A User-Study Protocol for Evaluation of Formal Verification Results and their Explanation

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**Abstract—Context:** Ensuring safety for any sophisticated system is getting more complex due to the rising number of features and functionalities. This calls for formal methods to entrust confidence in such systems. Nevertheless, using formal methods in industry is demanding because of their lack of usability, e.g., the difficulty of understanding verification results. Thus, our hypothesis is that presenting verification results of model checkers in a user-friendly manner could promote the use of formal methods in industry. **Objective:** We aim to evaluate the acceptance of formal methods by Bosch automotive engineers, particularly whether the difficulty of understanding verification results can be reduced. **Method:** We perform two different exploratory studies. First, we conduct an online survey to explore challenges in identifying inconsistent specifications and using formal methods by Bosch automotive engineers. Second, we perform a one-group pretest-posttest experiment to collect impressions from Bosch engineers familiar with formal methods to evaluate whether understanding verification results is eased by our counterexample explanation approach. **Limitations:** The main limitation of this study is its generalization, since the survey focuses on a particular target group and uses a pre-experimental design.

**Index Terms**—user study, error comprehension, counterexample interpretation, formal methods, model checker

I. INTRODUCTION

During the development of safety-critical systems, as and when the requirements or the system specification change, the consistency of the system specification must be verified. In an industrial setting where this re-verification is done almost always manually [1], contract-based design (CBD) [2] can substitute this manual work by automating the verification process using a model checker (cf. Fig. 1 and Sect. 2 in [3] for an example). Whenever an inconsistency is found during the verification, the model checker exemplifies the violation by generating a counterexample. It is then up to an engineer to understand the counterexample and to identify the root cause of the violation by manually tracing the violation back from the counterexample to the original system specification.

Identifying the inconsistent specifications from a set of specifications is challenging, though, because specifications of real-world use cases can comprise hundreds of pages [4]. Further, identifying faults from a counterexample is error-prone and time-consuming, especially for non-experts in formal methods because counterexamples are lengthy and cryptic [5]-[9]. Thus, an automated method for explaining counterexamples is highly desirable to assist engineers in understanding counterexamples and thus, in identifying faults in their models.

Formal methods are not new to Bosch. They are used to specify requirements as pattern-based specifications to support verification during product development [10], [11]. Additionally, we have presented a counterexample explanation method.
approach that attempts to ease the use of formal methods by reducing the manual work and difficulty of interpreting the verification results generated by model checkers [3]. Particularly, we target refinements in system design and the verification of their consistency. Usually, engineers refine a top-level component and its specification into sub-components and their respective individual specifications. A model checker can verify the consistency of such a refinement. If an inconsistency was introduced during the refinement by an engineer, the model checker returns a counterexample. Our approach provides an additional explanation of this counterexample to engineers in order to ease understanding of the model checker result and identifying the inconsistency of the refinement.

To explore whether our counterexample explanation approach [3] does improve the understanding of the model checking results, we intend to perform a one-group pretest-posttest experiment. Since we want to perform the study with professional engineers working at Bosch, our study requires working time from these engineers and thus implicitly incurs costs. Thus, the number of engineers to participate in the study will be limited. The one-group pretest-posttest experiment supports conducting the study with a limited number of participants. Further, to explore the general acceptance of formal methods and to contemplate on challenges and the complexity faced by engineers in identifying inconsistent specifications, we intend to perform an online survey. In this paper, we summarize the research questions that we evaluate, the design and execution plan of the study, target participants, analysis plan, and threats to validity.

II. Research Questions

Our study aims to explore and understand the challenges in identifying inconsistent specifications, and the acceptance of formal methods by Bosch automotive engineers. Therefore, this user study has two significant goals: (G1) to understand challenges faced by Bosch engineers in order to identify inconsistent specifications and challenges along with their opinions to use formal verification or formal methods in real-world development processes, and (G2) to explore whether Bosch engineers are interested in using formal methods, particularly model checking, in real-world development processes if the difficulty of understanding model checking results is reduced by our counterexample explanation approach. Considering these two goals, we formulate the following research questions:

**RQ1:** To what extent do engineers face challenges in identifying inconsistent specifications in formal models that are introduced during a refinement of a system? With this RQ we want to investigate whether:
- Understanding formal notations is difficult for engineers.
- Identifying inconsistent specifications that are introduced during a refinement of a top-level specification is difficult.

