Data collection framework for identifying and conducting root cause analysis of the causes of engineering deviations in product development

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Abstract

Unplanned deviations represent a significant challenge in agile product development, as existing methods predominantly focus on pre-planned engineering changes. This study introduces a data collection framework designed to systematically capture unplanned engineering deviations and their underlying causes within the context of agile systems generation engineering. The framework was implemented in a practical Live-Lab environment, where development data were collected and evaluated against identified requirements. The evaluation shows that the framework identifies engineering changes and deviations, facilitating detailed root cause analysis. The findings enhance understanding of deviation dynamics and support systematic analysis in engineering practice.

Keywords

Engineering Deviations, Data Collection Framework, SGE – System Generation Engineering, Engineering Changes, Live-Lab Case Study

1. Motivation

Engineering changes are an integral and inevitable part of the product development process, especially in complex and dynamic environments [1]. While they act as important drivers for innovation, they often cause cost overruns, delays, and quality issues if not managed effectively. Estimates suggest that nearly one-third of R&D capacity is consumed by change-related activities [2], studies indicating hidden efforts increasing that share up to 50 % [3]. In early development phases, the absence of appropriate instruments for early detection, systematic analysis, and targeted handling of changes presents a major risk [4]. Reducing the gap between planning and implementation is essential to mitigate development risks and costs.

Numerous studies have contributed to the development of engineering change management practices, including process models, taxonomies, and simulation-based assessments of change impact. Formal workflows, such as Engineering Change Requests, are well-established in industrial settings [5]. Yet, these methods primarily target pre-planned changes and rarely capture the emergent, often informal deviations that occur in agile system design. Research by FRICKE et al. emphasized that development teams benefit from a flexible and learning-oriented development process that allows them to better cope with and even learn from change [4]. Systematic handling of changes, particularly in the form of well-managed engineering change requests and orders, has been widely explored in the literature and applied in industrial practice.

Despite these contributions, one important gap remains: there is currently no framework to systematically document, analyze, and distinguish the emergence of planned engineering changes versus unplanned deviations during development. Targeted Data capturing during development and classification of deviations remains underexplored, particularly in agile hardware development environments. Consequently, the causes and propagation patterns of emergent changes often remain opaque, limiting proactive intervention and the development of effective theories.

This study addresses this gap by proposing a structured data collection framework tailored to complex development environments. This framework enables the collection and analysis of planning intent, realized outcomes, and contextual factors across an agile product development process. Using the Live-Lab *Generational Sheet-Metal Development* [6] as a realistic research environment. This data foundation enables a fine-grained analysis of engineering changes and deviations throughout the development project, thereby contributing to a deeper understanding of the nature, causes, and propagation of deviations in complex design tasks.

2. Theoretical background

The theoretical background required for the research at hand is explained below. Figure 1 illustrates the interaction of the individual topic areas.

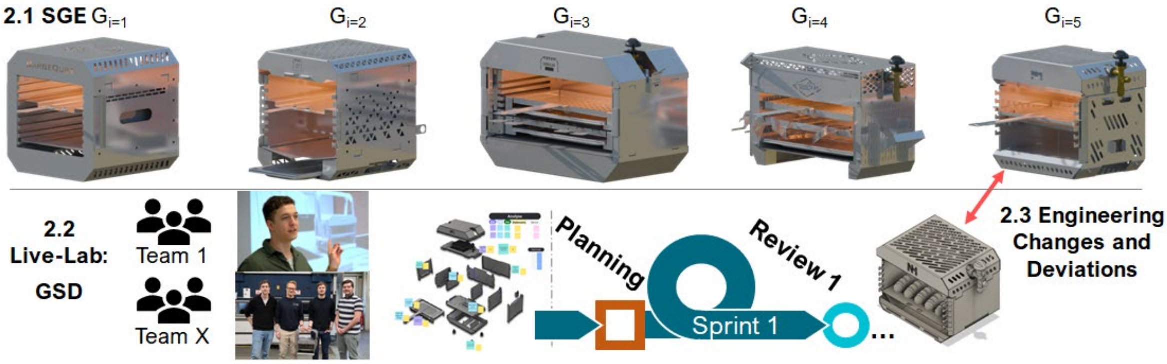

Figure 1: The present work is based on the research area of the model of SGE (chapter 2.1), takes place in a Live-Lab (chapter 2.2), and deals with the engineering deviations in product development (chapter 2.3)

