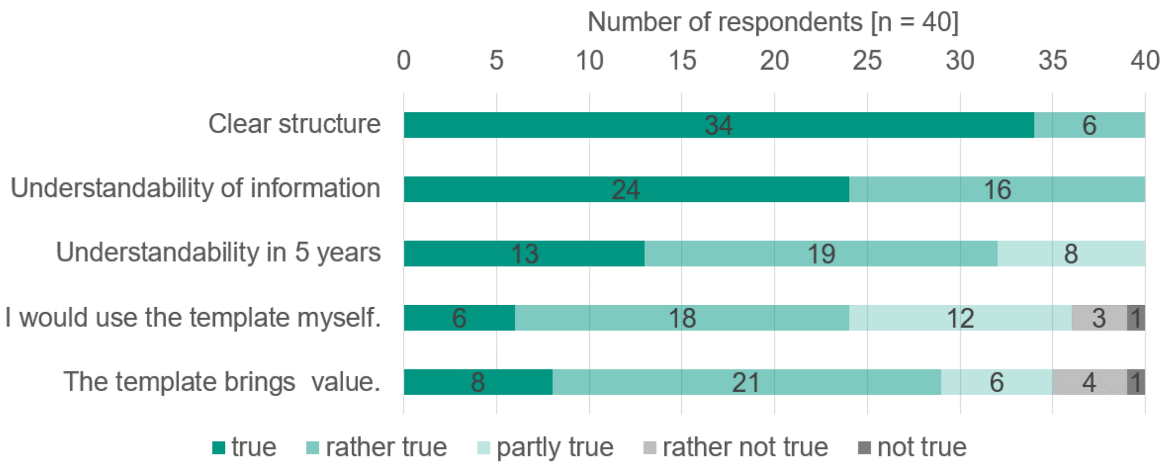

Figure 7. Evaluation of the template for the description of elements in the system of objectives

The feedback for all five theses was predominantly positive. 85% of the respondents fully agreed with the first thesis on the clear structure of the template. The division of the template into three thematic sections according to the three dimensions is highlighted as particularly positive as it makes the template easy to comprehend. Furthermore, the template is kept pleasantly short and allows a quick overview of all important information.

The second thesis on the comprehensibility of the information in the template is also predominantly positively evaluated. 60 % of the respondents fully agree with the thesis. The description of the goal and the specific questions are evaluated as useful for the general understanding of the use case. In addition, the naming of contact persons and the specification of links is helpful for the assignment of the use case within the organization and for further information and clarification of questions. Difficulties in understanding arise for some of the respondents in the section on data. Due to a lack of knowledge about data structures, it can be difficult to classify the data fields and parameters mentioned. It is helpful, however, that another contact person is named in the data section who can be contacted in this case. For the template to provide a long-term benefit, the information must also be

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traceable for years to come. Only 32.5% of the respondents fully agree with this third thesis. The comprehensibility of the filled-out templates depends largely on its structure and data landscape in the research environment. In terms of the structure and the designations in the template used for describing the technical systems and the data fields, the templates are geared to the status in the research environment. If new designations or new data storage locations are established over the years, the comprehensibility of the already completed templates will be severely limited. Therefore, it is important to maintain the filled-out templates as well as the structure and the designations in the template and to constantly adapt them to the current technical standard of the research environment.

The fourth thesis on the applicability of the template in everyday work is also positively evaluated. It emerges that some of the respondents do not have any direct application for the template in their field of activity. It has also been shown that many developers currently lack the necessary knowledge of the data structures for independent completion of the template. Independent completion of the template is therefore only possible in the first two dimensions. It can therefore be deduced that further assistance and additional expert knowledge are still needed to describe the data. Nevertheless, the concept of the template itself and its understanding are still rated positively.

The last thesis evaluates the added value that the template offers from the respondents' point of view. The added value for the developers surveyed lies in the fact that the template can be used to systematically obtain all the information required for the subsequent analysis. This builds up an understanding of the topic and the technical system being considered within a use case. Based on this basic understanding, the developer can find the correct data for the analysis and document it in the template. In addition to the consideration of the individual level, the template also creates added value at the multilateral level through its contribution to a sustainable knowledge management. The collected knowledge from the use cases processed to date is documented in the long term and can be reused for processing current use cases, thus increasing efficiency. In addition, domain knowledge from different areas can be combined through a central knowledge management structure. This results in a comprehensive validation of the use case from different perspectives. The basis for the reuse of knowledge and the data used is a transparent, well-structured and easily accessible storage structure.

7 DISCUSSION AND OUTLOOK

A systematization of data-driven validation activities through targeted standardized methodological support for developers offers great potential for accelerating and sustainably shaping a data-driven developing enterprise. This paper demonstrates the need to create a unified system and analysis goal understanding by describing elements in the system of objectives to perform data analyses in product development. In the descriptive study I, the descriptive attributes for the description of analysis use cases for the data-driven validation of elements in the system of objectives were identified and devided in three dimensions: General information, technical system, and data. For many developers the description of the technical system is no difficulty because they already have a lot of experience. However, due to historically low touch points with the use of machine data for development decisions, the description of the data dimension is still a challenge for many developers. Therefore, far-reaching assistance is necessary in this dimension in order to be able to support every developer in the description of use cases. Thus, in the prescriptive study, a template as standardized tool for the description of analysis use cases for the data-driven validation of elements in the system of objective was designed to provide adequate support for the developers to describe an analysis use case in all three dimensions. In the descriptive study II, this template was evaluated to identify and prove the benefits of the systematic description of an analysis use case. It was shown that the template is easy to understand the information and quick to fill out in an average of 10 minutes due to its clear structure. Due to the lack of basic knowledge about data structures and the complexity of data selection, it must be questioned whether the description of the data already makes sense in the second step of the process model or whether a final description only makes sense after the selection of the tools and data and the evaluation of their opportunities and risks.

Future research projects will investigate how the description of analysis use cases can be further optimized. Building on the findings of the case studies conducted, a stronger focus must be placed on the identification and selection of data and tools required for analysis in the methodological support of developers. The description of analysis use cases enables sustainable knowledge management and an efficient data-driven validation process.

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