**RQ2:** To what extent is identifying inconsistent specifications and using formal methods beneficial to a real-world development process? With this RQ we want to investigate whether:
- Usage of formal verification or formal methods is beneficial in a real-world development process.
- Identifying inconsistent specifications is beneficial in a real-world development process.

**RQ3:** To what extent do engineers prefer to use formal methods (model checkers particularly) if the difficulty is reduced for understanding verification results to identify inconsistent specifications? With this RQ we want to investigate whether:
- The counterexample explanation approach eases comprehension compared to interpreting the raw model checker output for engineers with a formal methods background.
- The counterexample explanation approach is understandable by engineers with a background in formal methods.
- It is possible for engineers with a background in formal methods to identify and fix inconsistent specifications based on the counterexample explanation approach.
- The counterexample explanation approach can promote formal verification and usage of model checking in real-world development processes.

III. Variables

To attain the goals G1 and G2, we perform two different types of exploratory user studies as shown in Figure [1]. The first study is an online survey (Part 1), the second study is a one-group pretest-posttest user study (Part 2).

A. Variables of Part 1: Online Survey

Our online survey evaluates the research question RQ1 and RQ2. The independent variables of Part 1 are participants’ professional background and experience. The dependent variables are different for each research question. For the research question RQ1, the dependent variable is the difficulty in understanding that infers that understanding formal notations and identifying inconsistent specifications by engineers are difficult. Similarly, the dependent variable for RQ2 is the increase in confidence in system safety, that is, the identification of inconsistent specifications and use of formal methods in real-world development processes can make systems safer.

B. Variables of Part 2: One-Group Pretest-Posttest Design

As per Babbie [12], an experimental stimulus (also called an intervention) is the independent variable. In the one-group pretest-posttest design, we use our counterexample explanation approach as the intervention. Therefore, it serves as the independent variable of Part2. Further, the research question RQ3 are evaluated based on the following four attributes that serve as dependent variables for Part 2 of our study:

1) Better understanding: Does the counterexample explanation approach allow engineers to understand model checking results and identify inconsistencies more effectively?
2) Quicker understanding: Does the counterexample explanation approach allow engineers to understand model checking results and identify inconsistencies more efficiently?
3) **Confidence:** Does the counterexample explanation approach make engineers more confident in their understanding of the system and its inconsistency resp. safety?

4) **No value:** This attribute is inversely related to the above attributes. Will the counterexample explanation approach provide no or only minimal value to real-world projects?

**IV. DESIGN OF THE USER STUDY**

In this section, we describe the design, questionnaires, and tools used for both the online survey (Part 1), and the one-group pretest-posttest user study (Part 2).

**A. Part 1: Online Survey**

For **Part 1**, we use a cross-sectional survey [13] to collect data from engineers to achieve the objective of G1. For planning and conducting the online survey, we follow the guidelines of Neuman [14, Chapter 7] (majorly), Kitchenham and Pfleeger [15], Fink [15]. In addition to Neuman [14], we follow Robson and McCartan [16, Chapter 11], and Babbie [5, Chapter 9] for the questionnaire construction. Further, we refer to and adapt some of the questionnaires from existing user surveys by Gleirscher and Marmsooler [17], and Garavel et al. [18]. Gleirscher and Marmsooler [17] perform the largest cross-sectional survey with 216 participants to study the existing and intended use of formal methods. Similarly, Garavel et al. [18] conduct a user survey with 130 participants and 30 questions to collect information on the past, present, and future of formal methods in research, industry, and education. Our main contribution wrt. similar surveys is: (1) we particularly focus on identifying challenges that engineers face in identifying inconsistent specifications, not general challenges of using formal methods, and (2) the study is performed with engineers who work on real-world automotive projects.