2.1. Model of SGE – System Generation Engineering

In corporate practice, the development of new products and systems is always based on existing elements [7]. This means that products are not developed on a blank sheet of paper, but rather through the enhancement of existing solutions, as shown in Figure 1, for example, of a top hear grill. The model of SGE – System Generation Engineering, according to ALBERS, can be used to describe the fundamental development of systems. The model of SGE is based on two hypotheses [8]:

- Every development is based on a reference system. The reference system is made up of elements from existing or planned socio-technical systems. The reference system forms the starting point for the development of a new system. [9]
- The development of a new system is based on the reference system using the three variation types: carryover, attribute, and principal variation. Carryover variation (CV), for example, refers to the reuse of a subsystem from a reference system element in a new system generation, with modifications limited to interface adjustments required for integration. Attribute variation (AV) retains the elements and links of the reference system elements but alters some of the attributes. Principle variation (PV) involves adding or removing elements and links compared to the element in the reference system. [7]

2.2. Live-Lab: GSD – Generational Sheet-Metal Development

In the context of product development, a Live-Lab is a research environment that allows the investigation of product engineering methods and processes in a development process that is as close to reality as possible, with specific boundary conditions, designed at the same time. The aim is to improve engineering methods, process elements, and the corresponding tools, so they can be used effectively in industrial companies. [10], [11]

The Live-Lab *Generational Sheet-Metal Development* (GSD) is a master's course in Mechanical Engineering at Hamburg University of Technology. In this course, students work in small groups to learn about sheet-metal design by designing a top heat grill out of sheet-metal parts. Teams of five develop a new system generation based on reference grills in three clearly defined sprints, including CAD design, formalized reviews with real stakeholders, and prototype production at an industrial partner's side. The Live-Lab GSD thus combines the didactic elements of a university course with the requirements of everyday industrial development in sheet-metal design. [6]

2.3. Engineering Changes and Deviations

Innovative product development is scarcely possible without engineering changes, as such changes inherently involve both risks and opportunities. Consequently, companies must develop effective strategies for managing these changes: while unplanned deviations should be minimized, intentional and early changes are crucial for adapting to technological advancements and shifting requirements [4]. To systematically analyze this area of tension, a clear conceptual distinction between intentional *engineering changes* and unintentional *engineering deviations* is essential, particularly within the context of an iterative and agile development paradigm [3], where not every iteration necessarily results in a change, but each iteration systematically contributes to the generation of insight.

Engineering changes are actively implemented across all systems relevant to product development (e.g., the product itself, the production system, the validation system, or the strategy) and can be deliberately introduced at any stage of the product lifecycle [12].

In the SGE model, an engineering change can be described as a targeted variation or a cluster of targeted variations of one or more reference system elements of the current engineering or system generation during the transition to the subsequent engineering or system generation. Engineering changes are consciously decided and planned as early as possible [4]. They must be implemented and documented systematically to support the targeted further development of the system under consideration, which, in very innovative projects, determines the entire development process [4].

Engineering Deviations [13]**,** also referred to as *emergent changes* [5], can occur in all systems relevant to product development as well as at any stage of the product life cycle.

In the model of SGE, an engineering deviation can be described as an unplanned variation or a cluster of unplanned variations of one or more reference system elements while developing a new system generation. These deviations can be categorized into variation deviations, where the type of variation changes unexpectedly, and planning deviations, where the type of variation remains constant throughout the product development process, but the required effort and activities increase unexpectedly due to other causes. In contrast to engineering changes, engineering deviations occur late, unplanned, or unintentionally [14]. They are not systematically implemented or documented, but under certain conditions, they can contribute to the further development of the system. Case studies in practice show that the proportion of engineering deviations significantly exceeds that of engineering changes [15].

Despite their potential contribution to the advancement of technical systems, engineering deviations are considered risky in research. As shown by JARRATT et al., they often result in a lack of traceability, unintended interactions, and increased modification effort, which jeopardizes adherence to schedules and budgets [1]. FRICKE et al. also point out that many engineering deviations are not based on well-founded decisions but arise from time pressure or a lack of coordination, leading to inefficiencies [4]. Although SJÖGREN et al., emphasize that engineering deviations can, in individual cases, help identify previously unknown weaknesses and thus enable targeted improvements, this potential benefit is offset by a generally higher risk because they often lead to unforeseen propagation, disrupted schedules, and incompatibilities within the evolving system [5]. From a methodological perspective, it is therefore advisable to avoid unplanned engineering deviations as much as possible and instead initiate engineering changes at an early stage, and in iterations, to ensure that technical developments are controlled, traceable, and effective.