Table I presents the questionnaire prepared for our online survey. The response for each question is captured either as qualitative statements, a set of predefined scale answers, or a combination of both. We use a 7-point scale as it increases the reliability of answers from participants over a 5-point scale according to Joshi et al. [19]. The scale answers set we use in this survey is listed in Table I.

**B. Part 2: One-Group Pretest-Posttest Design**

**Part 2** of our study is an exploratory pre-experimental user study following a one-group pretest-posttest design to attain goal G2. We follow the guidelines by Campbell and Stanley [20] to conduct this part of our study.

One of the main drawbacks of using a one-group pretest-posttest design is that it does not meet the scientific standards of an experimental design. For example, the pre-experimental study designs do not have a control group like a true experiment [21]. Thus, comparison and generalization of the results based on the provided intervention/stimulus may not be possible. However, we intend to use this pre-experimental user study design because of the scarcity of participants. To find a considerable number of participants (30 to 40) with knowledge of formal methods and model checkers inside an industrial organization is ambitious. Performing a true experiment with a lower number of participants raises the threat to external validity. Therefore, we intend to perform a one-group pretest-posttest experiment with Bosch automotive engineers that allows us to capture results from real-world user behavior, even with a limited number of participants. However, the pre-experimental study has several internal and external threats to be considered. We discuss handling of the threats listed by Campbell and Stanley [20] in Section V.

Along with the guidelines by Campbell and Stanley, we refer to the protocol by Zaidman et al. [22] for a one-group pretest-posttest experiment. They evaluate a tool called FireDetective that supports understanding of Ajax applications at both the client-side (browser) and server-side. Their evaluation is performed using two user study variants (i) pretest-posttest user study, and (ii) a field user study, where the former is performed with eight participants and the latter is performed with two participants. We plan to perform the one-group pretest-posttest experiment with Bosch automotive engineers and discard the field user study for our evaluation.

The questionnaire presented in Table III is used for the one-group pretest-posttest study (Part 2 of our overall study). Similar to Part 1, the response for each question is either a qualitative statement, or a set of predefined scale answers with 7-point scale, or a combination of both.

**C. Tools used for the Study**

Since we do not require time recording, we will use Microsoft Forms for Excel [23] for the user study that provides required features for performing a survey. Further, it is easily accessible within the company and already familiar to the participants. Later, we plan to transfer the results to an Microsoft Excel to perform the analysis.

All content-wise explanations for both Part 1 and Part 2 of the study are provided as a video and are accessible via an online platform, e.g., YouTube or the Bosch-internal equivalent called BoschTube.

**V. PARTICIPANTS**

Our counterexample explanation approach focuses on enhancing safety analysis for automotive systems [3]. Thus, we are interested in performing this user study only with Bosch automotive engineers, particularly engineers working on system development, requirement elicitation, and safety analysis. The target population for our study is very specific and thus, it is hard to make a finite list of participants by applying probabilistic sampling. As per Kitchenham and Pfleeger [13], when a target population is very specific and limited, non-probabilistic sampling can be used to identify the participants. Therefore, we intend to use two non-probabilistic sampling methods for Part 1 of our study, namely, convenience sampling and snowball sampling. Further, we invite participants with knowledge on formal methods for Part 2 of our study by
filtering the participants of Part 1 based on the responses to the demographic questions Q1 to Q3.

First, we start with the convenience sampling for Part 1. We send e-mails with the survey link to participants collected through department mailing lists and community mailing lists of all relevant Bosch business units. We perform snowball sampling with the accepted participants by asking for further potential participants at the end of the survey. In the e-mail invitation, we will explicitly mention that the anonymity of results will be preserved. So, while publishing results or sharing the survey responses for evaluation, we will remove all personal, product- and project-related information.

VI. EXECUTION PLAN

In this section, we describe the execution plan of both the online survey (Part 1) and the one-group pretest-posttest user study (Part 2), depicted in Figure 1.