3. Research methodology

The occurrence of engineering deviations in the development process can increase the costs and risk in development many times over [16]. To reduce the occurrence of engineering deviations, the first step is to systematically analyze and understand them as they arise. This article aims to develop a framework for collecting development data from a Live-Lab. The framework is intended to enable researchers to use the development in a Live-Lab for research into engineering deviations. The data collection framework developed is to be transferred and applied using the example of the GSD Live-Lab to make various engineering deviations visible in individual case studies. In order to achieve the proposed research objective, a three-stage procedure is developed based on the Design Research Methodology (DRM), which is shown in Figure 2 together with the main outcomes [17].

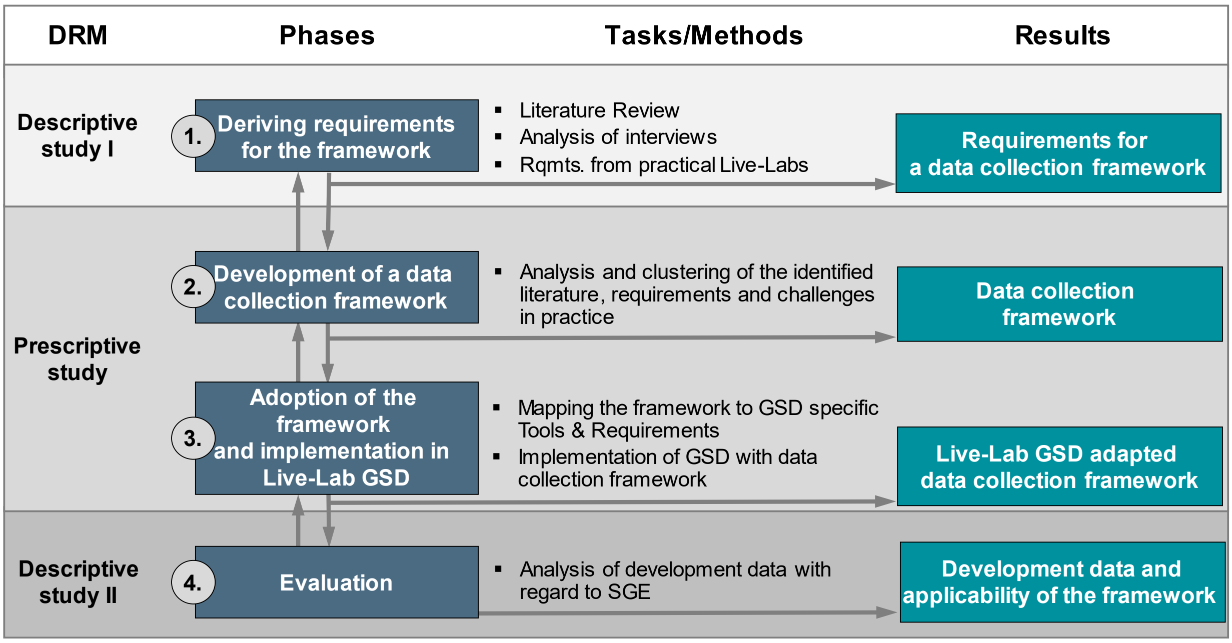

Figure 2: The phases and results of the study at hand based on the Design Research Methodology DRM [17].

The following research questions (RQ) are to be answered in the article:

- **RQ1:** What requirements does a data collection framework have to meet to systematically identify engineering deviations in development projects and analyze their causes?
- **RQ2:** How can a data collection framework be designed to collect data on engineering deviations in Live-Labs and apply it in the Live-Lab GSD?
- **RQ3:** What data can be collected using the data collection framework, and how far can engineering deviations in the development process be analyzed?

As part of **descriptive study I (DSI),** the requirements for the data collection framework are determined (RQ1). In the **prescriptive study (PS)** of the article, the data collection framework is created on the basis of the identified requirements and adapted and applied to the Live-Lab GSD in order to observe engineering changes and deviations in a realistic environment (RQ2). In the **descriptive Study II (DSII),** the data collection framework is evaluated. The case study discussed provides an insight into the extent to which the collected data is suitable for identifying engineering deviations (RQ3).

The Live-Lab GSD [6] provides a suitable research environment for the objectives of this study by combining real-world development conditions with a controllable experimental setup. Unified reference products enable the design of comparable datasets. Full availability of development artefacts, formalized reviews, and digitally documented decision-making processes enables targeted identification and analysis of deviations.

4. Results

4.1. Requirements for a data collection framework

Based on literature analysis, interviews, and findings from the implementation, 27 requirements for a data collection framework for the identification and root cause analysis of engineering deviations – from the areas of development process observation, the development environment, specifics regarding engineering deviations, methodological approach, and tool utilization – were identified.

One example of this is the need for a realistic development environment that reflects the complexity of real development processes [6] and is necessary for the emergence of unplanned deviations. Another aspect is the collection of target and actual values in order to be able to identify deviations [18]. Since engineering deviations are characterized both by the change in the type of variation according to the model of SGE and by increased, unplanned effort with the same type of variation, this means that the type of variation and the effort, for example, must be estimated and documented during planning.

4.2. Development of a data collection framework

Based on the requirements identified, a general framework for data collection can be created, as shown in Figure 3. The framework is designed to be generally applicable to agile product development processes and different issues. However, the focus of the framework is to identify and investigate the causes of engineering deviations in the product development process in Live-Lab case studies, for which it will be further adapted in the following chapter.

A distinction can be made between three forms of data - planning, realization, and process data - in the product development process.

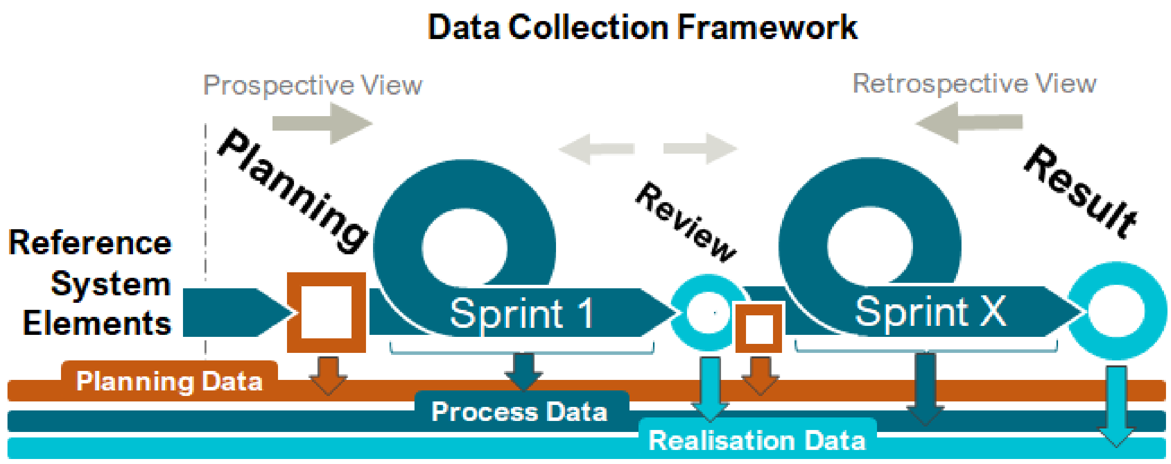

Figure 3: Data collection framework for the identification and root cause analysis of engineering deviations

The data collection framework thus offers the possibility of, for example, collecting the planning data that is associated with the corresponding reference system elements and planned variation types according to the model of SGE, as well as the planned effort and activities. This enables engineering deviations to be identified by comparing prospective planning and retrospective realization data. A comparison of the data is essential for identifying and distinguishing engineering deviations from engineering changes.

Root cause analysis is made possible by analyzing process data. This provides insights into decision-making or design processes in the product development process. A distinction must be made between observational process data collection and process data collection that is contextualized by the group afterwards. Observational process data collection, for example, provides data with less bias and makes it possible to observe the decision-making process and its trade-offs. Contextualization can, in turn, represent relationships over large temporal spaces.

4.3. Adaptation of the data collection framework to the Live-Lab GSD

The implementation of the data collection framework in the Live-Lab GSD illustrates the design of a research environment that effectively bridges practical application and scientific rigor. The methodical linking of teaching, practice, and research, the didactic embedding of supplementary measures such as workshops and surveys in the course of the event, and the targeted selection and expansion of digital tools led to the development of an integrated system for data collection.