A. Execution Plan of Part 1

With the accepted participants from the sampling process described in Section V, we perform an online survey (Part 1) that comprises four steps (cf. Figure 1).

First, we notify participants regarding the data processing agreement. Additionally, we also state explicitly that their names, project- and product-related information will be removed while results are shared for evaluation. Then we show a video, welcoming the participant and explaining the background and motivation of this survey. Then, we ask participant to answer the demographic questions (Q1 to Q5 in Table I), and further the main survey questions (Q6 to Q18 in Table I).

Finally we conclude the survey with a thanks note.

B. Execution Plan of Part 2

For the one-group pretest-posttest user study, we invite participants from Part 1 who indicated knowledge of formal methods. Similar to Part 1, Part 2 starts with a data processing agreement, followed by a background and motivation video. Our one-group pretest-posttest user study is executed with the invited participants as follows: a pretest experiment, then intervention, and finally the posttest experiment.

a) Pretest: The pretest experiment starts with a video demonstrating the pretest experiment with a simple example of an OR-gate behavior. After that, another video explains the system model and specification of an airbag system that serves as a use case for the pretest experiment.

During the actual experiment, the participant analyzes the violated specification and the counterexample returned by the model checker to understand the inconsistent parts of
the specification. Further, based on her understanding, the participant answers the task questions (TQ1 to TQ9 except of TQ4 in Table III). Finally, the pretest is concluded by answering the pre-questionnaire survey questions PRQ1 to PRQ4.

b) Intervention: After the pretest experiment, a video explains the counterexample explanation approach [3]. This serves as an intervention in our study.

c) Posttest: Like the steps followed for the pretest experiment, the posttest experiment starts with a demonstration video with the same use case of the OR-gate behavior, but this time with the counterexample explanation approach. This is followed by a video that explains the system model and specification of the electronic power steering system (EPS), a commercial Bosch product. Then the participants interpret the explanation provided by the counterexample explanation approach to understand the inconsistency. Based on the explanation, participants answer the task questions (TQ1 to TQ9 except of TQ3 in Table III). Subsequently, they answer the post-questionnaire survey questions POQ1 to POQ4.

After completing the posttest experiment, participants rate the features (FQ1 to FQ6 in Table III) provided by the counterexample explanation approach and respond to the feedback questions (FE1 to FE8 in Table III). Finally, Part 2 of our study concludes with a thanks note to the participants.

VII. ANALYSIS PLAN

To obtain the results from the study, we follow the recommendation by Robbins and Heiberger [23]. To plot the demographic questions (Q1 to Q5), we use a normal bar chart. The graph we intend to use is a diverging stacked bar chart. The graph we intend to use is a diverging stacked bar chart. The graph we intend to use is a diverging stacked bar chart.
chart with counts (see Figure 10 in [23]) to plot the results for questions (Q6 to Q18, FQ1 to FQ6, and FE1 to FE8). The X-axis label of the graph shows counts and percentages, the Y-axis label shows the demographic answers. To present the pretest and posttest experiment results in a comparative way, we use grouped bar charts. For the comparative graph of task questions (TQ1 to TQ9), X-axis labels are individual questions, and Y-axis are the number of correct answers. Likewise, for understanding the result questions (PRQ1 to PRQ4 and POQ1 to POQ4), X-axis labels are scale values (cf. Table II), and Y-axis is the count for every scale value. We do not associate demographic answers for plotting the comparative graphs. To make a reliable argument, we use the demographic answers for discussing the comparative graph. For example: "2 out of 10 participants who have more than ten years of experience answered TQx correctly”.