Four tools were used to collect different forms of data: the CAD software Autodesk Inventor, digital whiteboards in Miro, video recordings via Microsoft Teams, and anonymous surveys using Lime Survey.

The CAD data was systematically collected and archived at defined review dates. Especially in the early phase of the product development process, digital whiteboards in Miro offer creative freedom that the teams can use for structured planning and documentation even without special software knowledge. The automated recording of meetings supervised by researchers or tutors, as well as internal development and study team meetings using Microsoft Teams, including automated transcription, enables precise subsequent analysis of the meetings by the researchers without their physical presence. In addition, anonymous surveys from Lime Survey also allow implicit or sensitive aspects that may remain unspoken in personal conversations to be recorded.

4.4. Evaluation of the data collection framework with case study data

As part of the Live-Lab GSD, three project groups were supported in the product development process over a period of four months. In various review, workshop, and design sessions, around 2,100 information items were collected as planning data on digital Miro boards and then analyzed. In addition, 192 CAD components and assemblies were created, which served as realization data. In addition, 14.9 GB of video recordings and 413 DIN-A4 pages of transcripts were generated, from which primarily process data, but also planning and realization data could be extracted. In addition, 29 surveys were conducted, which contributed to the expansion of the process data.

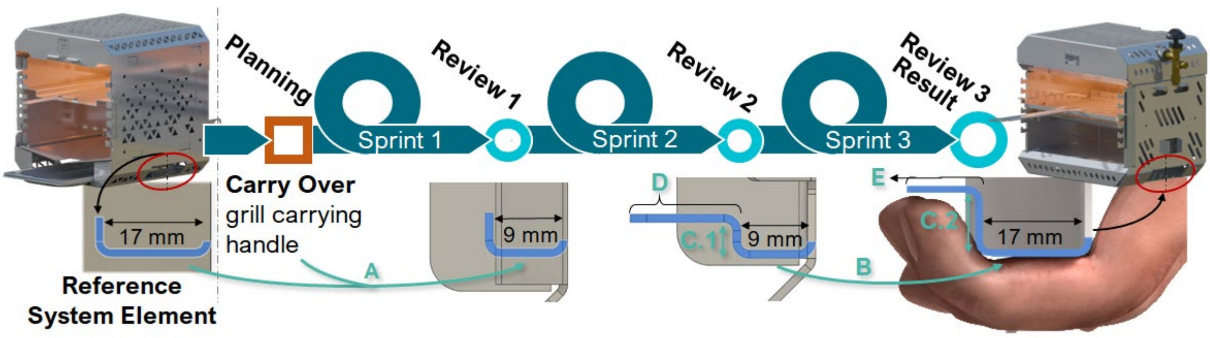

Figure 4: Deviations in the product development process using the example of a top heat grill carrying handle

Several case studies were derived from the data collected by manual analysis. One of these case studies is presented below as an example: Figure 4 shows the analysis of a subsystem with five identified deviations. It shows a grill carrying handle that is formed by two bends in the side wall and is used for two-handed, ergonomic transport of the reference grill.

According to the original planning (documented on Miro), the grill carrying handle was planned with a carryover variation (CV) from the reference system element. In this case, however, as documented in Review 1 in the archived CAD data and the video recordings, this was deviated from by reducing the handle's leg length in an attribute variation (deviation A). Analyzing the CAD data recorded over several sprints made it possible to identify four further deviations (B-E).

Video recordings of the reviews and workshops, as well as surveys on development progress, are available for root cause analysis, allowing different causes of deviations to be analyzed. This showed that the extension of the leg length in Sprint 3 (B), for example, was because the functionality of the handle, as in the original reference system element on the left-hand side, was to be ensured (reversing the previous attribute variation in deviation A). The extension of the vertical leg (C), on the other hand, is due to the manufacturing process. The implementation of a finger protection leg (D) was based on validation measures that led to an unplanned principal variation. However, due to assembly restrictions, the finger protection tab (E) had to be shortened in Sprint 3 (attribute Variation). In addition to the deviations themselves, this also illustrates the high number of interactions between the subsystems.

Based on the data collected in the case study, 16 of the 27 requirements for the data collection framework were completely fulfilled, nine requirements were largely fulfilled, and just two requirements were insufficiently fulfilled.

5. Discussion

In the Live-Lab GSD, extensive data were collected using the developed data collection framework, enabling both the identification and root cause analysis of engineering deviations. The model of SGE proved to be suitable for systematically describing engineering changes and deviations. With its real and complex product development process, the Live-Lab GSD offers a practical research environment in which engineering deviations can be authentically observed and analyzed.

CAD data predominantly formed the basis for identifying changes. Engineering deviations were identified by comparing them with planning data from Miro boards or recordings from the planning workshop. In individual cases, the lack of intermediate statuses made identification more difficult, although many development steps could still be traced. The manual effort required to search for deviations is also high.

Miro online whiteboards proved to be a helpful tool for supporting flexible planning and idea generation in the teams, particularly in the early, creative phase of product development. Although an automated evaluation is challenging, it was not of decisive relevance for the objectives of this study.

The root cause analysis of engineering deviations was supported by extensive video recordings. In particular, the retrospective contextualization of planning and realization data as part of a workshop proved to be an effective analysis tool. The preparatory work required for this and the early necessary identification of deviations could be reduced in the future by recording more design processes. In addition, individual video recordings have already enabled the direct identification of deviations, making it easier to link heterogeneous data sources and analyze them.

Anonymous surveys were also used but played a subordinate role in the root cause analysis, as most of the relevant information had already been collected through video recordings and retrospective contextualization. As a result, the lack of group-specific analyzability and low participation rate did not play a significant role in the analysis results.

The analysis showed that the linking of different forms of data - planning, realization, and process data - is particularly crucial for a comprehensive identification and root cause analysis of engineering deviations. A systemic view of the overall system, as carried out as part of this study, also proved to be essential. This is primarily due to the large number of interactions between the subsystems as well as the interrelationships that were unknown at the start of development.

The investigations in the Live-Lab were conducted with Master's students, so transferability to industrial contexts with experienced designers should be validated in future field studies.

The differentiation between engineering changes and engineering deviations is possible and can be further improved by a more refined and intensified collection of planning data compared to the data collection carried out in the Live-Lab GSD.

The developed data collection framework already addresses numerous practical challenges and fulfils the identified requirements, as described in Chapter 4.2. There is potential for optimization, particularly concerning the automation of data evaluation and the systematic storage of CAD data. Overall, the application in the Live-Lab GSD demonstrates the practical suitability and added value of the framework for research into engineering deviations.

6. Conclusion and Outlook

This study developed and applied a data collection framework designed to systematically capture engineering deviations and facilitate root cause analysis within agile development environments. The results demonstrate that the framework effectively integrates planning, realization, and process data into a cohesive structure. Applied in the GSD Live-Lab, the framework enabled the identification of both intentional engineering changes and unplanned deviations, offering a contextualized understanding of their occurrence and underlying causes.

In response to the first research question, the study derived 27 specific requirements that a data collection framework must meet to enable systematic detection and analysis of engineering deviations. These include a realistic development environment, documentation of planning intent, traceability of design decisions, and the collection of contextual data. Regarding the second research question, the framework was successfully adapted and implemented in the GSD Live-Lab, where data was collected using integrated tools such as CAD software, digital whiteboards, video recordings, and anonymous surveys. In addressing the third research question, the evaluation showed that the collected data facilitated the identification of deviations and, through triangulation of multiple data sources, enabled detailed root cause analysis in many cases.

The study contributes to bridging the methodological gap between formal change processes and the informal dynamics of agile development. The proposed framework serves both as a practical tool for deviation analysis and as a structured foundation for future research. However, several limitations were observed: incomplete CAD documentation and missing video recordings of meetings limited traceability, and automated data analysis was constrained.

The refined data collection framework in the next GSD cohort addresses these limitations. It will be refined through integration with a Product Data Management (PDM) system, an improved planning data collection structure, and enhanced by AI-based transcript analysis. In addition, the use of the tools is made even easier for students by providing suitable access points and motivating them to use the MS Teams rooms even more during the course. These enhancements aim to improve data completeness, reduce manual effort, and provide students with targeted feedback. The approach is transferable to other Live-Lab environments and, under certain conditions such as tool integration and process documentation, is also applicable to industrial product development. In the long term, the framework may support the development of resilient, learning-oriented environments that proactively manage and reduce engineering deviations.

Acknowledgment

The authors gratefully acknowledge the support of the research project "Development of an ontological model of the PGE and methodological support for the reduction of variation and planning deviations in sheet metal construction" with project number 530789856 by the funding of the German Research Foundation (DFG).

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