Qualitative statements received from participants are gathered, organized, and summarized individually for every question. We summarize the qualitative statements through the following three steps: (i) **Microanalysis:** The answers from participants are gone through individually by the first author and he assigns labels to statements. The rest of the authors will validate the initial labels and provide feedback for improvement. At the end of this step, all authors come to a mutual agreement on the initial labels. (ii) **Categorization:** Based on the feedback for improvisation, the first author performs second iteration. As a result, a set of themes are extracted which are deemed to be essential. (iii) **Saturation:** This is the final step where all the authors come to the final agreement on labels, themes, and summarized statements. Since the qualitative statement is a medium to express an individual opinion, the categorization of labels are associated with the demographic answers. For example: "an engineer who has seven years of experience states that the counterexample explanation approach can promote the usage of model checkers among system engineers”.

### VIII. Threats to Validity

In this section, we discuss threats that may jeopardize the validity of our study results as well as measures we take to reduce these threats.

We consider threats to validity as discussed by Wohlin et al. [21], Kitchenham and Pfleeger [13], and Campbell and Stanley [20]. In the following, we structure them according to construct validity, internal validity, and external validity.

#### a) Construct Validity: The prime threats to construct validity are related to the completeness of the questionnaire and in phrasing questions in a way that is understood by all participant in the same way. To mitigate these threats, we have taken the following measures during our survey preparation: (i) we incorporated feedback from two senior engineers with a background in formal methods and model checking, (ii) we incorporated feedback regarding unbiased questions from a psychologist, and (iii) we intend to perform a pilot test with five research engineers to check for completeness and understandability.

#### b) Internal Validity: The critical internal threat to be considered for the online survey is the selection of participants. Since we follow snowball sampling for participant selection, there could be a possibility of several participants working in the same project, which could bias the final result. Therefore, we will consider only a small number of participants from each project and neglect further project members.

We consider threats to internal validity listed by Campbell and Stanley [20] for the pretest-posttest experiment. To mitigate the *history* and *maturity* threats, we plan to perform both the pretest and the posttest experiments on the same day. The most severe threat to be considered in this experimental design are *testing* and *instrumentation*. Those threats arise because participants get overwhelmed with the intervention. Consequently, participants could answer more positively in the posttest experiment than the actual value.

To mitigate these threats, we state to the participants explicitly that the obtained study results will serve as a reference in the future to use our counterexample explanation approach for real-world projects at Bosch. Additionally, to avoid overwhelmed responses and accept only valid responses, we will cross-check the answers provided for the task questions (TQ1 to TQ9). Further, to reduce biasing between the pretest and the posttest experiment, the use case of an airbag system (a toy example) used in the pretest is significantly less complex than the use case of the Bosch EPS system. However, to adjust the difficulty level of the systems used for the experiment, we plan to perform a pilot study with five research engineers. Adjustment of difficulty will be done by increasing or decreasing the number of components and size of the specifications that need to be understood by the participants.

#### c) External Validity: One of the severe drawbacks of the one-group pretest-posttest experiment is its generalization. However, the benefit of our study is that we use a real-world system for the posttest experiment, and the participants are professional engineers who work on real-world automotive projects at Bosch.

### IX. Implications

*Part 1* of our study will find the importance and difficulty of finding inconsistent specifications introduced during the refinement of top-level specifications as well as the necessities, acceptance, and challenges of using formal methods at Bosch. Further with *Part 2* of our study, we will evaluate whether our counterexample explanation approach is beneficial for the difficulties and challenges identified in *Part 1* and therefore for the adoption of formal methods in industrial projects at Bosch.

### References

[1] G. S. Walia and J. C. Carver, “A systematic literature review to identify and classify software requirement errors,” *Inf. Softw. Technol.*, vol. 51, no. 7, pp. 1087–1109, 2009.

[2] A. Cimatti and S. Tonetta, “A property-based proof system for contract-based design,” in *38th Euromicro Conference on Software Engineering and Advanced Applications, SEAA 2012, Cesme, Izmir, Turkey, September 5-8, 2012*, 2012, pp. 21–28.
[1] A. P. Kaleeswaran, A. Nordmann, T. Vogel, and L. Grunske, “Counterex-
ample interpretation for contract-based design,” in Model-Based Safety and Assessment - 7th International Symposium, IMBSA 2020, Lisbon, Portugal, September 14-16, 2020. Proceedings, 2020, pp. 99–114.

[2] V. Schuppan, “Extracting unsatisfiable cores for LTL via temporal resolution,” Acta Informatica, vol. 53, no. 3, pp. 247–299, 2016.

[3] L. van den Berg, P. A. Strooper, and W. Johnston, “An automated approach for the interpretation of counter-examples,” Electron. Notes Theor. Comput. Sci., vol. 174, no. 4, pp. 19–35, 2007.

[4] S. Leue and M. T. Befrouei, “Counterexample explanation by anomaly detection,” in Model Checking Software - 19th International Workshop, SPIN 2012, Oxford, UK, July 23-24, 2012. Proceedings, 2012, pp. 24–42.

[5] F. U. Muram, H. Tran, and U. Zdun, “Counterexample analysis for supporting containment checking of business process models,” in Business Process Management Workshops - BPM 2015, 13th International Workshops, Innsbruck, Austria, August 31 - September 3, 2015. Revised Papers, 2015, pp. 515–528.

[6] G. Barbon, V. Leroy, and G. Salaun, “Debugging of behavioural models using counterexample analysis,” IEEE Transactions on Software Engineering, pp. 1–1, 2019.

[7] P. Ovsiannikova, I. Buzhinsky, A. Pakonen, and V. Vyatkin, “Oeritte: User-friendly counterexample explanation for model checking,” IEEE Access, vol. 9, pp. 61383–61397, 2021.

[8] A. Post, I. Menzel, J. Hoenicke, and A. Podelski, “Automotive behavioral requirements expressed in a specification pattern system: a case study at BOSCH,” Requir. Eng., vol. 17, no. 1, pp. 19–33, 2012.

[9] A. Post and J. Hoenicke, “Formalization and analysis of real-time requirements: A feasibility study at BOSCH,” in Verified Software: Theories, Tools, Experiments - 4th International Conference, VSTTE 2012, Philadelphia, PA, USA, January 28-29, 2012. Proceedings, 2012, pp. 225–240.

[10] E. R. Babbie, The basics of social research. Cengage learning, 2016.

[11] B. A. Kitchenham and S. L. Pfleeger, “Personal opinion surveys,” in Guide to Advanced Empirical Software Engineering, 2008, pp. 63–92.

[12] W. L. Neuman, Basics of social research. Pearson/Allyn and Bacon, 2014.

[13] A. Fink, The survey handbook. sage, 2003.

[14] C. Robson and K. McCartan, Real world research. John Wiley & Sons, 2016.

[15] M. Gleirscher and D. Marmsoler, “Formal methods in dependable systems engineering: a survey of professionals from europe and north america,” Empir. Softw. Eng., vol. 25, no. 6, pp. 4473–4456, 2020.

[16] H. Garavel, M. H. ter Beek, and J. van de Pol, “The 2020 expert survey on formal methods,” in Formal Methods for Industrial Critical Systems - 25th International Conference, FMICS 2020, Vienna, Austria, September 2-7, 2020. Proceedings, 2020, pp. 3–69.

[17] A. Joshi, S. Kale, S. Chandel, and D. K. Pal, “Likert scale: Explored and explained,” Current Journal of Applied Science and Technology, pp. 396–403, 2015.

[18] D. T. Campbell and J. C. Stanley, Experimental and quasi-experimental designs for research. Rand McNally Chicago, 1963.

[19] C. Wohlin, P. Runeson, M. Höst, M. C. Ohlsson, and B. Regnell, Experimentation in Software Engineering. Springer, 2012.

[20] A. Zaidman, N. Matthijssen, M. D. Storey, and A. van Deursen, “Understanding ajax applications by connecting client and server-side execution traces,” Empir. Softw. Eng., vol. 18, no. 2, pp. 181–218, 2013.

[21] N. B. Robbins and R. M. Heiberger, “Plotting likert and other rating scales,” in Proceedings of the 2011 Joint Statistical Meeting, vol. 1, 2011.